A 3 m Class Telescope with Active and Adaptive Optics

With special regard to the
Iranian National Observatory

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Abstract

A 3m ground-based optical telescope, with active and adaptive optics, is a powerful and versatile research tool. This type of telescopes is affordable and manageable also for communities with limited previous telescope experience. While there are many scientific and technical reports regarding modern 3m class telescopes, there is no document giving a comprehensive description. This paper is an attempt to fill this gap.

For a 3 m class telescope, some properties of active and adaptive optics are discussed and the corresponding benefits described. The statements have been validated and illustrated via some results obtained from laboratory simulations and on-sky observations at Lund Observatory. A brief account is given of some science targets adequate and attractive with this class of telescope. Requirements are presented for a site adequate for a telescope of the type discussed. Some crucial site properties are commented.

Concerning telescope design, special attention is dedicated to important properties of optomechanics, optics and mechanics, while control functions are briefly described. Emphasis is given to concepts of foci and their properties, optical elements, their design, production and characteristics, optical telescope parameters, mechanical systems as mirror cells, centre sections, tubes and top rings and their combinations mutually as well as with optical elements. A brief account is given of telescope enclosures, emphasizing their critical role for high-quality observational results.

The topics and properties discussed are, to some extent, condensed in a closing chapter. Here a brief proposal is given for a high-quality yet affordable telescope of 3 m class.

To

Reza Mansouri

Acknowledgment

This dissertation would not have been possible without the guidance and help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this study.

First and foremost, my utmost gratitude to Prof. Arne L. Ardeberg, my supervisor in this work, whose professionality, generosity and encouragement I will never forget.

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A 3 m class telescope

In the beginning of 2009, for multi-task studies at visible and adjacent wavelengths, there are twelve Very Large Telescopes (VLTs), with apertures between six and a half and ten metres, or combinations thereof, in full or partial operation. In addition, there are three Extremely Large Telescopes (ELTs) in early progress with projected first light around 2018. The ELTs are intended for observations in a wavelength range from visual to thermal infrared. With apertures in the range three to six and a half metres, there are sixteen telescopes in operation and two in progress. Of these, many are relatively old and more competitive for light collection than regarding high image resolution. In addition, the sites of some of these telescopes are not among the best ones with modern ambitious requirements on atmospheric turbulence and frequency of observationally useful nights. Reference is made to the world-wide list of prominent telescopes for observations at visible and adjacent wavelengths made available Arnett (2009).

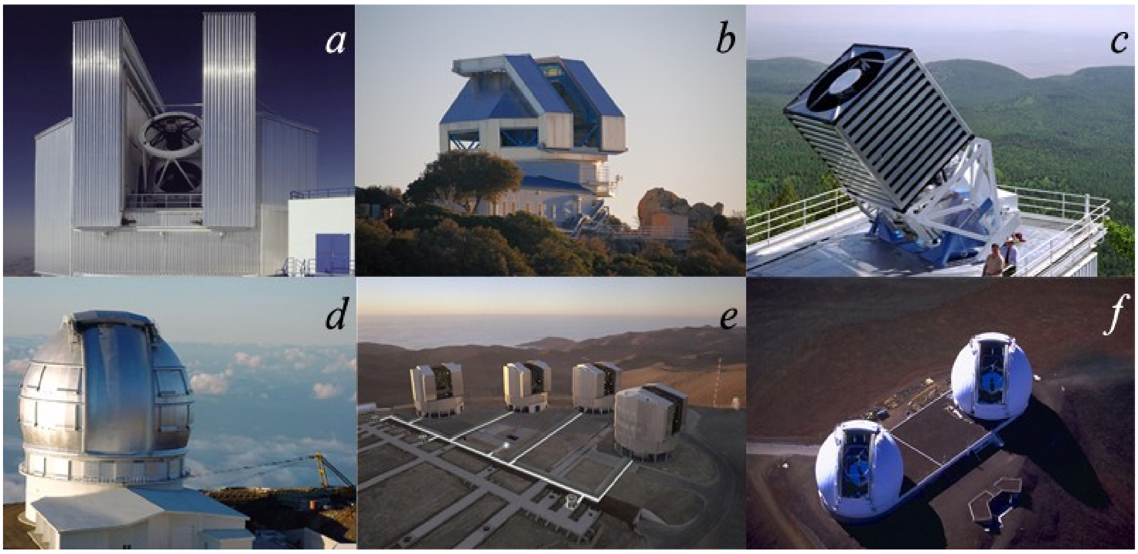


Figure 1. Upper panel: Some modern 3 m class ground based optical telescopes. a) NTT 3.6 m telescope at La Silla, b) WIYN 3.5 m telescope at Kitt Peak, c) Sloan 2.5 m telescope at Apache Point. Lower panel: Some very large optical telescopes, d) Gran Telescopio Canarias (GTC) with a 10.4 m segmented primary mirror at La Palma, e) VLT telescopes at Cerro Paranal, each with a monolithic 8.2 m primary mirror, f) Keck telescopes at Mauna Kea, each with a 9.6 m segmented mirror. (Photos from official websites).

A modern 3 m class telescope providing, at the same time, a generous wavelength range, a reasonably large field of view and images well resolved is an attractive tool for observational astronomy within a wide range of subjects. For highest usefulness, the telescope must be equipped with frontier auxiliary instrumentation, accommodating observations both for a wide spectrum of science applications and in a non-restrictive range of observational circumstances. The telescope with its instruments can, if well prepared, serve a multitude of scientific tasks. These include investigations based solely or largely on observations with the 3 m class telescope only. Further, and importantly, they concern collaborative research such as multi-telescope studies and follow-up programmes related to survey programmes and/or to science projects conducted with both space-born and ground-based telescopes. For all these, and other, programmes, a 3 m class telescope as discussed will provide important possibilities for successful initiatives and participation in modern research in astrophysics. At the same time as a modern 3 m class telescope sets the scene for conduction of important programmes in astrophysics, it defines a project within telescope technology that is, albeit challenging, well within reach of proven techniques. In addition, while ambitious in many respects, it is possible to manage within a budget of reasonable proportions. A modern 3 m class telescope may be seen as a choice for observational astrophysics that combines a large scientific potential with a moderately ambitious budgetary demand. Currently, the available number of 3 m class tele-

Table 1- Telescopes for visual and adjacent wavelengths with apertures 2.5 – 3.5 m

Telescope	Site	Alt. (m)	Year	Seeing (arcsec)	Aper. (m)	M1 ***f/***	Asp. Ratio	Act. Opt.	AO	Foci	Enclosure
Hooker	Mount Wilson	1800	1917	0.8	2.5	5	7.7	No	Yes, short time	Prime, Cass., Coude	Classic
Isaac Newton	La Palma	2336	1967/ 1984	0.7	2.54	2.94	6.5	No	No	Prime, Cass.	Classic
Du Pont	Las Campanas	2500	1977	0.6	2.54	3.0		No	No	Cass., Coude	Classic
Sloan	Apache Point	2788	1997	~1	2.5	1.3	7	No	No	Cass	Retractable
NOT	La Palma	2382	1988	0.7	2.56	2	13.4	Yes	Yes	Cass.	Co-Rot.
Shajan	Crimea	600	1961	1.3	2.64	3.85		No	No	Prime, Cass., Nas. ,Coude	Classic
Byurakan	Byurakan AO	1500	1979	1.7	2.6	3.85		No	No	Cass., Coude	Classic
Harlan Smith	Mont Loke	2030	1968	1.3	2.72	3.93		No	No	Cass., Coude	Classic
Shane	Mont Hamilton	1280	1959	≤2	3.05	5	7	No	Yes	Prime, Cass., Coude	Classic
WIYN	Kitt Peak	2080	1994	≤2	3.5	1.75	7.5	Yes	Yes	Nas.	Cube, Co-Rot.
MPI-CAHA	Calar Alto	2168	1984	0.9	3.5	3.48	8.5	No	No	Cass., Coude	Classic
ARC	Apache Point	2788	1994	~1	3.48	1.75		No	No	Cass.	Classic cubical

scopes as discussed is quite limited. Table 1 gives a list of the telescopes for visual and adjacent wavelengths with apertures between 2.5 and 3.5 m and in operation by the beginning of 2009.

Added benefits

There are a number of added benefits of the design, construction, installation and commissioning of a 3 m class telescope, not least in communities without previous installations of similar type. A project around a 3 m class telescope will imply activities in a number of disciplines, such as science-case priority discussions and programmes. These discussions will revitalise community activity concerning both science and technology. There will be ample feasibility discussions, modelling and testing of advanced systems of optics, mechanics, electronics and automatic control regarding the telescope targeted. Corresponding projects will in a most natural way develop around different types of auxiliary equipment for imaging, photometry, spectroscopy and polarimetry.

Further, options for the enclosure and its various effects on observations will tie together with site testing, evaluation and selection. To this we can add discussion of support facilities such as control buildings and coating plants. Important activities will concern evaluation of similar installations in other parts of the world as well as a number of contacts and consultations with exterior experts. All these activities will, in a rather natural manner, serve as catalysts and motors of scientific and technical strengthening and renewal. At he same time, the network of international contacts will be refreshed and intensified.

An important part of the impact of a 3 m class project is its influence on young astronomers and engineers. They will be most positively attracted, alerted and challenged. An initiative concerning a distributed yet orchestrated programme for training, project work and hands-on experience will further add to the positive impact. Internationally, there is as ample as convincing experience of the scientifically and technically beneficial influence, direct as well as indirect, of new and ambitious telescope projects. Adequately constructed and equipped, a modern 3 m class telescope will attract the interest of many astronomers not only from its home country but also from the rest of the world. This will substantially strengthen the international profile of the national science and technology community as well as its quality development.

Seen in a wider context, even more positive effects will result from the erection of a 3 m class telescope. It will stimulate and strengthen the public interest in both science and technology. It will increase the interest in these disciplines among young people, a movement highly beneficial to many aspects of modern society, its quality and sustainability. In a similar manner, it will greatly stimulate the community of amateur astronomers and other people interested in astronomy. Mass media will support and further increase the interest of the general public, not least when spectacular results and images get public.

The advanced technology inherent to the construction of a modern, competitive 3 m class telescope will favour industrial frontier activity. This will concern a number of aspects of industry. Examples are optics, mechanics, electronics, servo systems, automatic control and civil engineering. Reference in this context is made to Sánchez and Padrón, 1995, and to the European Commission, 2000.

Science with a 3 m class telescope

A modern 3m-class telescope equipped with active and adaptive optics is a powerful tool for science, provided that it is located at a site offering favourable atmospheric conditions. If, in addition to the active and adaptive optics facilities, and, thus, images with high spatial resolution, the telescope can provide both a generous field of view, with a diameter of at least 15 arcminutes, and a wavelength range from around the atmospheric ultraviolet limit to approximately 2000 nm, the scene is set for a wide variety of science programmes. In addition, then, the telescope is highly adequate as an instrument for collaborative programmes on the international arena. With a set of auxiliary instruments well selected, a number of projects with high scientific weight can be successfully conducted. Examples of science programmes include from objects in the Solar system and extra-solar planetary systems to stellar evolution, compact objects and various projects concerning galaxies and the evolution of galaxies.

Image quality and optical arrangements

A competitive 3 m class telescope means a telescope with, among other assets, a competitive image quality. That, in turn, implies a number of requirements on optical arrangements as well as on site selection and control of local air turbulence. First, the quality of optical elements as well as that of the mechanical dispositions maintaining optical alignment have to be of high standard. Second, the telescope site has to be chosen for excellent atmospheric conditions, with favourable turbulence parameters. Third, the telescope enclosure as well as the surrounding infrastructure have to be designed and constructed with minimum local production of air turbulence in mind. Fourth, observing routines have to adhere to strict routines not to jeopardize the image-quality improvements obtained via telescope, enclosure and site arrangements.

For high image quality, the precautions mentioned are an absolute necessity. Unfortunately, they are no guarantee, at least not in case of high ambitions regarding image quality. In practice, even excellent optical elements will, under operation, be more or less distorted and displaced at the same time as the mechanical structures supporting them will bend and turn. The higher the image-quality ambitions are, the higher is the practical vulnerability to such disorders. Also, the larger the telescope is, the more difficult is it to maintain its optical alignment in perfect order. In this sense, a 3 m class telescope defines a large challenge.

The ambitious installation must, first of all, as much as possible adhere to and conserve the intrinsic image quality as defined by the effects of the atmosphere. Thus, all additional image-quality degradation caused by the telescope and other installations must be kept to an absolute minimum. For higher requirements on image quality, this calls for active optics. In case of highest ambitions concerning image quality, also the degradations produced by atmospheric turbulence (Fried, 1965; Noll, 1976; Roddier, 1981; Kolmogorov, 1991) have to be counteracted. At this ambition level, some installation of adaptive optics has to be taken into account. For the very highest image-quality ambitions, with image sharpness approaching the diffraction limit, requirements on adaptive optics, as well as on active optics, get extremely high and demanding.

Passive optics

Below, optical systems of telescopes will be discussed as passive, active and adaptive. These denominations refer to the way in which the optical elements are controlled for optimum image quality performance. In a passive optical system, this control is limited to a pre-set correction system with regard to the primary mirror and, sometimes also, the secondary mirror. In the most basic version, the primary mirror is equipped with a support structure under a control system designed to compensate for effects of gravity only, while a more sophisticated solution includes effects of temperature variations as well, all through variations of support pressure. These effects, adjusting the form of the primary mirror surface, are taken to follow standard patterns. Supports are attached to the back side of the mirror and, although not always, along its rim. The goal is to maintain the de-facto form of the mirror as close as possible to its ideal form or to the form to which it was figured. Reference is made to Wilson (1996). In case also the secondary mirror is controlled, it can have its cell moving axially and in two orthogonal directions laterally as well as changing its inclination with respect to the corresponding two axes. This means that the secondary-mirror control system covers five degrees of freedom, the

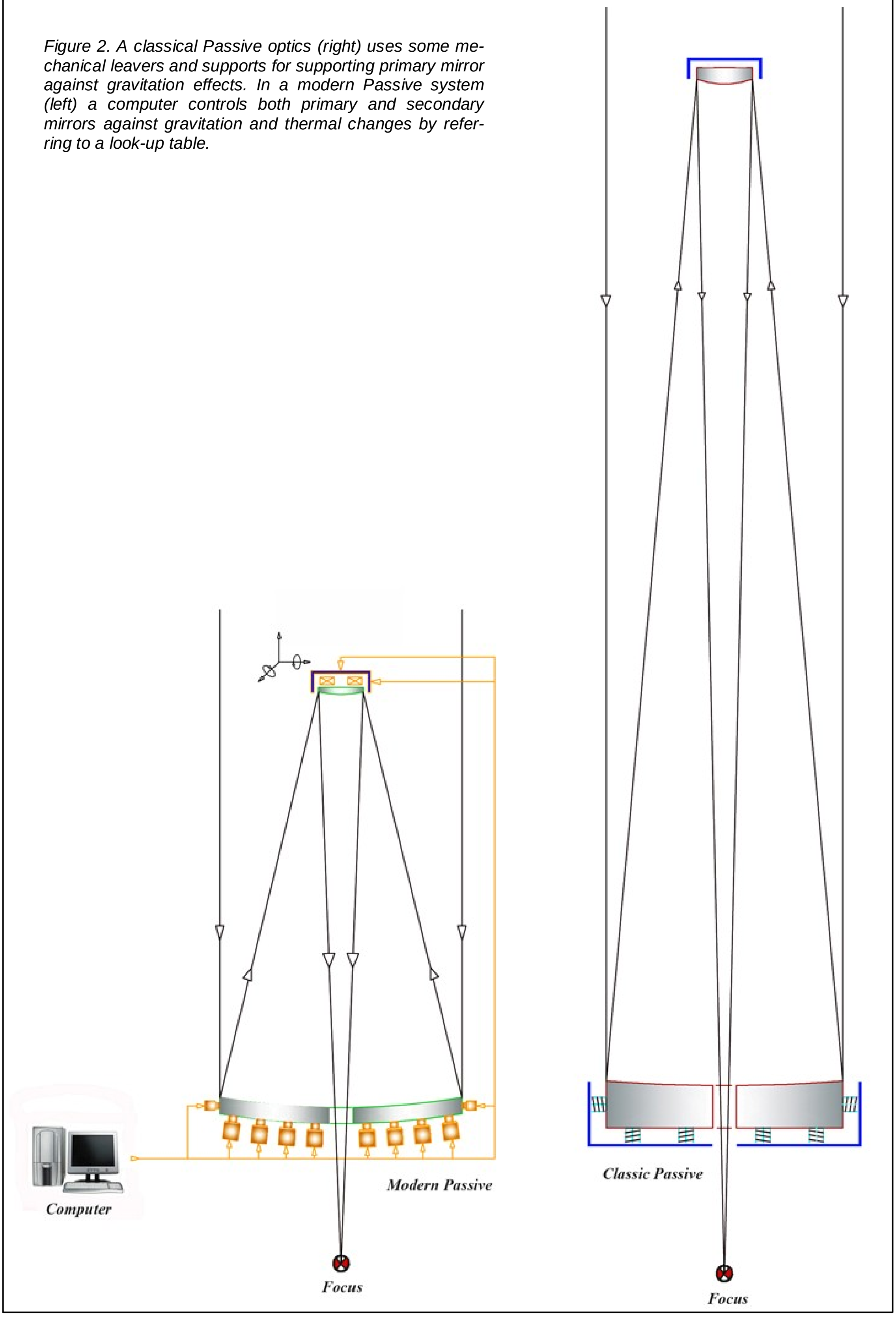


Figure 2. A classical Passive optics (right) uses some mechanical leavers and supports for supporting primary mirror against gravitation effects. In a modern Passive system (left) a computer controls both primary and secondary mirrors against gravitation and thermal changes by referring to a look-up table.

actuation of which, in a passive system, are tied to standard influence patterns in a manner similar to that of the support system for the primary mirror. As no real-time evaluation of influence parameters is made, the band width of the passive optical system is referred to as zero. In Fig. 2 the configurations of a basic and a more modern and sophisticated passive optical arrangement are illustrated.

Active optics

A passive optical system may well be seen as adequate as long as the primary mirror is reasonably small and has a relatively low aspect ratio and as long as the relative positions of the primary and secondary mirrors can be regarded as sufficiently stable for the image-quality ambitions at hand. When the aperture is significantly larger than two metres and image-quality ambitions are high, a passive optical system is, however, not any more fully sufficient. For apertures around two and a half metres and larger, a low aspect ratio, say 5-7, does not anymore guarantee a stable mirror surface. In addition, if, or rather when, forces of gravity and temperature variations modify the form of the primary mirror, a low aspect ratio makes all corrective attempts futile. Correspondingly, for such a telescope, it is very hard to maintain, under general observational conditions, the relative positions of the primary and secondary mirrors such as to guarantee adequate optical alignment and high image quality. The sole remedy is, in both cases, to introduce an active optical system.

The aim of the acquisition of an active optical system is to provide real-time, or, sometimes, corresponding look-up table based, corrections of the optical telescope system. While the passive optical system is based on standard patterns of influences of gravity and temperature variations, the active system is set to address these influences as they occur in practice. Thus,

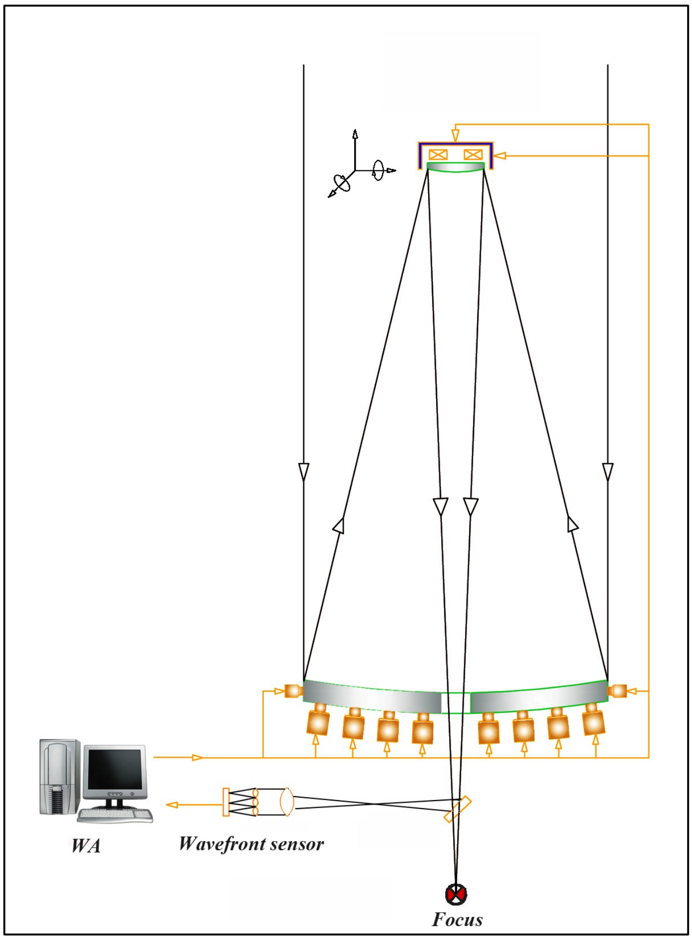


Figure 3. A modern telescope with active optics. A wave-front sensor detects aberrations and delivers results to a wave analyser. The latter sends correction commands to the primary mirror actuators and the secondary mirror controllers.

in this case, also influences on the optical telescope system other than those given by standard patterns are taken into account when corrections are derived and introduced.

Data from a wave-front sensing and analysis unit are used in a feedback manner to control the support system of the primary mirror and the attitude system of the secondary mirror, both of which are conceptually very close to those described above for passive optical systems albeit generally more advanced. A corresponding conceptual active-optics arrangement is illustrated in Fig. 3. In closed-loop mode, the system is used either strictly in a real-time fashion or in a pseudo real-time fashion. The former alternative foresees parallel reference-source calibration and target observation, in which case the calibration source is either identical with the target or located close to it. The pseudo real-time fashion implies reference-object calibration followed by target observation or some similar combination of reference and target objects. For reliably stable opto-mechanical systems, it is often highly advantageous to employ an open-loop observing mode. In this case, a set of reference objects are used to calibrate the primary-mirror support system and the secondary-mirror attitude system. Such calibration series should be as frequent as required and their results form a look-up table of corrective measures, up-dated as frequently as defined by stability and ambition levels. For well-designed telescopes, it may be sufficient to calibrate the systems once per month or with even longer intervals. As compared to the closed-loop mode, the open-loop mode promotes faster and more efficient observing sessions. Combination of open-loop and closed-loop modes is an interesting possibility offering a combination of high quality image data and rational operation routines.

In practice, active optical systems typically have bandwidths of around 1 Hz, although also bandwidths considerably, even order of magnitude, smaller than that can work excellently well, as gravitationally as well as temperature-variability induced mechanical forces and deformations in all practical applications progress relatively slowly. The corresponding corrections to be applied have, on the other side, relatively sizeable amplitudes, normally of the order of a millimetre or even somewhat more. In any case, a system well designed will support and promote correction routines that are, also under standard observing conditions, rather stable and repeatable. The bandwidth, the amplitude and the system stability are of prime importance for the performance of active optical systems.

In the early phases of the development of the foundations of active-optics concepts, theoretical studies were conducted, together with systems designs and laboratory tests of prototypes. The feasibility of active optical systems was confirmed and various strategies were investigated. Strategies were developed and early experimental work was performed by Wilson et al. (1987), Noethe et al. (1988), Hardy (1989), Wilson et al. (1989), Tarenghi and Wilson (1989), Iye et al. (1990), Wilson et al. (1991), Stepp et al. (1991), Ray (1991), Parodi et al. (1992), Ardeberg et al. (1992a, 1992b), Noethe (1993), Ragazzoni (1993), Saxena et al. (1993), Hubin and Noethe (1993), Bortoletto et al. (1994), Noethe and Zago (1994), Hardy (1994), Nardinocchi et al. (1994), Smith et al. (1994), Gray et al. (1994), Bortoletti et al. (1994), Martin et al. (1994).

At the same time as rather reliable active-optics systems are in current use in many telescopes, the development of such systems continues. This work concerns all aspects of active optics, hardware, software and strategies. Reference is made to Schipani et al. (2007), Hill et al. (2008), Molfese and Busatta (2008), Molfese et al. (2008a, 2008b) and Hugot et al. (2008)

When the first active optical systems were run on major telescopes, the great advantages as compared to passive optical systems were beyond doubt (Ardeberg and Andersen, 1994; Roddier et al., 1995; Schumacher et al., 1995). The corresponding highly encouraging experience was followed by further system development, testing and running, now not least intended for use with large and very large telescopes (Ardeberg et al., 1996; Cho, 1997; Castro et al., 1998; Martin et al., 1998; Code et al., 1998; Andersen et al., 1998; Ardeberg and Andersen, 1998; Andersen et al., 1999; Claver et al., 2000; Su et al., 2000; Guisard et al., 2000; Pernechele et al., 2000; Dayton et al., 2000; Andersen et al., 2002; Schechter et al., 2003; Guisard et al., 2003; Andersen et al, 2003a, 2003b; Neufeld et al., 2004).

An essential prerequisite for adequate performance of an active optical system is a primary mirror with a suitable aspect ratio. The primary mirror of a 3 m class telescope should have an aspect ratio, defined as the ratio between its diameter and thickness (close to its centre for a non-meniscus-shaped mirror), in the range 13-20 or, possibly, larger. A lower aspect ratio will hamper the quality of surface corrections considerably, while a larger aspect ratio implies the necessity of elaborated support structures and handling routines, or the risk of mirror breakage will be significant, not least so during its handling for recoating and other similar purposes.

Active-optics observations of reference objects, in real-time mode as well as in calibration mode, require highly well-exposed images for analysis. This translates into the need for a somewhat generous brightness of the reference objects. To a large extent, however, the adequate photon collection can be achieved through extended observing times. At any rate, all observations of reference objects, brighter or fainter, have to extend over a certain time, normally in practice of the order of half a minute, to avoid small-scale temporal effects of atmospheric turbulence. Thus, in nearly all practical observing situations, there should be little problems finding reference sources of a brightness level adequate for measurements with a 3 m class telescope.

Adaptive optics

Even an ever so well functioning active optical system can do little to compensate for the influence of atmospheric turbulence on image quality. While careful site selection is highly helpful, and mandatory, the observer with high ambitions concerning image quality will always be at the mercy of the atmosphere. If our observer requires images providing a resolution corresponding to a width at half intensity maximum, FWHM, better than some tenths of an arcsecond, she or he needs adaptive optics of higher or lower order, depending mainly on a combination of ambition level, technical facilities and funding. While wind gusting severely deforms very large mirrors, for a 3 m class telescope with a primary mirror as discussed above, the wind forces will mainly imply effects of jitter. The latter effect has to be taken into careful account concerning construction as well as observing routines.

It is important to remember that introduction of an adaptive optics system (Tyson, 1991, 2009) does not mean that the corresponding active optics system can be eliminated. In practice, choosing adaptive optics implies relying on a combination of two optical correction systems, one active and another adaptive (Wilson, 1999). There are a number of explanations for this fact.

First, and important, the combination of the bandwidths and amplitudes required for successful corrections of significant errors differ highly, as they have their origin in highly different sources of disturbances. The effects on the target light source wavefronts caused by turbulence in the atmosphere show a high-frequency pattern, far beyond the bandwidth range possible for an active optics system. On the other hand, the amplitudes of the atmospheric wavefront disturbances are comparatively low, in practice of the order of a few micrometres.

The effects coming from the field of gravity and temperature variations are, while of limited frequency, characterized by rather high amplitudes, typically a factor of 10^3 higher than those resulting from atmospheric turbulence. Such corrections can safely be made with an adequate support system below the primary mirror but not with an adaptive optics system functioning at high bandwidth. On the other hand, the high-frequency but low-amplitude effects of atmospheric turbulence naturally call for a low-weight optical component, such as an adequately designed secondary mirror unit.

Another important difference between effects curable with active and with adaptive optics system is that of field size. Regarding active optics corrections, the field coverage is the same as that defined by the telescope system, with no further limitation. The same is far from the truth concerning adaptive optics corrections. As a consequence of the limited size of the atmospherically defined isoplanatic angle, adaptive optics can correct errors, albeit highly precisely in terms of quality, over no more than, typically, one arcminute or, with special arrangements, a few arcminutes.

Effects of air turbulence, or of variable, in time and location, refractive air index, induced by air density, in turn caused by temperature variations, nearly always have their origins in a number of air layers. High-altitude air turbulence, or turbulence occurring at altitudes well above those of the highest local mountain peaks, can often be regarded as dependent on mainly large-scale effects, with pattern sizes of several kilometres or more. Corresponding air turbulence, originating in layers with altitudes comparable to those of the higher local mountains, tends to be more variable over shorter distances as well as with respect to wind direction and time. At even lower altitudes, air turbulence is largely driven by local effects and especially by the heat exchange with the local ground and turbulence driven by local topographical effects. Finally, there are similar effects caused by observatory and other human-constructed installations and heat-producing activities. In the latter case, special attention should be paid to the telescope enclosure and its equipment, the telescope itself and its auxiliary instrumentation.

Conceptually, the methods of adaptive optics (Tyson, 1991, 2009) are not entirely different from those adopted in active optical systems. In practice, however, the systems are not the same nor even similar. The explanation is the band-width required for successful compensations of the effects of atmospheric turbulence. While full active optics corrections demand a band-width of not more than 0.5 to 1.0 Hz, even low-order adaptive optics corrections need a band-width of 25-50 Hz. Thus, the methods employed in active optics are inadequate in the case of adaptive optics systems (Fig. 4).

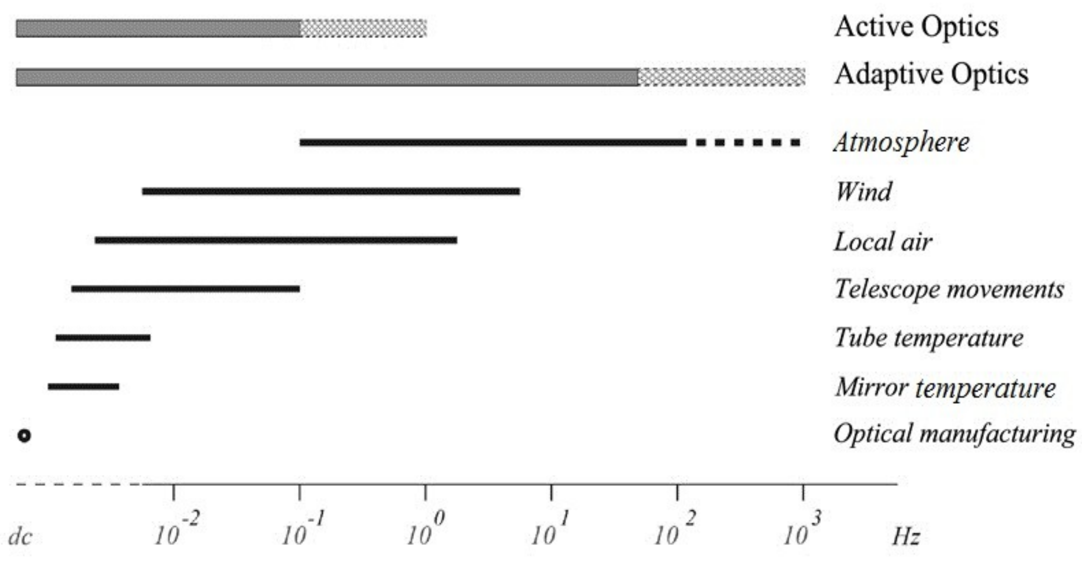


Figure 4. Different parameters that affect wave-front shape and temporal frequencies. Typical bandwidth regimes for active and adaptive optics are indicated in figure (Wilson et al., 1989).

While adaptive optics require a compensation system of much higher bandwidth than that sufficient for active optics, it should be remembered that, on the other hand, the phase errors introduced by atmospheric turbulence are much smaller than those caused by effects of gravity and temperature variations. While the corresponding amplitudes met in adaptive-optics corrections are of the order of some micrometres, this advantage is, nevertheless, largely drowned by the photon starvation plaguing adaptive-optics corrections as a result of the high bandwidth required.

The need for generous photon flows implies definite restrictions for the use of adaptive optics. With the isoplanatic patch growing with wavelength, the photon collecting challenge is, disregarding the wavelength dependence of stellar flux, at its severest for shorter wavelengths. At the same time, for telescopes of 3 m class, there is, relative to larger telescopes, a comparative advantage concerning adaptive optics corrections at shorter wavelengths. While the isoplanatic patch is the same, independent of aperture, the corresponding number of sub-apertures and, thus, the number of correction elements necessary for adaptive optics corrections is smaller for telescopes with more modest apertures.

A notable difficulty of adaptive optics is the generally small isoplanatic angles. Again, the largest problems occur at shorter wavelengths. For visual light, practical isoplanatic angles are hardly ever larger than a few arc-seconds, even at the very best sites available. Thus, added to the problem of photon starvation is another problem of scarceness of stars adequate as reference sources for adaptive optics. Both problems can be solved via the introduction of artificial reference objects. However, in this case, instead, other problems come into play such as the cone effect, elongation of reference images and highly substantial implications on operation complexity and cost.

An adaptive optics installation can be located either in a pre-focus version or as a post-focus arrangement. In the pre-focus mode, normally, the secondary mirror is used for adaptive corrections (Andersen et al., 2003), even if other arrangements, involving more reflecting surfaces, are sometimes introduced (Gilmozzi, 2008; Spyromilio, 2008). In the post-focus mode, additional optics are introduced as correcting elements situated behind the telescope focal point. A third possibility is to apply post-facto adaptive corrections. In this latter case, high-frequency, short-exposure images of the target object(s) and the reference source are observed in parallel for later correction procedures. Combinations of the alternative adaptive-optics modes are possible. In practice, the dominating versions are pre-focus and post-focus adaptive optics, in many cases combined.

Pre-focus adaptive optics

The most ambitious approach to adaptive optics is the pre-focus mode. In its most ideal version, this arrangement does not require any additional optical element. This, however, presumes that the secondary mirror is fully flexible and that it can be adequately controlled regarding both amplitude and bandwidth. Already for low-order corrections only, this is a considerable challenge, while for full adaptive-optics corrections it is a major challenge. For optimum results, the weight of the secondary mirror and of its cell and mounting has to be minimized as far as possible. However, the size of the secondary mirror is, for a number of reasons, a parameter far from free.

In practice and importantly, low-order adaptive optics means correction of atmospheric tip-tilt effects. At the same time, it seems natural to add corrections for effects of de-focus and coma using de-centring. To a major extent, the practical effects of de-focus and de-centring are those encountered also in active optics, although additional effects caused by the band-width regime can be significant. Limiting the corrections to effects of tip-tilt, de-focus and coma de-centring has the important advantage that no mirror deformation has to be attempted. Thus, in many cases, rather considerable image-quality improvements can be achieved with corrections that are, while far from simple, still very much less demanding than those required in case of a full adaptive optics scheme.

The importance of tip-tilt effects depends on both the atmospheric turbulence, notably its outer scale, and the aperture of the telescope. In the case of a 3 m class telescope, normally, tip-tilt correction alone implies a considerable improvement of the image quality. This improvement, however, depends on the correction band-width. The importance of the weight of the secondary mirror assembly for the correction bandwidth feasible means that decisions regarding pre-focus adaptive optics, also when limited to low-order effects, have to be made in close orchestration with the optical design of the telescope and, not least, of its secondary mirror. While a high bandwidth, safely controlled, is of high advantage for resulting improvements of the image quality, also tip-tilt corrections made with more modest bandwidth can give substantially increased image sharpness. In Fig. 5, the concept of a low-order pre-focus adaptive optics system is illustrated.

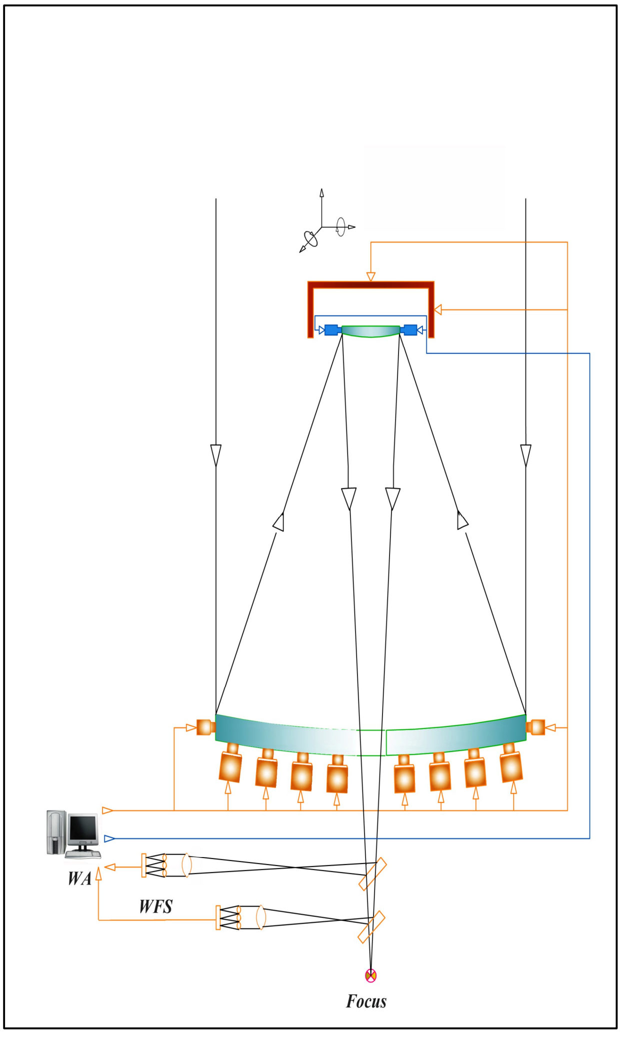


Figure 5. Conceptual drawing for low-order pre-focus adaptive optics in a modern telescope with active optics. Two different wave-front sensor and analyser sets influence the active and adaptive optics, respectively. See also caption for Fig. 3.

Aiming at full pre-focus adaptive optics corrections means embarking on a telescope project with very high ambitions and challenges. It is a decision that should be taken only after thorough considerations and evaluation of the expertise, experience and budget available. A fully successful outcome of such a decision will result in a telescope of frontier nature. A less successful outcome will imply highly noteworthy problems.

For full pre-focus adaptive optics, the design of the secondary mirror and its mounting is an advanced part of the telescope project. The demands on high flexibility imply, among other things, that the choice of mirror material has to be given high attention as has the design of the mirror mount. Producing a mirror that combines low weight with high flexibility and reasonable handling procedures without imminent risk of accidents is a rather demanding undertaking. In addition, the corresponding design and construction of sensors and actuators is a challenge in itself. While low-order adaptive optics corrections can be quite successful also with a relatively modest bandwidth, this is, unfortunately, not the case for full adaptive optics. Full corrections are meaningful only with high bandwidths, preferably of the order of 500 Hz or, even better, around 1 kHz. Fig. 6 provides a conceptual illustration of a pre-focus approach to full adaptive optics.

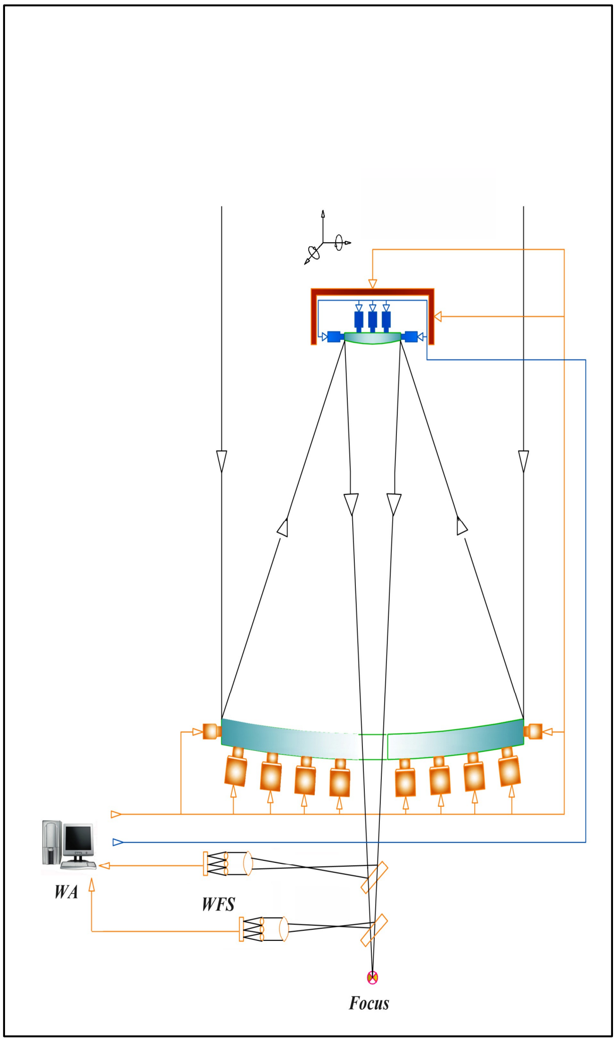


Figure 6. Conceptual drawing for high-order pre-focus adaptive optics accompanied by an active-Optic system. In this case, the secondary mirror is deformable. The control scheme is similar to that for low-order adaptive optics but with higher bandwidth.

Post-focus adaptive optics

A post-focus approach to adaptive optics is, while doubtlessly quite demanding, considerably less challenging than a corresponding pre-focus version. Both the dimensioning and the lay-out of the adaptive system have much more freedom in the case of post-focus adaptive optics than concerning the corresponding pre-focus concept. Also, the conditions regarding then design and operation of the control system are much more favourable in post-focus than in pre-focus mode.

The reason for the superiority of a pre-focus adaptive optics system as compared to its post-focus counterpart is simple. While the pre-focus system can work with the telescope optical elements only, in the case of a Cassegrain or Gregory concept, a primary mirror and a secondary mirror, the corresponding post-focus system needs additional optical components. If, but only if, the adaptive post-focus mirror can be figured for re-imaging, two additional elements are required and sufficient. Such an arrangement, however, calls for a most sophisticated construction of the adaptive element, in practice beyond regular possibilities. In practice, the adaptive post-focus mirror is flat, and, thus, the post-focus adaptive optics system has to include three additional optical components. This has implications on throughput as well as on optical contrast. A typical post-focus arrangement of an adaptive optics system is shown in Fig. 7.

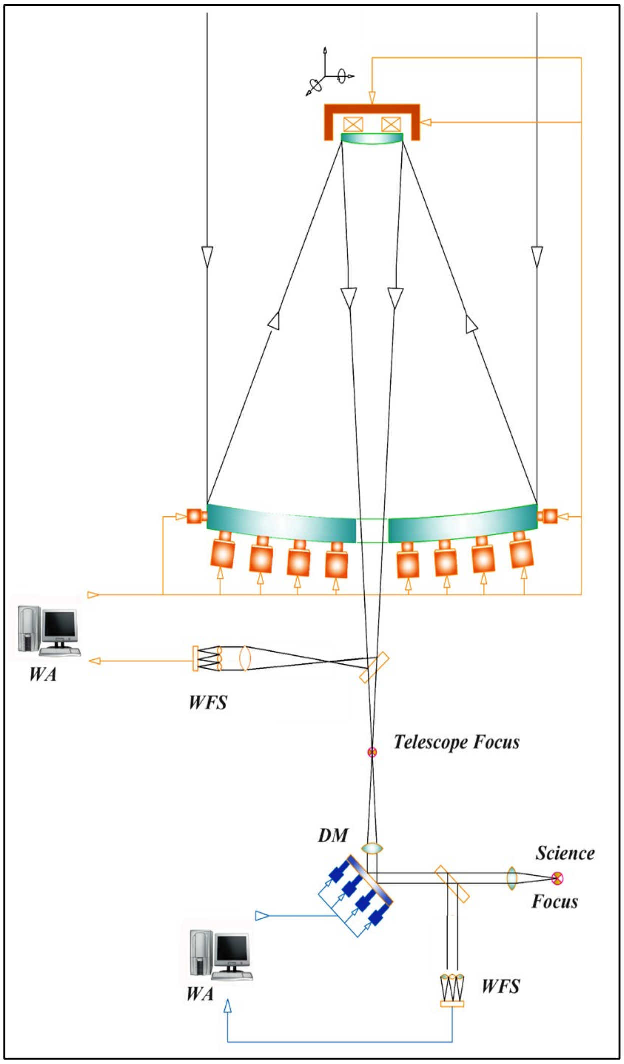


Figure 7. A conceptual drawing for a high order Post-Focus Adaptive Optics.

Post-facto adaptive optics

Both pre-focus and post-focus adaptive optics rely on real-time corrections, or at least corrections made very close to in real time. Alternatively, corrections can be derived and applied in a post-facto mode. Measurements of target and reference objects, made in parallel, are stored with high frame rate, ideally of the order of 500 Hz or even faster. Later, the parallel records are used to correct for effects of atmospheric turbulence.

Compared to real-time adaptive optics corrections, post-facto corrections have a fundamental shortcoming. While the real-time correction systems all the time maintain the optical system ideally, or at least close to ideally, configured, post-facto corrections have to be made for an optical configuration far from ideal. For this reason, post-facto adaptive optics may well be seen as a technique for image sharpening more comparable to conventional image processing than to real-time adaptive optics. The post-facto adaptive optics method has, however, the distinct problem of photon noise. The need for well-exposed reference objects, together with the requirement on very short exposures imply that only very bright objects are eligible as reference objects. The very large amounts of data that must be stored for later correction procedures define an additional weakness of the post-facto adaptive optics scheme. While no doubt possessing quite some potential, it has not found much application in practice. In the discussion following, only real-time adaptive optics systems will be considered for corrections of atmospheric turbulence.

Lucky Imaging

The image-quality degradation caused by atmospheric turbulence is of statistical nature. Thus, regarded as a time sequence, the resulting quality of the image of an object varies very much, especially if the time resolution is large. This fact paves the way to a conceptually simple and straightforward method of image sharpening, the so called lucky imaging. It can be seen as a simple form of speckle imaging.

The relative simplicity of lucky imaging is best illustrated by the fact that it was applied and discussed with some success already more than 50 years ago, then with film cameras, sometimes combined with image intensifier equipment. See for instance Baum (1956) and Fried (1978). It should be emphasised that lucky imaging, also in the era of active and adaptive op-

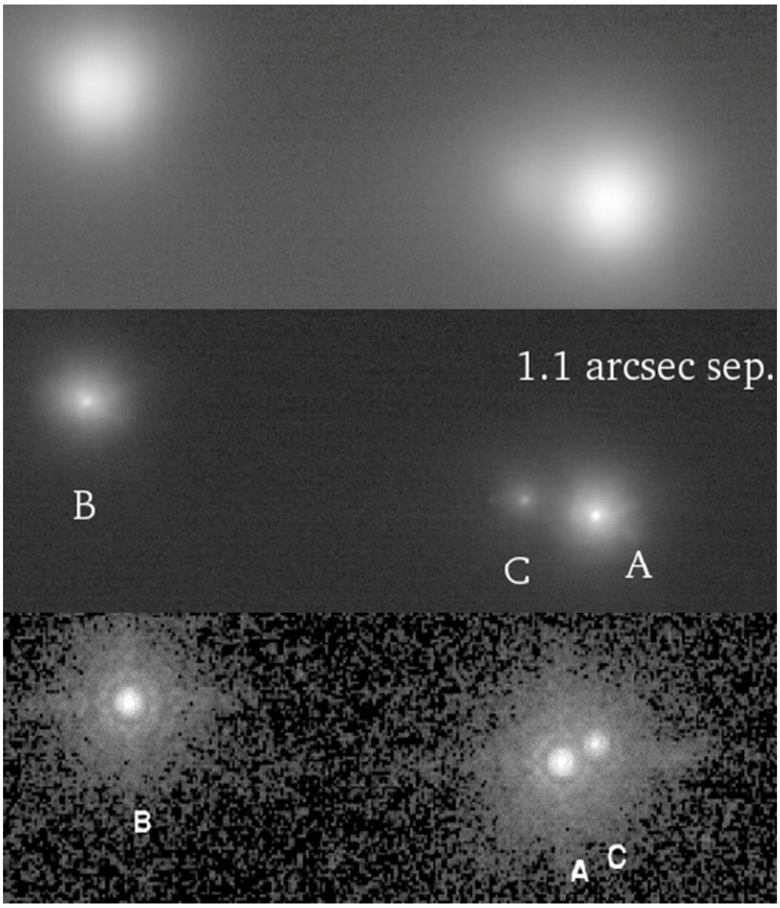


Figure 8-.Astrometric binary "GJ 1245AC" in seeing limited, upper panel, lucky-imaging, middle panel, and HST, lower panel, versions (Nicholas M. Law, 2006).

tics is a method for image-quality enhancement very much alive. Reference is made to Dantowitz et al. (2000) and Baldwin et al. (2001).

The increase of spatial resolution using lucky imaging can easily be an order of magnitude compared to that achieved even from relatively short exposures. From longer series of ultra short exposure images, compatible with the coherence time of the atmospheric turbulence (exposure times preferably some milliseconds only), those showing highest spatial resolution are selected, shifted in position with the help of a reference object and co-added. An unavoidable price to be paid is the loss of fainter objects. Another is that the method is applicable to fields of view smaller than or roughly equal to the turbulence coherence length only. Depending on the wavelength used, the field achievable may be no more than a few arcsec in diameter.

A competitive 3 m class telescope

The light-collecting surface of a 3 m class telescope is sufficiently large to promote conduction of a wide range of science programmes, including frontier research projects. The prime challenge involved is the spatial resolution of the images obtained. The resolving power of the telescope will define its ability to serve for successful studies of crowded and/or highly structured target objects and fields. A 3 m class telescope with arrangements for high-quality imaging can, if adequately used, provide large amounts of advanced and highly interesting scientific data. Moreover, high image quality implies high light concentration and, thus, largely improved abilities concerning photon collection for point-like faint objects.

Even located in a site offering excellent atmospheric conditions, a 3 m class telescope with passive optics only is doubtful as a tool for successful international scientific competition, also if the optical quality as such is good or even impressive. A telescope with passive optics, even if excellently designed and constructed, is unable to provide images with a spatial resolution better than that defined by the turbulence of the atmosphere. In practice, it will nearly always deliver images with a resolution inferior to that allowed by the atmosphere. Adequate active optics provides the possibility to reach, also in standard operational modes, the resolution limit set by the atmosphere above the site, or, at least, a resolution very close to that limit.

Taking full advantage of the resolution limit allowed by the action of the atmosphere is far from trivial. Still, it can, in 2011, be seen as a challenge achievable with advanced techniques. Proceeding to image resolutions higher than those defined by atmospheric turbulence is, however, a truly difficult defiance requiring frontier knowledge, skill and resources as well as determined efforts. At the same time, the scientific reward possible is huge. This is true not only with access to a full adaptive optics system but, to a large degree, also with application of low order adaptive optics.

Spatial resolution with passive optics

The spatial or angular resolution of a telescope is a measure of its resolving power. The resolving power of the telescope is a description of its capability to separate crowded point objects in an image. Normally, the limiting resolution is defined as the angular separation between two identical point objects barely distinguishable as separate.

Telescopes with passive or active optical systems generally, if well constructed, have an intrinsic resolving power significantly superior to the best possible image resolution as determined by the turbulence of the atmosphere, a parameter in itself normally highly variable. In this case, the point-spread function of the test objects is, in principle, always that defined by the atmosphere, or the “seeing”. In real life, a telescope equipped with nothing but passive optics can, in a reliable manner, reach the atmospherically delimited point spread function only if it has a primary mirror small enough to be controllable in a passive mode. Small enough tends, in practice, to imply a diameter smaller than somewhere between two and two and a half metres. Even then, with a telescope with passive optics only, the atmospheric resolution limit is, in practice, hardly ever reached, and especially not in case of favourable turbulence conditions. The simple explanation is that, in real life, it is very hard, if not impossible, to maintain all telescope optical parameters as defined by their design.

Spatial resolution with active optics

The explicit aim of an active optics system is to maintain, in all circumstances, the form, orientation and relative position of the telescope's optical elements such as defined by their design parameters. Thus, with a telescope designed and constructed with an image resolution significantly better than that set by best possible atmospheric turbulence conditions and equipped with an active optics system, all disturbing influence of gravity and temperature variations

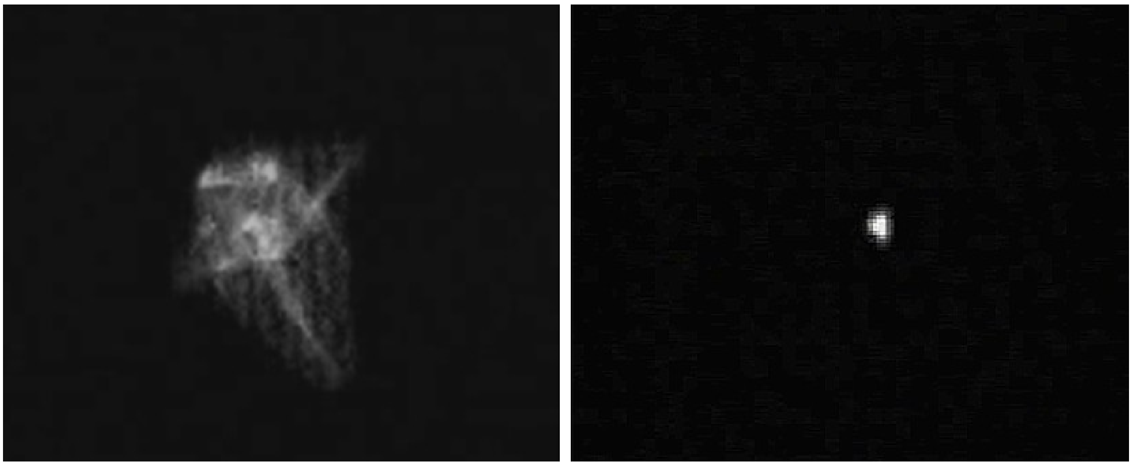


Figure 10. Effect of active optics on image quality. Left panel shows a short-exposure image taken with strongly distorted telescope optics, while right panel shows the corresponding image, corrected with an open- loop active optics system on the ESO VLT (Photos from ESO website).

should, at any time, be eliminated. Thus, the practical image resolution should always be that defined by the atmosphere, or, at least, very close to that limit. While challenging, such active optical systems have, when well constructed, demonstrated rather high reliability.

Spatial resolution with adaptive optics

The ultimate limiting, or intrinsic, spatial resolution of a telescope is defined by the effects of diffraction. In this case, the telescope aperture can be understood as an analogue of a two-dimensional slit. Passing through the telescope aperture, light is diffracted at the aperture edge and interferes with itself. This results in a circular diffraction pattern, provided that the phase of the light transmitted can be regarded as spherical with respect to the exit aperture. We refer to this as an Airy pattern. The resolution angle, R_a, is then, expressed in radians, $R_a = 1.22\lambda/D$, where λ is the wavelength and D the aperture. In arcseconds, we get, accordingly, $R_a = 1.2 * 2 \times 10^5 \lambda/D$, or, approximately, $Ra = 2.4 \times 10^5 \lambda/D$.

Obviously, conceptually, a telescope with full, real-time, adaptive optics should always deliver images with a spatial resolution equal to, or at least very close to, its diffraction limit. In practice, however, this has to be accepted as a truth with a number of restrictions. There are several reasons for this caution. They are the results of a number of shortcomings, all possible to limit but not to eliminate.

A rather fundamental limitation is defined by the way corrections are made. First, wavefront errors are measured, analysed and converted to corresponding corrections. Then, via the mirror support systems, the corrections are applied. The time delay for the corrections can be minimised, but it cannot be eliminated. Thus, unavoidably, corrections will not be fully in phase with the wave-front errors recorded. While of reasonably limited importance in case of favourable atmospheric turbulence conditions, the out-of-phase error rapidly increases with increasing effects of turbulence in the atmosphere.

Another, rather fundamental limitation is due to the observations of the reference object/s. If a natural reference source, or several such sources, is or are used, the flow of photons will always, in practice, limit the ultimate precision of the corrections determined. If, on the other hand, artificial reference sources are taken into account, while photon currents may be adequate, other problems are unavoidable, coming from the cone effect and source elongation.

Further, in practice, errors in the different steps of the total correction procedure cannot be fully avoided. Wave-front sensing is, independent of the concept applied, never a fully perfect operation, and a similar limitation affects the corresponding analysis procedure. Mirror sensors and actuators do not work fully perfectly, and the corresponding response of the mirror surface does not either. Noting and taking into account all these shortcomings of adaptive optics corrections, it must, at the same time, be remembered that the experience of the adaptive optics facilities already operating demonstrates that the potential of adaptive optics is huge.

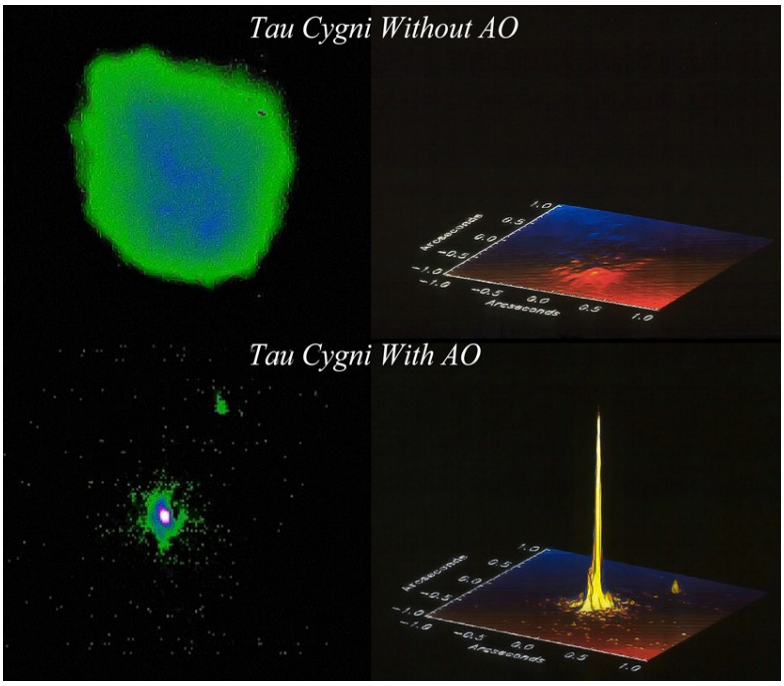


Figure 11. Enhancement of image quality and spatial resolution with adaptive optics on Hooker telescope. Hooker telescope was used with a single-conjugate post-focus adaptive optics system with a natural guide star (Photos: Mike Simmons, Mount Wilson Observatory).

Site quality

For all telescope installations concerning observations in the optical and adjacent parts of the spectrum, the quality of the site is of fundamental importance. The influence of the site performance has to be taken very seriously, irrespective of the type of telescope(s) to be installed. For most installations, site quality depends on a large amount of parameters. A site with favourable characteristics implies a scene for vast possibilities concerning observing quality, even if it is far from sufficient for higher ambition levels. On the other hand, a site with unfavourable conditions is bound to cause endless problems, no matter how ambitious the design, construction and operation of the telescope(s) are conducted.

The obvious conclusion is that highly serious site evaluation is an unavoidable prerequisite for any ambitious observatory project. The amount of parameters determining the site quality as well as the, often, rather considerable efforts necessary for their analysis make proper site evaluation a prominent part of serious observatory programmes. Much work and the need for a proper evaluation period must be taken into full account concerning resources, in terms of staff and technical resources as well as budgetary conditions.

Of the many site parameters existing, some seem more important than the other ones, at least for observatories covering most forms of observations at visual and adjacent wavelengths. Prominent roles are played by the amount of cloud cover, the content of water vapour in the atmosphere, including the amount of local relative humidity, the atmospheric turbulence, including ground-layer turbulence, and atmospheric extinction. Similar importance can be attached to the pattern of wind strength, wind buffeting and wind direction, the temperature variations, the sky brightness level, the amount of air pollution as well as the seismic activity, including the micro-seismic signature of the site. Of high importance is, further, the frequency of air traffic, present and future, above the site sky line.

While the site parameters so far mentioned require more or less detailed study for serious evaluation, there are a number of other site parameters easier to determine but still of considerable importance. The altitude of the site above the prevailing local atmospheric temperature inversion layer is, in itself, of highest importance for the image quality. Even if adequate consideration of the atmospheric turbulence should take care of the safe distance above the inversion layer, a safe estimate of the altitude difference seems a most natural part of any site evaluation. The topographical setting of the site is another parameter of highest importance, although its implications ought to be well considered via the turbulence data. Clearly, the topographical situation should be one of the very first parameters taken into consideration for site selection.

An additional parameter with strong influence on the practical quality of a site is its position relative to human-produced disturbances. This clearly refers to urban settlements such as communities, larger and smaller, with more or less artificial illumination and dust production. Serious implications may further be due to installations of mines and other industrial enterprises.

Regarding the site parameters discussed as defining, in a more definite sense, the over-all quality of a site, mention should also be made of another set of site parameters affecting its suitability in a less definite yet often rather important manner. Such parameters concern the latitude and longitude of the site. While the site latitude determines the sky available for observations, its longitude may well have implications for the importance of the observatory in terms of international programmes involving monitoring and stand-by availability.

Not directly affecting the quality of the site as such but still of importance is its general accessibility. This can affect the cost of the observatory establishment to a high extent and, thereby, have important indirect implications on the installations needed and wanted. Similar considerations are due regarding the supply of water and electricity. Often given too little attention are convenience parameters such as the distances to the home institute and to the nearest community with high-class service in terms of schooling, hospitals, social care, reasonable supply of general consumer goods and culture. The latter factors may well to a considerable degree determine the attraction of the site for the staff with the expertise needed for the proper operation of the site.

Telescope enclosure

Traditionally, telescope enclosures have been regarded primarily as protections against adverse weather conditions and, at best, as day-time climatic seals. In addition, they have, to a considerable extent, been designed and constructed to support handling of the telescopes and their instrumentation in terms of maintenance, exchange operations and regular observations. The telescopes have been seen as sophisticated devices providing light collection and good images. The enclosures have been regarded mainly, often entirely, as necessary support installations.

With the ambitions regarding image quality discussed above, the role of telescope enclosures has to be very much up-graded. While still having the same protective importance as ever, the enclosures must now be designed and constructed as part of the telescope installation. Importantly, a modern telescope enclosure should, as far as ever possible, be aimed at preserving the image quality offered by the site at the same time as it provides adequate protection against wind forces and support for maintenance and observations.

In practice, these considerations translate into a set of requirements concerning the size, structure and installations of the telescope enclosure. Also, it emphasises its facilities regarding thermal equilibrium and stability, calling for both smart design and choice of materials. At the same time, free air flushing of the telescope, not least of its primary mirror, is a target of utmost importance. These considerations have gradually matured over the latest decades (Ardeberg, 1990).

A modern telescope enclosure should act in tandem with the telescope. Also, and very importantly, it should actively co-operate with the site in its support of the quality of the observations. Clearly, for optimum results, an ensemble view of the telescope, the enclosure and the site as well as the adhering infrastructure must be applied throughout. This calls for a challenging co-ordination of the design of the telescope and the corresponding enclosure in strict consideration of the site qualities. Orchestrated efforts in this vein have opened a new world of possibilities regarding image quality, spatial resolution and, as one of many results, limiting magnitude (Ardeberg and Andersen, 1990).

Observing parameters

Even for a first, tentative pre-design technical study of the telescope, it is essential to have a number of telescope parameters defined, at least in a preliminary version. The choice of these parameters depends on the science case but also on other considerations including various site-quality measures and other technical and also economical realities. While early definition of a set of telescope parameters is a necessity for a rational work on pre-design issues, later modifications of this parameter set should be seen as a natural part of project development.

Working wavelength

Choice of a tentative interval for the observing wavelengths should be made at an early phase in the project initiation. This choice will define and limit a number of parameters determining essential opto-mechanical features of the telescope. Even more essential is the fact that the wavelength range of the telescope will to a large, partly definite, extent set the scene for the scientific exploitation of the telescope, including its auxiliary instrumentation. At the same time it must be remembered that optimisation of the performance level in a certain wavelength range normally necessitates a corresponding acceptance of a less than optimum output potential in other wavelength intervals, at least when the total working wavelength range is generously chosen.

There are some fundamental restrictions concerning the range of wavelengths possible to include in the working range of an earth-based telescope. This is due to the combination of a number of effects regarding transmission, emission, sensitivity, spatial resolution, energy distribution and the positions of atomic lines. All these effects are rather or at least basically well known and have to be considered with regard to the choice of working wavelength.

Transmission of Earth's Atmosphere

In all cases, the atmosphere of the Earth will imply some rather definite limitations. While the degree of these limitations depend on the altitude of the site and its prevailing weather conditions, a basic set of atmospheric influence parameters is always present and has to be accepted. In general, the most definite restrictions concern the shortest wavelengths at which an adequate throughput efficiency can be obtained. Thus, a clear limitation at a wavelength somewhat larger than 300 nm is, in all practical and realistic applications, impossible to avoid. Further, normally, only at wavelengths longer than those of the Balmer discontinuity, at around 365 nm,

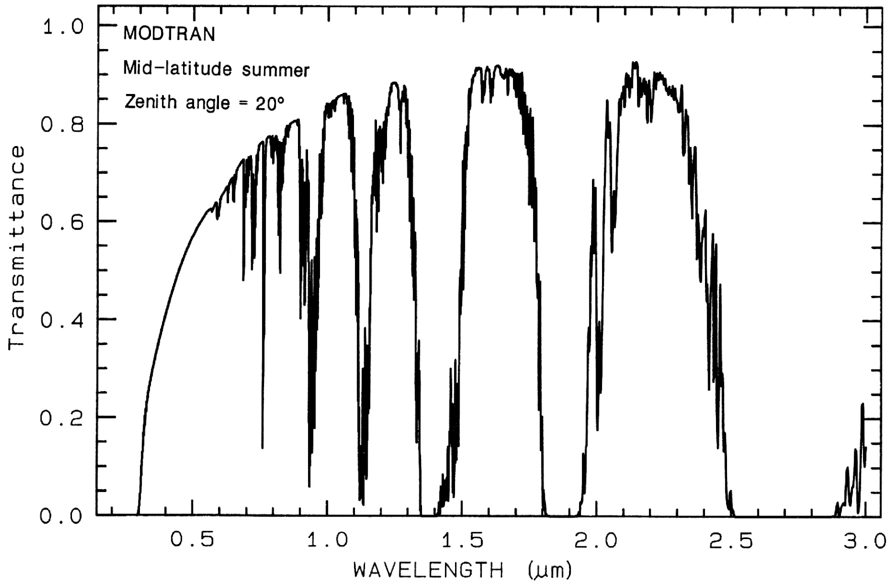


Figure 12. Atmospheric summer-time transmission at a mid-latitude observatory and referring to an observing zenith angle of around 20° (Clrak , 1999).

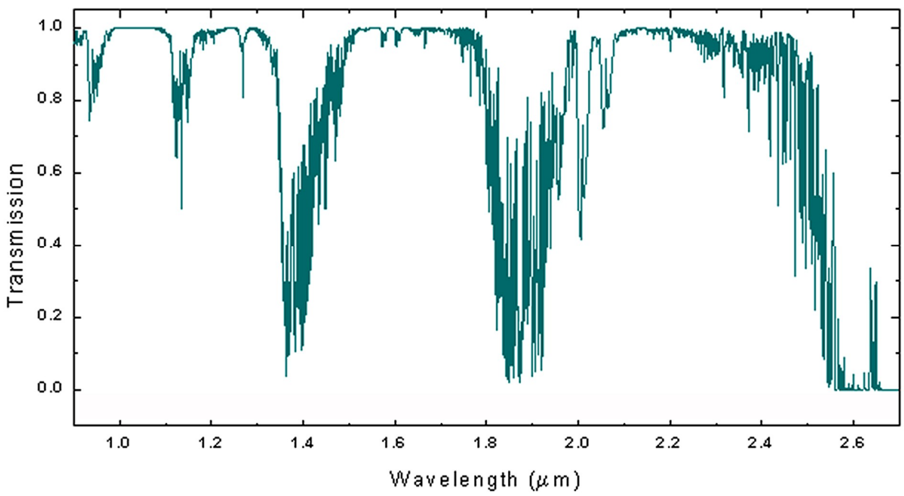


Figure 13. Atmospheric transmission at near-infrared wavelengths above the Mauna Kea Observatory (Lord, 1992).

higher efficiency can be expected. Consequently, observations of ultraviolet radiation on both sides of this discontinuity are feasible but limited with respect to throughput. Reference is made to Fig. 12.

The difficulties regarding efficient practical work at wavelengths shortwards of the Balmer discontinuity has, among other things, resulted in a general hesitation concerning both the design of instrumentation and development of science programmes favouring this range of wavelengths. While this is, in itself, rather understandable, it has caused some unfortunate scientific limitations. Thus, there is, parallel to the obvious practical limitations, some clear competitive advantage of efforts to design telescopes and their instrumentation with an intention to include wavelengths as short as possible.

The transmittance of the atmosphere in the visible wavelength region, approximately from 400 to 700 nm, is comparatively rather favourable. Not least is it, in this region, both relatively high and smooth. In the near infrared part of the spectrum, beyond 700 nm and up to around 2 500 nm, the situation is more complicated. While the general ("continuum") transmittance is

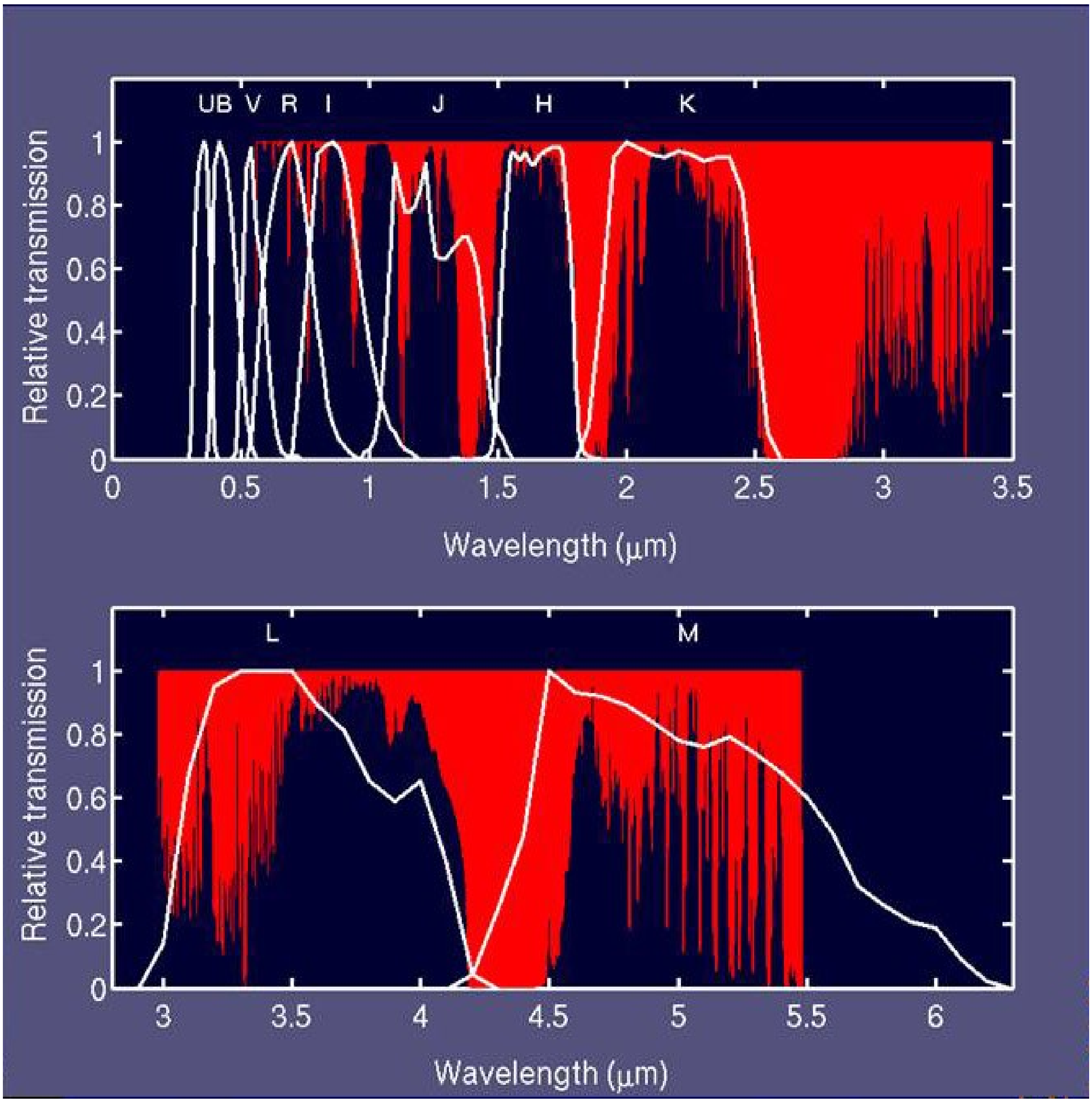


Figure 14. Relative atmospheric transmission above Kitt Peak Observatory (Hinkle et al., 2004). Projected are the measurement bands of the Johnson broad-band photometric system as described by Bessell (2005).

even more favourable than in the visual part of the spectrum, the near infrared region is partly plagued by the influence of absorption caused by O_2, H_2O and CO_2. This influence is not only highly significant but also notably variable. As a result, observations, and not least high-precision photometry, in this spectral region is a complicated undertaking.

Towards around 2500 nm, the atmospheric transmission rapidly decreases and reaches a level that is, for most practical observing purposes, close to nil. Thus, as far as observations in the infrared wavelength region, beyond and well beyond 2500 nm, are not considered, the long-wavelength limit is close to and hardly much beyond 2500 nm, although the influence of the altitude of the observatory is significant. For details, reference is made to figs. 12 and 13.

The dilemma of precision photometry with respect to the influence of prevailing atmospheric transmission is illustrated in Fig. 14. Projected onto the transmission spectrum are the Johnson -system photometric pass bands. While the conditions are reasonably favourable at visible wavelengths, difficulties abound towards both shorter and longer wavelengths. In the ultraviolet spectral region, throughput is rather low, and at wavelengths longer than around 800 nm the transmission is highly variable. As one result, even slight mismatching of measurement bands often has severe consequences. Also, it should be recalled that the strength of the atmospheric water-vapour bands show pronounced and often rapid variability (Trenberth et al., 2005; Paine and Blundell, 2008).

From experience, it is well known that Johnson-system photometry from U to H works (reasonably) well, while K-band photometry is a challenge. Concerning photometry in the Johnson L, M and N bands, pronounced difficulties are the rule. From Fig. 14, not including the N band, at least one explanation seems obvious.

Emissivity of Earth's atmosphere

The smoothed-out transmittance of the terrestrial atmosphere decreases with wavelength beyond approximately 1000 nm. The emissivity of the same atmosphere increases rather rapidly already from 800 nm. For the wavelength range covering from the ultraviolet part of the spectrum and to somewhat beyond the near infrared wavelength region, the atmospheric "continuum" emissivity is demonstrated in Fig. 14 (Ardeberg and Linde, 2008; Ardeberg, 2009), referring to an atmosphere above a site at an elevation of approximately 1200 m above sea level. A more detailed albeit in wavelength somewhat more restricted atmospheric emission spectrum is given in Fig. 15, valid for a site at an altitude above sea level of around 4200

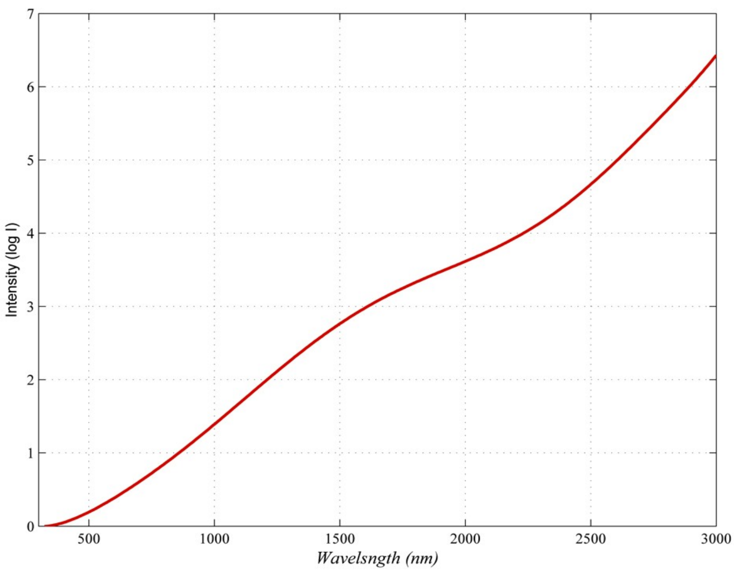


Figure 15. Typical run of atmospheric emissivity at an altitude above sea level of approximately 1200 m (Ardeberg and Linde, 2008; Ardeberg, 2009).

m. Finally, in Fig. 16, an atmospheric emissivity spectrum is shown for a region of longer wavelengths, also in this case obtained at an altitude above sea level of approximately 4200 m.

The sky emission at longer wavelengths is not only rather strong, it is also quite variable, often rapidly so. Already in its own right, the emissivity of the Earth's atmosphere sets serious limits regarding both general throughput and photometric precision.

Together with the corresponding atmospheric transmission, it causes effects important to consider for observing activities as well as for definition of the working wavelength ranges of telescopes. More precisely, while it seems prudent to take efforts to cover, in at least a reasonable manner, the wavelength range from ultraviolet to, and including, the K band, everything beyond 2500 nm should, for a non-specialised 3 m class telescope, be included only in case of special requests emphasising the longer wavelengths.

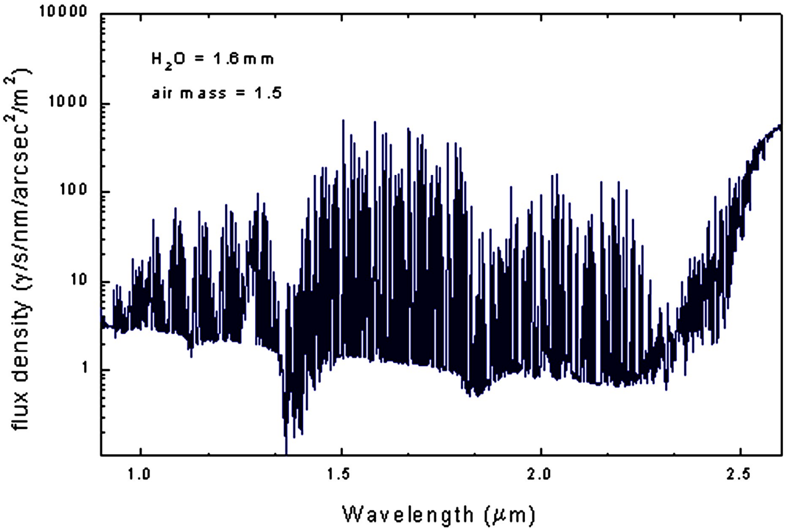


Figure 16. A detailed spectrum of atmospheric emissivity valid for an altitude of approximately 4 200 m above sea level.

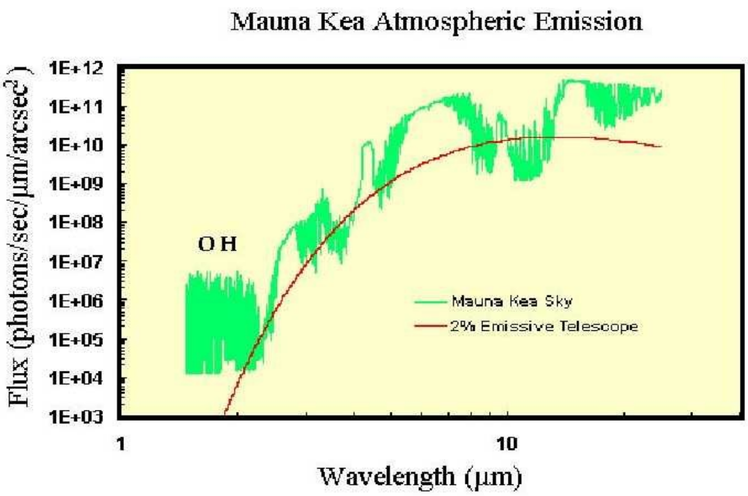


Figure 17. Atmospheric emission above Mauna Kea. (Gillet and Mountain 1998)

Emission from telescope and instrumentation

The emissivity of a telescope and adhering instrumentation follows, to a first approximation, a Planck curve and, consequently, depends on the temperature of these units. For a number of reasons, not least concerning image quality, they should be maintained as cool as possible. Still, even with proper temperatures maintained, structures will inevitably emit light at wavelengths of interest for observations, in the near-infrared part of spectrum.

Some science targets

General considerations

Any modern 3 m class telescope well configured and equipped is a powerful tool for research in astrophysics. At the same time, optimisation of its function and abilities should be made as far as possible. Compared to the total challenge involved in the design and construction of a 3 m class telescope for visual and adjacent wavelengths, a definition of the science case made by the home community of astronomers is a limited effort with a large refund in terms of observing facilities well matched to scientific expectations.

The science case for a 3 m class telescope due for regular operation from around 2015 should take into account not only the technical parameters of the telescope as such but also its role at an epoch with a world-wide offer of the services of more than half a dozen facilities including telescopes with primary-mirror diameters in the 8 to 10 m range, some of them including more than one such telescope. Moreover, it must be remembered that at the same time, two or three extremely large telescopes, with primary-mirror diameters from more than 20 to more than 40 m, might well be in an advanced phase of construction. Can, in such a situation, a 3 m class telescope be designed in a manner making it a tool for truly rewarding scientific endeavours? While there should be little doubt regarding the general scientific benefit of such a telescope, the aim should be a telescope adequate for cutting-edge research, proper application provided.

The science competitiveness of telescopes with different classes of apertures has been studied in the era of very large telescopes (Hellemans, 2000; Benn and Sánchez, 2001; Oswalt, 2003; Trimble et al., 2005). The results confirm the more general notion that a telescope of the size and general sophistication as discussed in the present paper is an efficient tool for frontier observational work in astrophysics. This is, not least, true for work involving the use of telescopes with various sizes and priorities.

A 3 m class telescope with active optics and some version of adaptive optics can satisfy a large range of science objectives. Considering possible science cases for such a telescope, there are few parts of modern astrophysics that should not be closely examined. Here, only some tentative and rather general considerations will be offered. More explicitly, comments will be given regarding our solar system, other planetary systems, stars, brown dwarfs and planets, the Galaxy and other galaxies, including aspects of cosmology.

A 3 m class telescope with frontier mechanics and optics and high image quality, at a site with a dark sky and favourable atmospheric conditions, can, in addition to imaging, photometry, spectroscopy and polarimetry, be used for astrometry. Such a telescope, if properly equipped concerning instrumentation and detector facilities, can produce high-resolution images also of rather faint objects. Relative positions and proper motions of competitive precision are often highly interesting additions to results of photometry and spectroscopy. Reference is made to Zacharias et al. (2000) and Zacharias (2007)

Solar system

Highly valuable scientific contributions with a 3 m class telescope can be made for a number of objects in our solar system. Excellent proof is provided by solar-system science using the Sloan telescope (Ivezik, 2008). Our very closest neighbours are good examples. Interesting projects can be conducted for Mercury, Venus and Mars as well as for the Moon. Studies of the surfaces can be highly rewarding for Mercury and the Moon, especially with a rather valuable combination of high spatial resolution and a generous spectral resolution at wavelengths in the near infrared spectral region. Surveys for minerals need extensive observing programmes.

Corresponding studies of atmospheric properties are of great interest for Mercury, Venus and Mars as well as for the Moon. Targets are high-atmosphere processes for Mercury, gas inventories for Venus, including time series, water-vapour investigations for Mars and surveys for element abundance concerning the Moon. Spectroscopy and imaging should be considered.

Time series of from intermediate to large extent open a window of opportunity concerning Jupiter and Saturn as well as, and not least, their satellites. Such data benefit in their competitiveness if obtained based on high spatial resolution and auxiliary instruments with optimised designs. An interesting over-all theme is evolution with respect to formation and development of the planetary system, its planets and their satellites as well as composition of elements and prerequisites for life, its thriving and its extinction. Reference can be made to Sprague (2003) and Simon-Miller and Chanover (2003).

Asteroids are both highly accessible for observations with a 3 m class telescope and able to provide results of high scientific value. While many arguments may be forwarded for the need of extended data on orbits, sizes and shapes of asteroids, there is also a pronounced need of studies of their physical characteristics (Chapman, 2006). Such studies should, preferably, be made for all the major families of asteroids existing.

Interestingly, there is a general emphasis on investigations of the class of so-called near-Earth asteroids (Kaasalainen and Ďurech, 2007). Together with other near-Earth objects (Binzel and

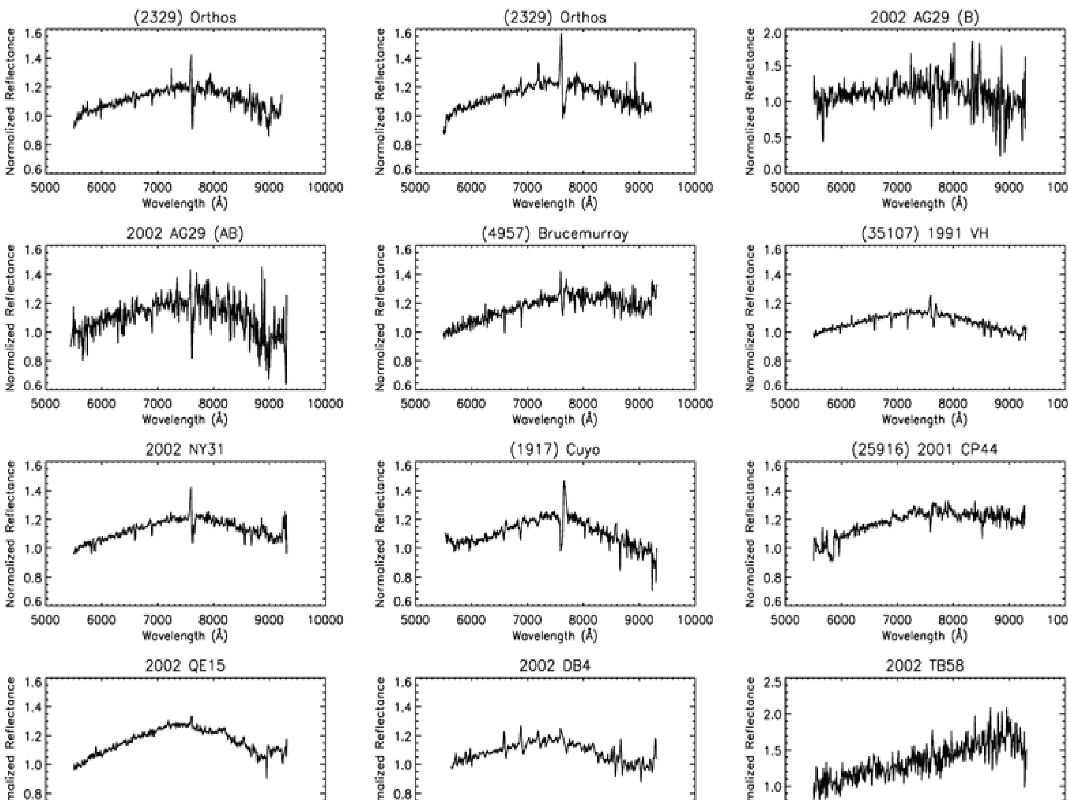


Figure 18. Near-Earth asteroid spectra (Michelsen et al., 2006).

Lupishko, 2006; Noll, 2006; Lupishko et al., 2007; Larson, 2007; McMillan et al., 2007), they are of high interest in a number of respects (Donnison, 2007; Reddy et al., 2005, 2006a, 2006b; Pravec et al., 2006, 2007). These are both interesting objects and well suited for observations with 3 m class telescopes (Remo, 2003). Notably, for object identification, characterisation and follow-up, astrometry is a highly useful tool (Ferrín et al., 2001). At the same time, with a 3 m class telescope, spectroscopy can be made with very good results. Examples are the data published by Michelsen et al. (2006).

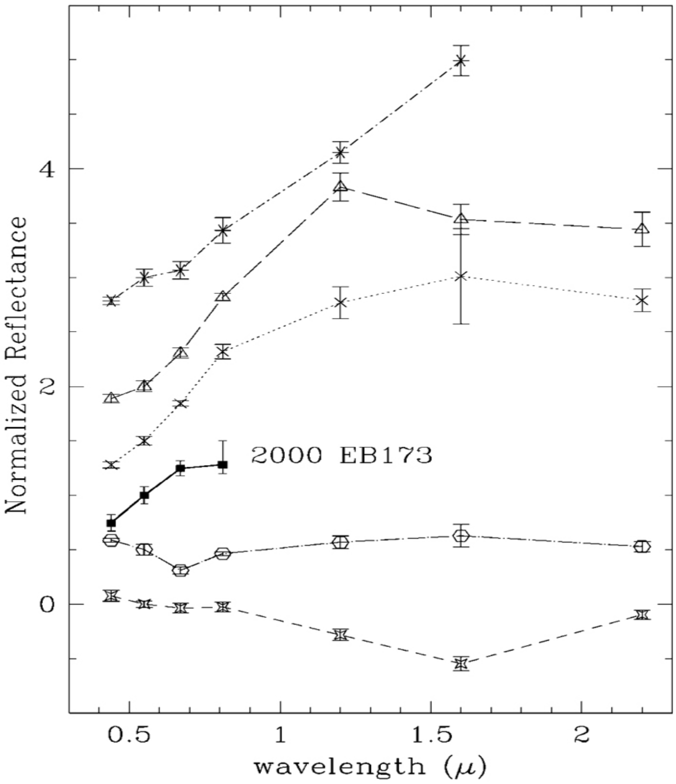


Figure 19. Spectral reflectance of the Trans-Neptunian Object 2000EB173 (Ferrin et al., 2001).

As demonstrated by Parker (2008), the 2.5 m Sloan telescope is highly useful for asteroid research. It should be added that the class of potentially hazardous asteroids define observing targets interesting from many points of view. Reference is made to ESA SP-1310 (2009). In addition, much highly rewarding work remains to be conducted regarding the asteroids belonging to the main belt as well as to concerning Jupiter-related and Neptune-related Trojan asteroids (Blair, 2002; Morbidelli et al., 2005).

Another scientifically rewarding class of targets for a 3 m class telescope is that of comets (Toth, 2006; Sheppard, 2006; Harris and Pravec, 2006). In this context, the content and nature of the nuclei of comets are as challenging as evasive in terms of the approachability of general observations. Out-gassing events, including larger amounts of matter ejected, caused either by perihelion passages or impacts, supplemented by studies of less active phases, can reveal physics of highest relevance for our insight into the shaping of planetary systems in general. Imaging and photometry can contribute a wealth of much-needed data. An important strength of the observations discussed is the possibility of longer time series, impossible to obtain with spacecraft missions (Mumma et al., 2001; Harris et al., 2001; Lynch et al., 2002; McLaughlin et al., 2003).

Studies of objects beyond Neptune are still in an early phase (Barucci and Peixinho, 2006). The Kuiper Belt Objects (KBO) carry important messages regarding the formation and early evolutionary phases of our planetary system. At the same time, understanding the KBO is a prerequisite for solid insight into the world of extra-solar planetary discs and systems. Much needed are data on orbits and families of orbits but also on individual objects. Surveys and monitoring define important contributions to the field. The development of KBO research is ample proof of the value of such observations with a 3 m class telescope (Howard, 2008).

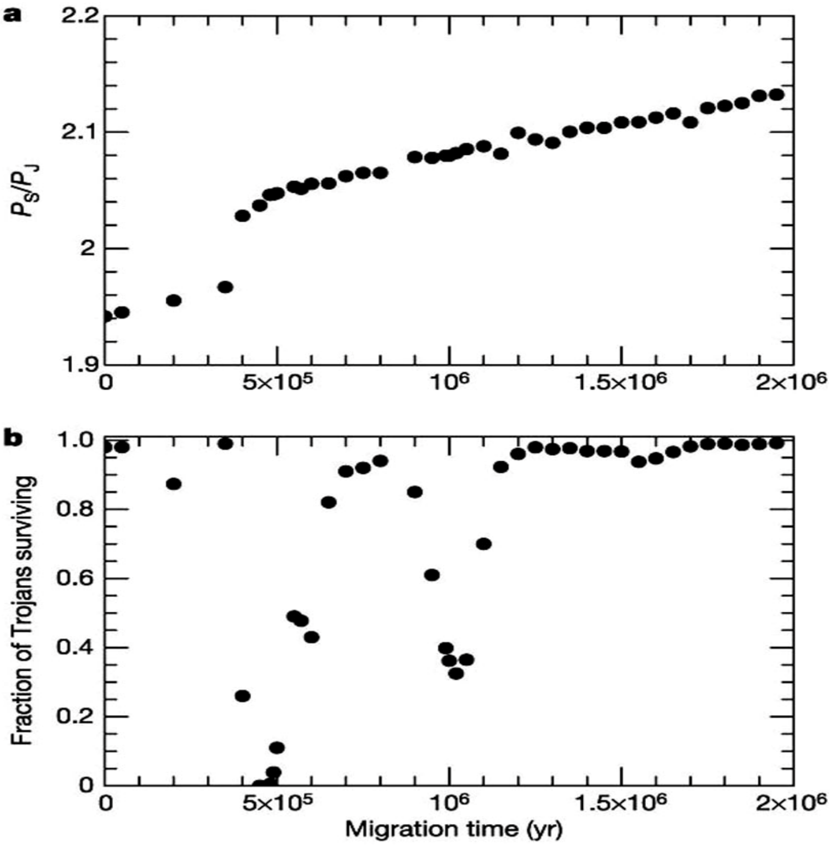


Figure 20. Stability of Trojans during planetary migration (Morbidelli et al., 2005)

Other planetary systems

The dramatically increased activity regarding other planetary systems developed especially since the end of the previous millennium is clearly just the initiation of a new phase of stellar and planetary research. In the coming few decades both general surveys of planetary systems and more detailed data for interesting systems will be of importance for the investigation of the formation, development and nature of planetary discs and planetary systems (Mannings et al., 2000). More detailed studies requiring larger telescopes, there are many essential fields of exo-planet research that can be forwarded with the help of 3 m class telescopes. Mention may be made of identification of such objects as parts of larger survey projects or as special undertakings as well as corresponding studies of planetary transits and, even, imaging of planets in external systems. Reference is made to Trimble and Aschwanden (2004).

For many reasons, statistical surveys of the occurrence and characteristics of planetary systems with different types of central stars are of fundamental importance. The stellar distinguishing traits may refer to their mass, effective temperature, gravity, abundance of heavy elements, stability, multiplicity, encounter history and interstellar environment. There are indications of correlations between some of these parameters and the occurrence of planetary systems. For our search for Earth-like planets, such correlations may prove rather important. While studies of planetary parameters may require larger telescopes, studies of corresponding stellar parame-

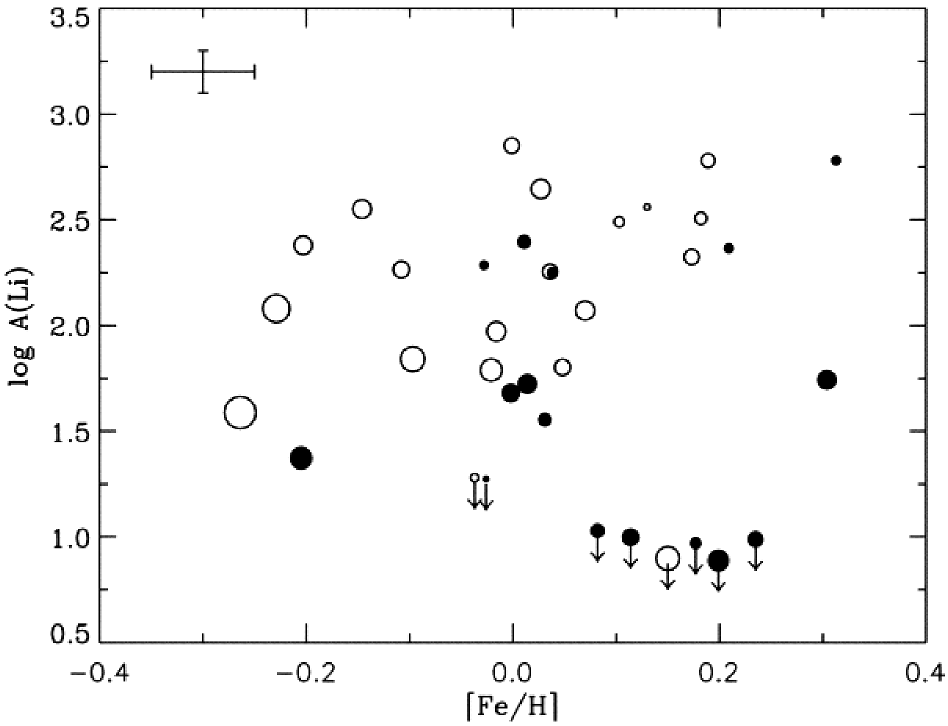


Figure 21. Litium abundance versus [Fe/H] for stars with (filled circles) and without (open circles) planets (Chen and Zhao, 2006).

ters can, highly successfully, be made with a modern high-quality 3 m class telescope. Reference is made to Gustafsson et al. (1999), Gonzales et al. (2001) and Chen and Zhao (2006).

More in general, orbital velocities and periods are most valuable yet possible to determine with 3 m class telescopes. Even if only planets with larger masses and/or planets orbiting stars of smaller masses can be found and characterized, the advance is important. It is noted, that such observations, with a 3 m class telescope can attain rather high precision (Lloyd et al., 2009). It should be kept in mind that also confirmation of stars showing no detectable signs of the presence of planetary companions is essential (Heiter and Luck, 2003; Paulson and Yelda, 2006).

Also, the relation between stellar binarity and planetary systems and their stability is an issue of high importance. In this context, the case of planets orbiting circumbinary stars has an interest of its own (Ofir, 2009). Further, the encounter story of stars hosting planetary systems is of vital importance, with a seemingly substantial advantage of the so called singletons (Malmberg et al., 2007a, 2007b, 2007c). At any rate, for planetary systems identified, observational studies of the parent stars are of utmost importance. In total, observational data are needed in a wavelength interval comprising both the optical-visual and the near-infrared parts of the spectrum.

Parameters of special interest can be delivered using successful monitoring of planetary transits (Pont et al., 2009). Such data can enrich our data bases via detections and statistics (Jha et al., 2000; Hidas et al., 2005; O'Donovan et al., 2006; Charbonneau, 2009; Mazeh, 2009; Boss, 2009). The significance of planetary transits is also driving the development of specialised instrumentation (Carson, 2009). Another method that has proven highly successful is observations of gravitational lensing. Exceedingly valuable work in this latter vein has been performed by the OGLE team and project (Soszyński, 2009; Dong et al., 2009; Gold et al., 2009).

It should be emphasised that highly successful and productive surveys for and studies of planetary transits can be made with telescopes the apertures of which are much, even very much,

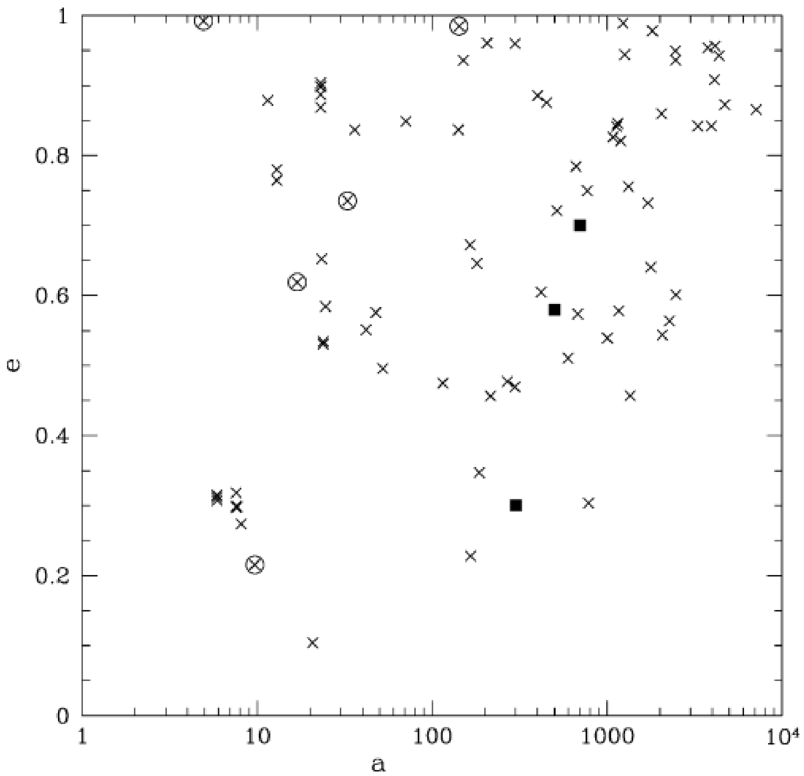


Figure 22. Close encounters in young stellar clusters and planetary systems. Eccentricity as a function of semi-major axis for binaries containing stars that were initially single in a reference cluster. Crosses mark binaries that existed sometime during the lifetime of the cluster. Crossed circles mark binary objects that survived the end of the run and that, thus, would be seen in the field today. Filled squares mark binary systems the planetary systems of which would be broken up over at time scale of a few million years if the inclination between the planets and the companion star were sufficiently large (Malmberg et al., 2007c).

smaller than that currently under discussion. Ample practical proof is readily available. Examples are given by Bakos et al. (2009), Collier Cameron et al. (2009), Irwin et al. (2009), Sackett et al. (2009), Beatty (2009), Shporer et al. (2009), Bayliss et al. (2009), Crouzet et al. (2009), Eigmüller and Eislöffel (2009), Siverd et al. (2009), Bakos et al. (2009), Fukui et al. (2009), Eastman et al. (2009), Street and Lister (2009), Proctor et al. (2009), Rabus et al. (2009), Raetz et al. (2009), Vaňko et al. (2009), Saito et al. (2009), Boisse et al. (2009) and Janes and Kim (2009).

With a 3 m class telescope, rather accurate parameters can be derived for transiting planets as shown by Winn (2009). It is emphasized that this is the case not only for photometry but also for spectroscopy (Barbieri et al., 2009). In addition, quite deep survey programs can be conducted. The latter fact is well proven. See Miller and Albrow (2009). Further, such a telescope is well suited also for observations at near infrared wavelengths (Blake et al., 2009).

Especially in combination with data on radial velocities, observations of gravitational lensing can also provide highly detailed and essential information on the nature of planets. There is ample evidence of the ability of even smaller telescopes to be competitive in this field. Monitoring can be made for objects of special interest as well as in survey mode. In the latter case, large-field observations can produce a wealth of data, for planetary systems as well as for multiple stellar systems.

It is well worth noting that the rather sophisticated technique of micro-lensing for the identification and study of extra-solar planets can be successfully carried out also with telescopes of modest sizes (Gold and Loeb, 1992; Bennett and Rhie, 1996; Abe et al., 2004; Bond et al.,

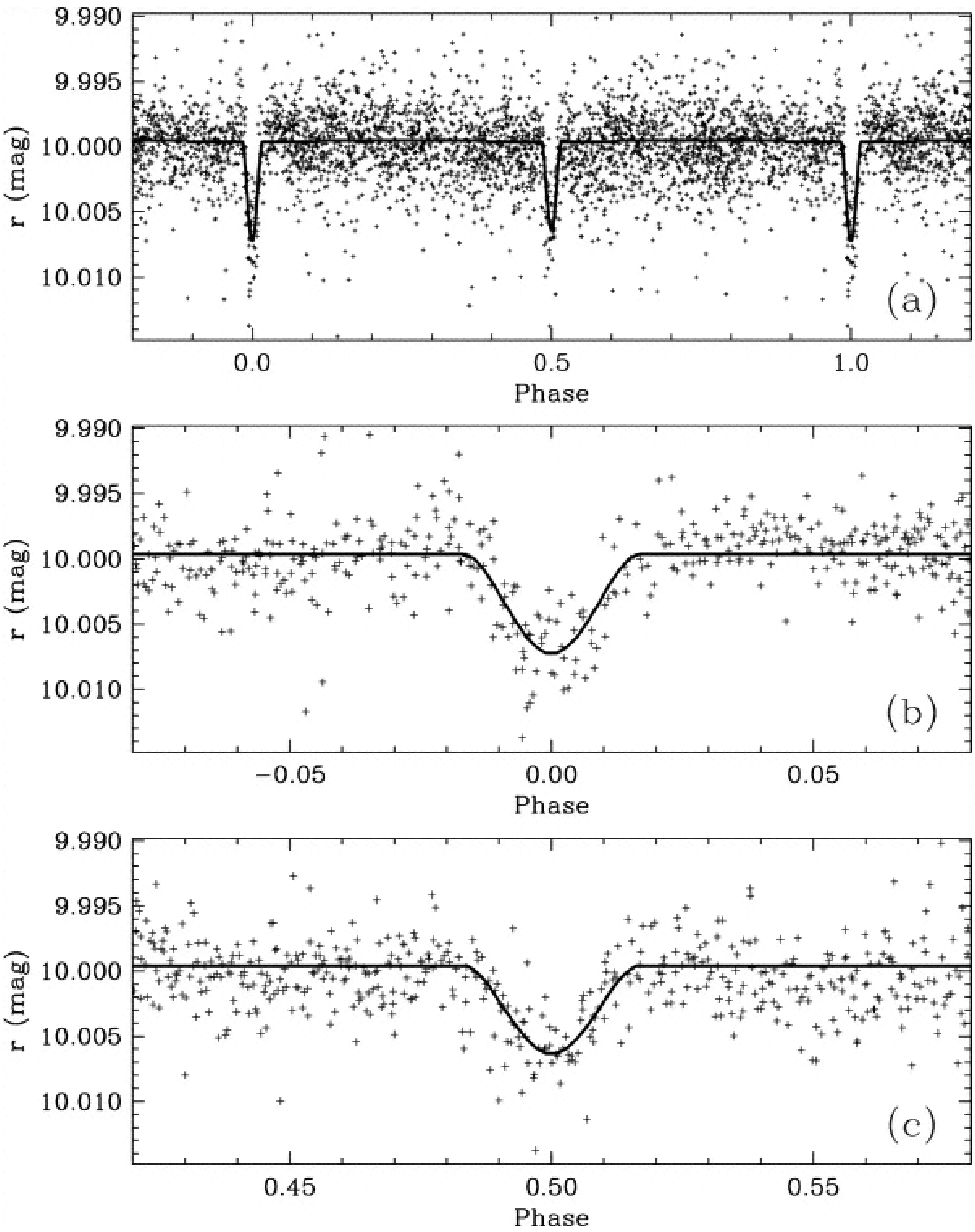


Figure 23. TrES r-band photometry of GSC 03885-00829 folded using a period twice that of a candidate planet (2 × 1.441 days). (a) Best-fit blend model consisting of the bright F star and a pair of eclipsing K dwarfs. (b) Enlargement around the primary eclipse. (c) Enlargement around the secondary eclipse (O'Donovan et al., 2006).

2004; Udalski et al., 2005, Bennett et al., 2008). While telescopes with apertures even less than one metre can make important contributions, a 3 m class telescope is a rather powerful tool for this type of investigations. In addition, with such a telescope, both micro-lensing observations and radial-velocity monitoring can be made.

With a 3 m class telescope, planets with sizes from those of Jupiter to Neptune and Uranus can be rather successfully studied. For such planets and with such a telescope, even imaging can be made. In this case, however, rather advanced adaptive optics and coronagraphs are required, auxiliary equipment of a challenging nature but by no means incompatible with the telescopes under discussion. Reference is made to Brown et al. (2001), Silva and Cruz (2006), Fischer (2003), McGruder et al. (2003) and Oppenheimer et al. (2003).

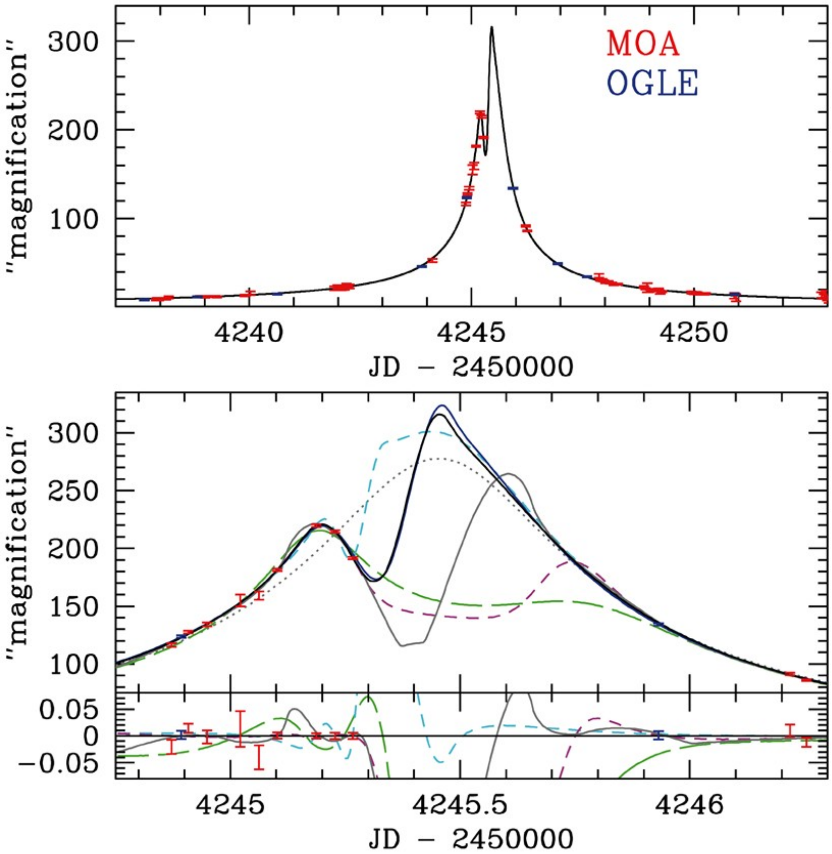


Figure 24. Microlensed portion of the light curve of MOA-2007-BLG-192 as seen by the MOA telescope, plotted in normalized flux units (Bennett et al., 2008).

From large planets via Brown Dwarfs to small stars

A mass regime of special interest in astronomy is that including from small-mass stars down to planets. So far, we have to accept that the objects populating this regime are, in general, neither well observed nor well understood. Symptomatically, our ideas concerning the division lines between, on the one hand, small stars and brown dwarfs and, on the other hand, between brown dwarfs and large planets are, to say the least, confused. As long as we do not have any solid ideas regarding the similarities and differences between these three classes of objects, we cannot really claim to have understood any of them, their physics and conditions for formation and evolution (Burgasser, 2004; Allen et al., 2005).

There have been several attempts at definitions of criteria more or less clearly distinguishing small stars from brown dwarfs and brown dwarfs from large planets (Burrows et al., 1997; Basry and Marcy, 1997; Oppenheimer et al., 1998, 2000; Burrows et al., 2001; Burningham et al., 2008; Delorme et al., 2008; Leggett et al., 2009). The perhaps most fundamental and clearly defined of these division criteria seems to be reasonably clearly connected with the main central source of energy. An object with conversion of hydrogen to helium as its prime, initial, energy-generating process is defined as a star. If the prime initial energy-producing process is that of gravitational contraction accompanied by fusion of deuterium or lithium, the object is labelled a brown dwarf. An object fully unable to fuse even deuterium is regarded as a planet.

In this scenario, stars should have a lower mass limit of approximately 0.08 solar masses. Brown dwarfs fusing lithium only should have masses larger than around 0.065 solar masses, while those producing their main energy from the fusion of deuterium should have masses above 0.013 solar masses. Bodies with masses below 0.013 solar masses are believed to be

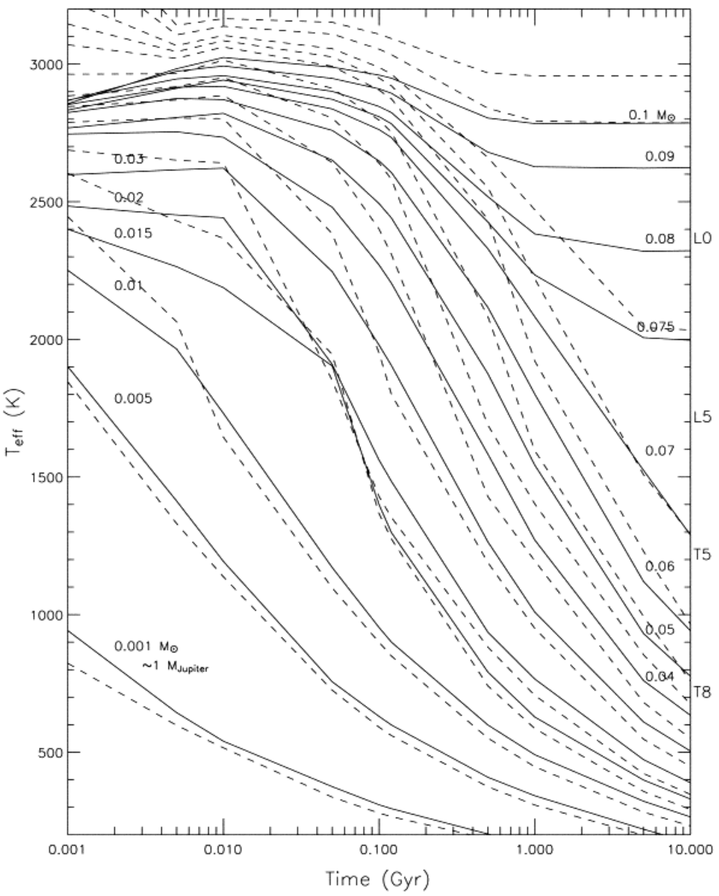


Figure 25. Evolutionary tracks of sub-stellar objects with different masses (Burgasser, 2004).

fully unable to burn even deuterium and are, normally, regarded as planets. Stars are relatively long-lived as bodies with nuclear energy production and pronounced general stability, while brown dwarfs are much more short-lived as such. Whatever the case, our understanding of the low-mass objects and their interrelations is far from solid. Reference is made to Larson (2002), Padoan and Nordlund (2002), Jayawardhana et al. (2003), Jayawardhana (2004), Béjar et al. (2004), Chiu et al. (2006) and Bouvier et al. (2008).

For some time, the brown dwarfs were regarded as objects of very special interest in and for astrophysics. They were seen not only as failed stars (Reipurth and Clarke, 2001), but were also suspected of being the clue to the so-called missing-mass problem. In this context, some impressive attempts were made at studies of the brown dwarfs as related to the Salpeter function and the slopes of the low and sub-stellar mass function (Tej et al., 2003; Moraux et al., 2001, 2002, 2003, 2004a, 2004b, 2005, 2007; Henry, 2007). Investigations of spectral signatures (Testi et al., 2001; Testi, 2004) greatly contributed to the understanding of the challenging objects.

In spite of rather ambitious investigations, observational as well as theoretical, the nature of the brown dwarfs remained beyond real understanding. The low absolute magnitudes, the most luminous brown dwarfs having R magnitudes fainter than 20, and the short time as active bodies set a clear limit to observational studies. The pronounce lack of observational data in turn has made theory building an effort plagued by great uncertainties. At any rate, it has become gradually more and more obvious that the brown dwarfs, while probably rather numerous, cannot, due to their modest masses, provide the explanation of the missing-mass problem.

An interesting and highly valuable conclusion in itself, the disconnection of the brown dwarfs from the missing-mass enigma caused a pronounced negative effect regarding the efforts spent on this class of objects and their nature. Still, there is every reason to pursue a vigorous study of brown dwarfs and their nature. This is especially realised by a smaller number of astronomers devoting large efforts to objects with masses below those of what we usually define as those typical for the smallest stellar objects (Barrado y Navascués et al., 2004; Basri and Brown, 2006; Delorme et al., 2008; Burningham et al., 2008).

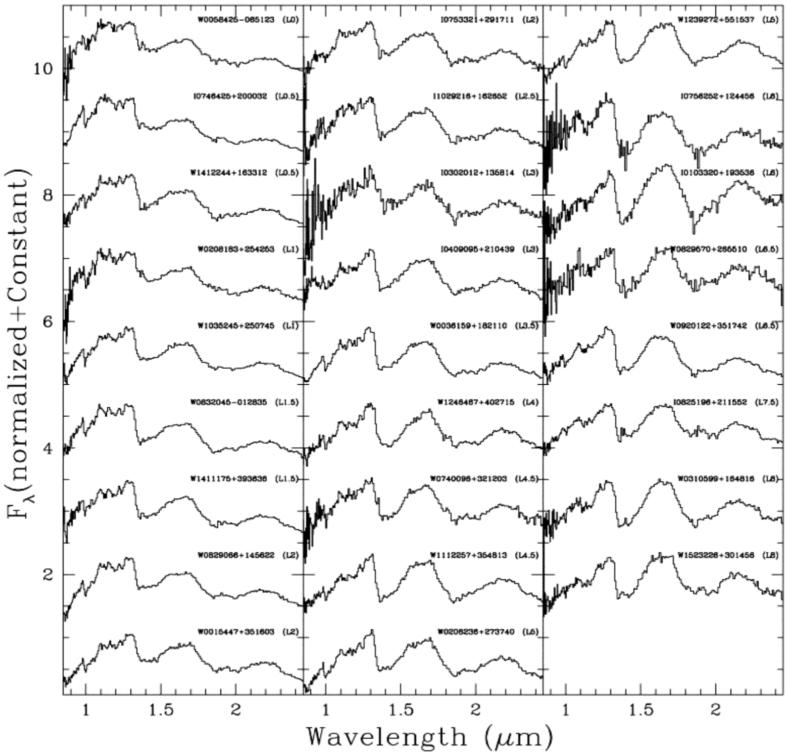


Figure 26. Low-resolution spectra of L dwarfs (Testi et al., 2001).

Ambitious surveys for brown dwarfs are in progress. The Expérience pour la Recherche d’Objets Sombres (EROS) experiment (Afonso et al., 2003; Tisserand et al., 2007) is such a programme. Another is the conducted by the Microlensing Observations in Astrophysics (MOA)

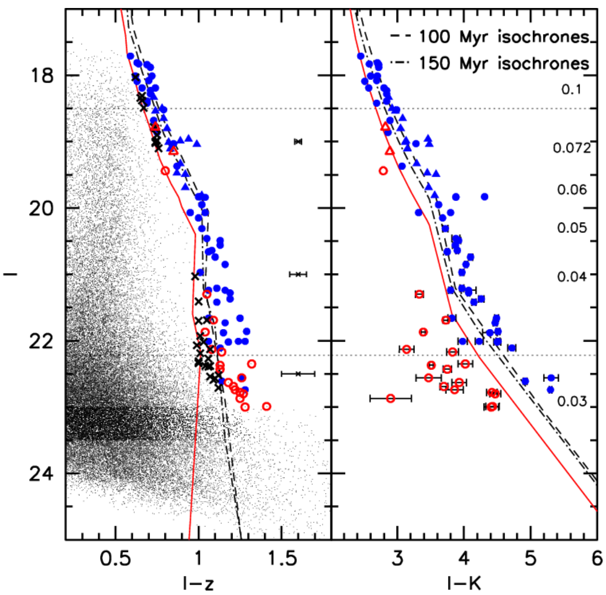


Figure 27. I, I-z and I, I-K CMDs for point-like objects in the lower-mass range of the open cluster Blanco 1 (Moraux et al., 2007).

Gould et al., 2009). Having experienced major results concerning lensing detections of exoplanets, this programme is commented under the heading “Other Planetary Systems”.

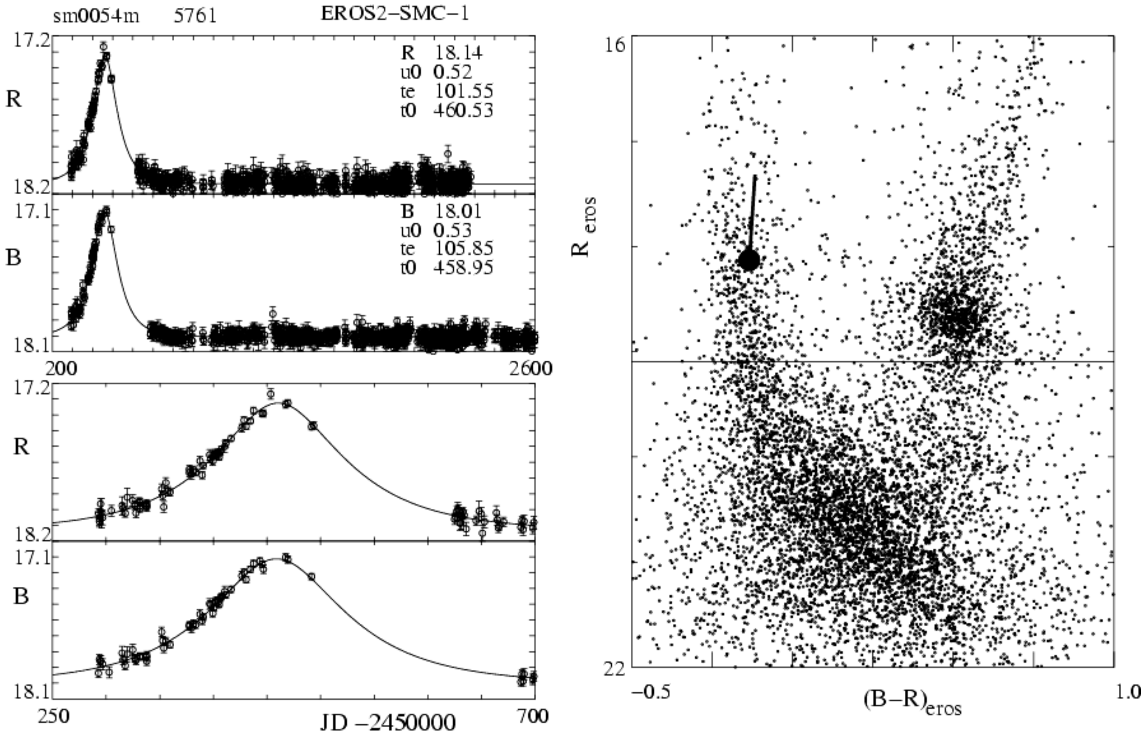


Figure 28. Light curves of EROS-2 microlensing candidate EROS2-SMC-1 (Tisserand et al., 2007).

Stars and stellar systems

After the Big Bang, the formation and evolution of stars define what can be labelled the most fundamental processes in the universe. Stars convert gas and dust into more or less compact bodies, they host nuclear reactions and convert lighter elements into heavier ones. Through various forms of mass loss, they enrich the interstellar matter with matter marked by higher abundance of heavier elements. They form a range of structures, associations, open clusters, globular clusters and structures of galaxies. In addition, stars are the central parts of planetary systems and a highly essential key to conditions supporting the formation and evolution of life like that on Earth.

The evolution of stars, including their nucleosynthesis processes (Wallerstein et al., 1999; Woosley et al., 2002), is a prime motor of the evolution of galaxies and the universe as a whole. Accordingly, studies of star formation and stellar evolution are of prime importance for our understanding of astrophysics. Such studies can, with a 3 m class telescope, if adequately designed and accomplished, give highly valuable information on a range of key questions in astrophysics. Moreover, many stars and stellar groups constitute excellent laboratories regarding the processes in question. In addition, for many stars of fundamental evolutionary importance, such a telescope can successfully be used for asteroseismology (Aerts et al., 2002, 2003; Aerts and Harmanec, 2004; Aerts, 2007; Lebreton and Montalban, 2008; Bernabei et al., 2009; Stello et al., 2009). An excellent example of the usefulness of telescopes with apertures in the range 1.2 – 3.5 m for asteroseismology is given by Desmet et al. (2009).

A wealth of nearby stars with different basic parameters, such as mass, surface gravity, effective temperature, abundance of heavier elements, age and kinematics as well as those of the

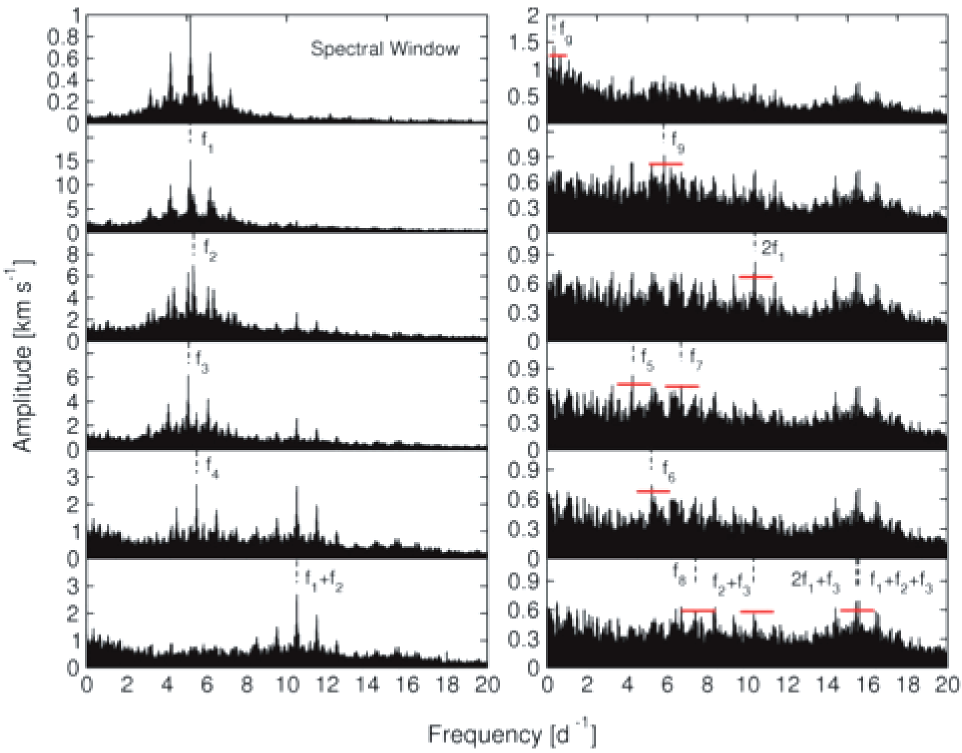


Figure 29. Amplitude spectra of 12 Lac computed from the first moment of the SiIII λ 4553 line (Desmet et al., 2009).

surrounding matter at and following their formation, provide a rich amount of samples for the study of evolutionary parameters and their dependence on dominant stellar characteristics. Identification of stars close to the Sun is important for many reasons, not least regarding our understanding of our local populations of stars and their physical parameters. Programmes for such identifications have since long and repeatedly been undertaken (Gliese, 1957; Jahreiss, 1992; Jahreiss and Gliese, 1993; Jahreiss, 1994; Nordström et al., 2004; Prieto et al., 2004; Holmberg et al., 2007).

At the same time as modern work on identifications of nearby stars is a natural target for missions concerned with space astrometry, such as Hipparcos (ESA, 1997) and Gaia, detailed studies have to be made by other means. In practice, a 3 m class telescope is a powerful tool for such work. Highly valuable additional information can be obtained from studies of more special objects. Examples are massive stars (Kenicutt, 2005), various types of variable stars, double and multiple stars and stellar clusters and aggregates.

The stars and stellar aggregates discussed are highly useful not only as probes of star formation and stellar evolution but also as standard light sources. As such, they provide very valuable tools for distance determinations. These, in turn, are of prime importance for tracings of structures in the Galaxy as well as for establishment of a rather large range of distances (Szabados, 2003). In the latter context, the value as tools for cosmology is more than significant. An additional aspect of these relations is provided by the strong evidence for a universe only to a minor part composed of matter and energy of the type well known to us (Peebles and Ratra, 2003; Baum and Frampton, 2007; Kowalski and Rubin, 2008).

Photometric and spectral variability are highly frequent features of most stars. Stating it in a somewhat different manner, it is probably rather difficult, if at all possible, to find a larger sample of stars that do not show any variations, neither in luminosity nor in their spectrum. The signatures of variability differ as functions of fundamental stellar parameters, not least as a function of age. Especially concerning photometric variability patterns, their interpretation in astrophysical terms and usefulness for distance determinations, a 3 m class telescope, well utilised, can deliver data of utmost importance. This concerns classes of objects well known but with new features detected (Kamper and Fernie, 1998; Macri et al, 2001; De Cat, 2002; Quirion et al., 2007) as well as newcomers in the field (Kaye et al., 1999; Koen and Laney, 2000; Nagel and Werner, 2004).

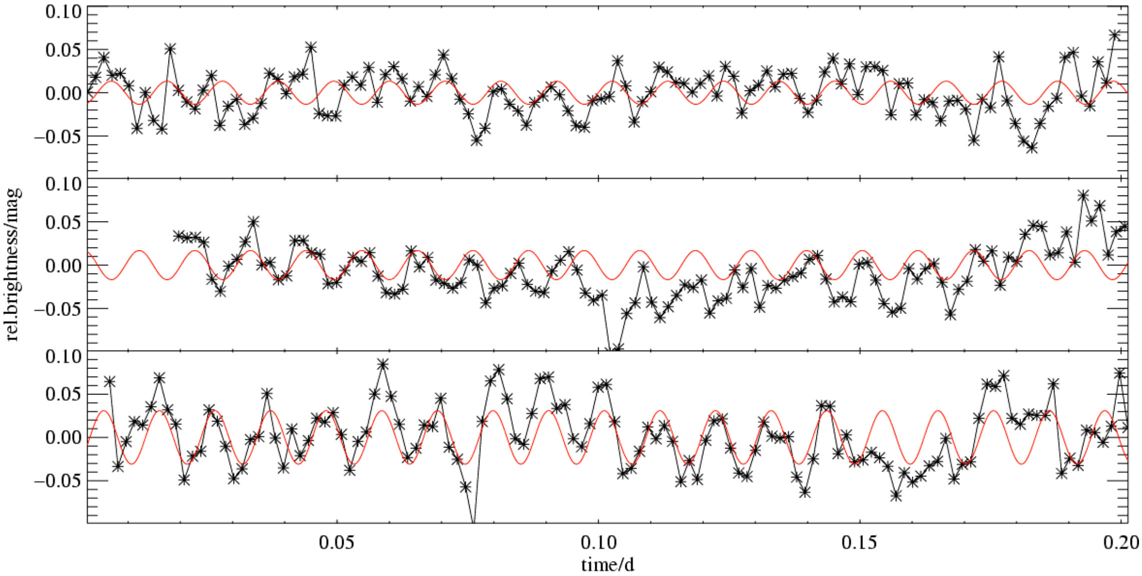


Figure 30. Light curve of HE1429-1209 during three consecutive nights plus a sine fit with the detected period of 919 sec (Nagel and Werner, 2004).

(Double or binary stars offer exceptionally favorable possibilities for the determination of some parameters of fundamental importance for our understanding of star formation and stellar evolution (Guinan et al., 2007; Clarke, 2007). Mention is made of the statistics of stellar binary systems and the relation between the mass and luminosity of stars. While binary-star statistics still are rather poorly known and an often troublesome source of uncertainty in photometric work in astrophysics, the current insight into the mass-luminosity relation and its physics leaves much to be desired. In both cases, a considerable improvement in the determination of distances via space astrometry means a huge advance in the field (European Space Agency, 1997; Horch, 2003). The binary stellar systems, long conceptually promising as evolutionary standards, are now ready for a new era of interesting investigations. Notably, also the micro-lensing technique with a 3 m class telescope is highly interesting as applied to close binary stars (Rattenbury, 2009).

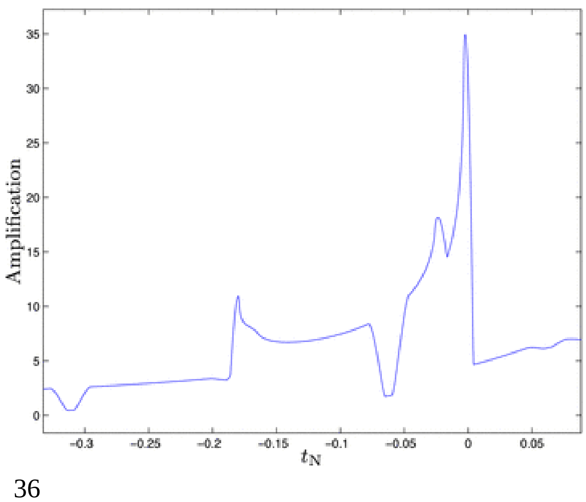


Figure 31. Light curve of TW And arising from a binary lens with mass ratio q_1 = 0.11, u_{min} = 0.1, d = 0.95, M_1 = 0.3M(Sun), D_1 = 6 kpc and D_s = 8 kpc (Rattenbury,2009).

Stellar clusters provide special facilities concerning the study of star formation and stellar evolution. Normally regarded as coeval, co-distant and with common intrinsic chemical composition, members of stellar clusters are excellent sources of information in terms of both star formation and stellar evolution and their relation to stellar mass as well as other stellar parameters. At the same time, stellar clusters define a field of research in vigorous development, also regarding well-known objects (Koch et al., 2004; Koch and McWilliam, 2008).

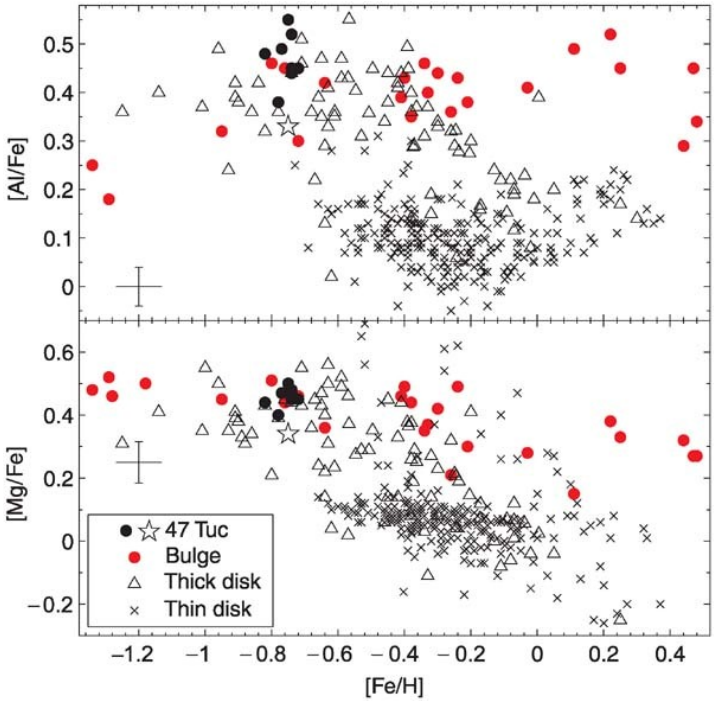


Figure 32. α-element abundance ratio versus iron ratio for various galactic stellar samples (Koch and McWilliam, 2008).

Recent (clear) indications of the co-existence of more than one population in the same stellar cluster (Piotto, 2008; D’Antona and Caloi, 2008), both complicate matters somewhat and turn the cluster studies even more interesting than before. Stellar clusters remain prime targets for investigations of stellar evolution but also for the evolution of galaxies. Accordingly, great attention is paid to a number of samples of stellar clusters (Mathieu, 2000; Gieles et al., 2008). Highly valuable properties of stellar clusters can be obtained via broad-band or intermediate-band photometry and construction of colour-magnitude diagrams (CMDs), complemented with metallicity diagrams (MDs) and, for fainter objects, luminosity functions (LFs) as well as other observational data (Sajedini et al., 2003; von Hippel, 2003).Not least for studies of the very first phases of stellar evolution do clusters offer a number of advantages (Herbst, 2003). This is true also for the evolution of the stars before they reach their phase of equilibrium on the main sequence. Time series of this evolution, including pronounced stages of variability, is a scientifically highly rewarding undertaking. The scenario of a very young cluster with its most massive stars already on the main sequence and the rest of them gradually evolving towards the same sequence provides most valuable series of very early evolutionary tracks in the Hertzsprung-Russel diagram. Especially in the early epochs of cluster evolution, studies are favoured by the still relatively low frequency of stellar image super-positioning.

Stellar clusters in more advanced stages of evolution are of special value for studies of less massive stars and their initial evolutionary processes (Zepf, 2008). Such studies are very much needed for a range of low-luminosity stars. These studies, though, are inevitably challenged by rising image crowding. Accordingly, high image quality is of special importance. Concerning advanced stages of stellar evolution, observational data on white dwarfs are of special value (Oppenheimer et al. 2001; Gates et al., 2004).

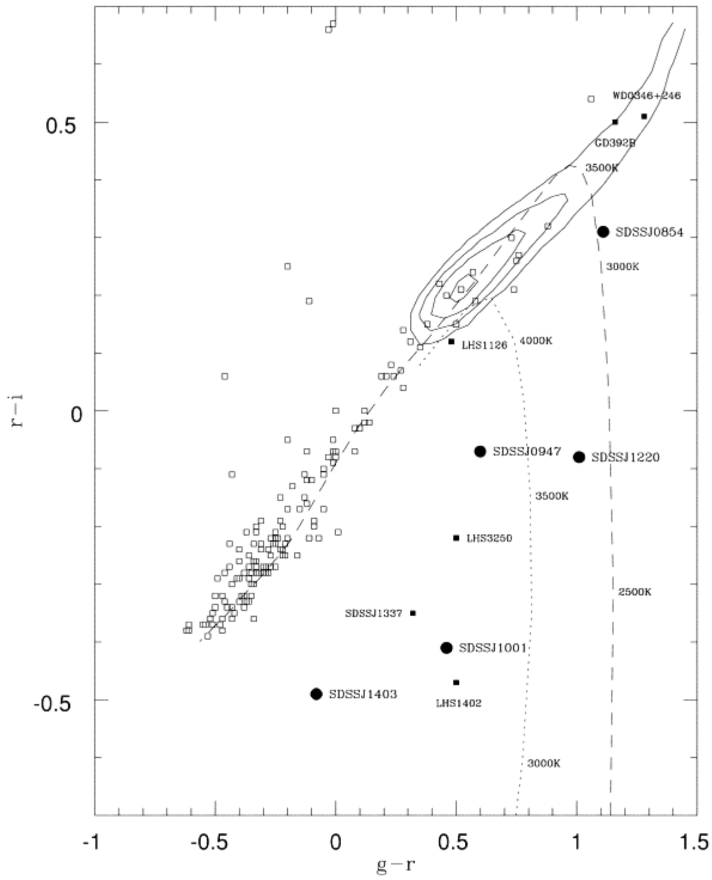


Figure 33. Colour-colour diagram showing five new ultra-cool white-dwarf stars, solid circles, together with previously known counterparts, solid squares. Data are given in estimated colours on the system of the Sloan Digital Sky Survey (Gates et al., 2004).

Regarding star formation and stellar evolution, the initial mass function (IMF), or distribution of stellar masses, is of prime interest (Kroupa, 2007). Describing the mass distribution of newly formed stars, it is a fundamental parameter for investigations of stellar evolution, theoretical as well as observational. The IMF has often been regarded as a universally well-defined function, not least due to the break-through work of Salpeter (1955). At the same time as later investigators have extended the IMF studies to gradually smaller stellar masses and intrinsic luminosities, the uncertainties concerning the uniqueness of the IMF and its dependence on the conditions of the surrounding environments have become considerable (Kroupa, 2001, 2002; Andersen et al., 2005). Not least with respect to brown dwarfs, discussed above, this is a matter of highest importance.

In general, much more observational data are required for stars of smaller masses. Very much the same is true concerning the stars with the lowest abundance of heavy elements. Also, in both cases, efforts are made to collect basic data for such objects. We refer to Reid (1994), Beers (2008), Bergeron (2008), Bochanski (2008), Lai (2008) and Kollmeier (2008).

The Galaxy

The Galaxy is the ensemble of our, in some meaning, own, local stars and interstellar matter with all its aggregates and structures on various scales. At the same time it is a relatively normal spiral-type galaxy of type Sb or Sbc with an exponential bulge and a bar (Sandage and Bedke, 1994; Möllenhoff and Heidt, 2001; Carollo et al., 2001; Alard, 2001). Nevertheless, the relative nature of our galaxy is far from clear-cut. Since long, the Galaxy and M 31 have been regarded as twin galaxies of the same type. In consequence, they have been given the same or at least very nearly the same galactic classification. At the same time (Stephens et al., 2003), it has, over the latest few years, become increasingly evident that the two galaxies are significantly different in a number of important aspects. Interestingly, the Galaxy and M 31 are the hosts of halo populations that are considerably different (Durrell et al., 2001; Ferguson et al., 2002; Brown et al., 2003; Burstein et al., 2004). In addition, the two galaxies have sets of globular clusters that demonstrate, at the same time, obvious similarities and clear differences (van den Bergh, 2000).

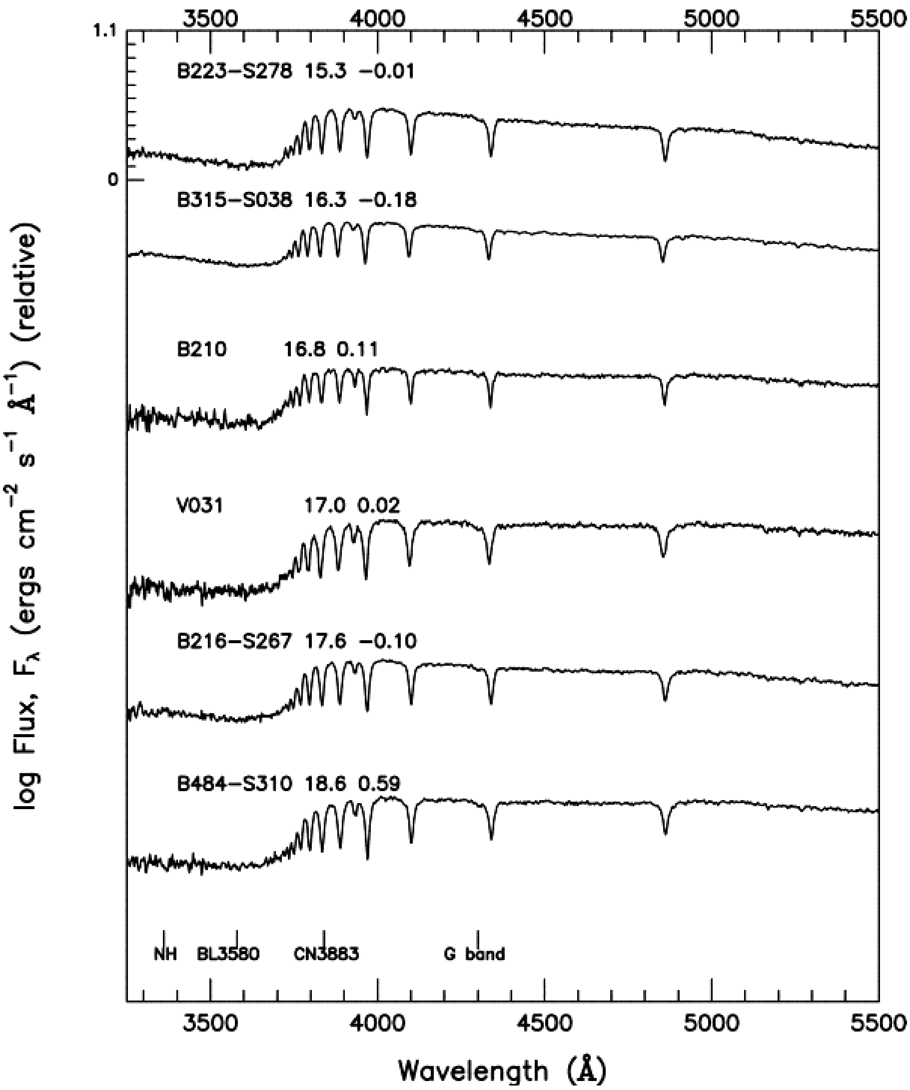


Figure 34. Spectra for six 500 Myr old M 31 globular clusters (Burstein et al., 2004). Compare with spectra in following figure.

So far, no convincing explanation for the combination of similarities and differences between the Galaxy and M 31 has been offered. Accordingly, for further conclusions and advance, it is highly important to study the stellar populations of the two galaxies in a manner as equal as possible. A 3 m class telescope with high image quality is a strong tool for such work.

While many features on a truly galactic scale can be much better studied in external galaxies than in our own, the Galaxy allows incomparably much better detailed work than any other galaxy. It is our standard reference in the world of galaxies, also in the Local Group of Galaxies. As such, it is a most basic reference object well worth detailed study (Gilmore et al., 1990). This constitutes an important observational challenge regarding a wide range of modern

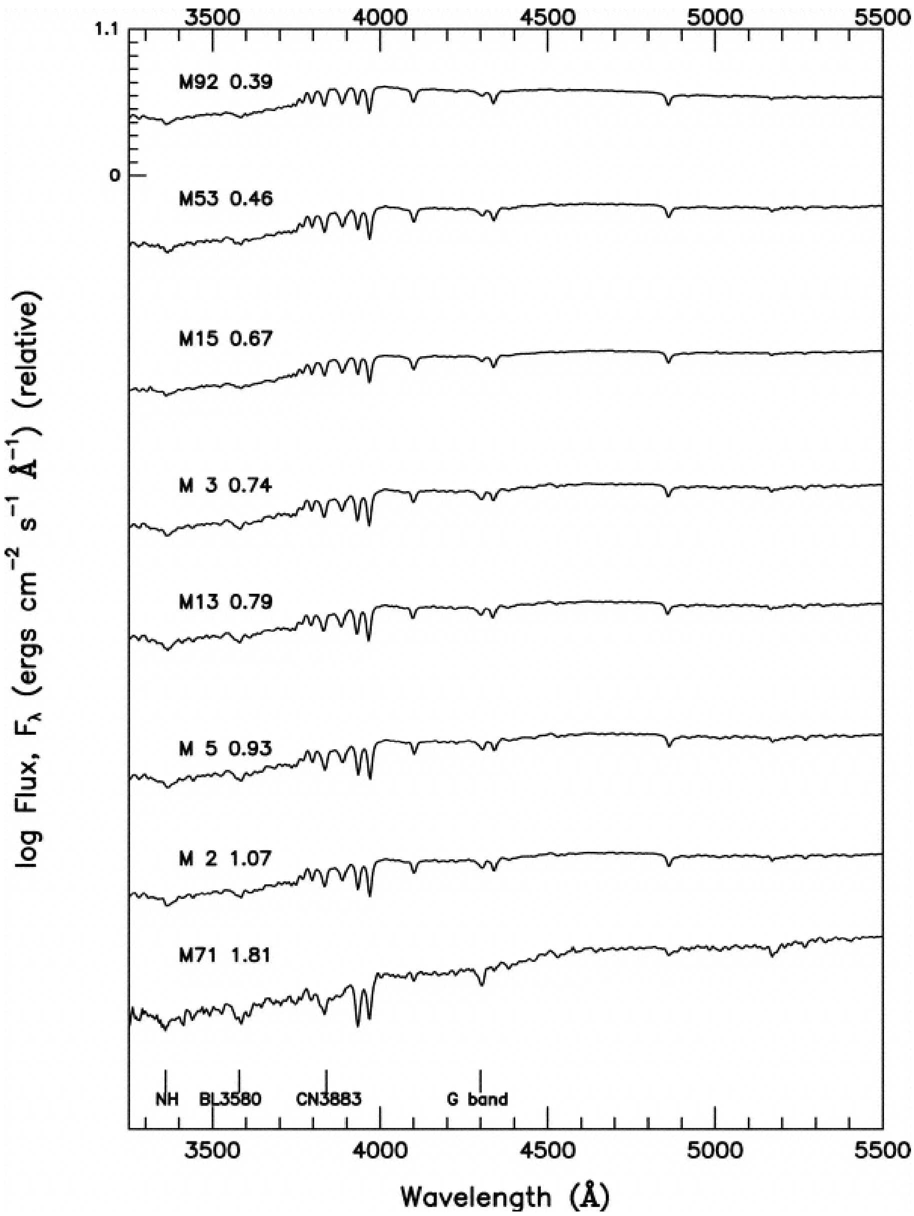


Figure 35. Spectra for eight Milky-Way globular clusters (Li and Burstein, 2003). Compare with spectra in previous figure.

telescopes, with apertures from moderately large to extremely large (Ardeberg and Linde, 2006a, 2006b). In this context, a high-image-quality 3 m class telescope, adequately equipped with auxiliary instrumentation, can be used for very competitive studies.

Depending on the position in the Galaxy relative to the Sun, galactic features can be studied with often rather high resolution, also with telescopes with more modest dimensions. Such observations, well made, form the basis for our insight into the formation and evolution of galaxies in general, of even larger structures and of the physics of the universe as a whole. The corresponding observational data come from various types of imaging, photometry, spectroscopy, polarimetry and time series. Spectral resolution of these observations ranges from around 4 in the case of broad-band photometry to more than 105 in case of dedicated high-resolution spectroscopy.

Spectroscopy provides data for determination of effective temperatures, surface gravity, abundance of heavy elements and ages as well as of kinematics. That a 3 m class telescope can provide important contributions to these scientific topics has been clearly proven by, for instance, the monumental results obtained with the 2.5 m Sloan telescope (Gunn et al., 1998). Reference can be made to Drew et al. (2005), Newberg (2008), Lucas et al. (2008), Juric (2008), Schlaufman (2008), Morrison (2008) and Wakker (2008).

Single-object dedicated studies of specially selected objects in high-resolution spectroscopy is a natural counterpart of broad-band photometry of objects in larger fields. Wide-field data often form part of large-scale survey programmes. Such programmes are used as bases for searches for objects with determined qualities and provide material for more detailed investigations, using imaging, photometry and spectroscopy. As a result, a number of surveys of stars in the Galaxy have been made. Reference can be made to Garzón et al. (1993), Epchtein et al. (1994), Kent (1994), Appenzeller (1994), Hammersley et al. (1999), Skrutskie et al. (2006). More, highly efficient, surveys are due to come (Jordi et al., 2006). Inspection of these surveys and their implications for galactic and other astronomy clearly demonstrates the huge potential of a modern 3 m class telescope and the acquisition of more detailed data.

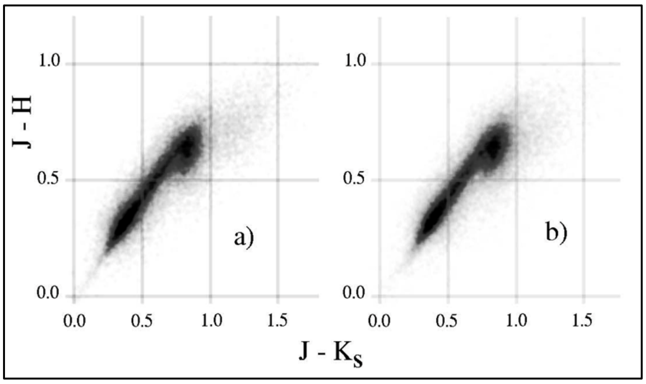


Figure 36. Hess diagrams of colour-colour distributions representing a) a local region in the northern hemisphere and b) sources selected at random from southern latitudes, between -40° and -70°. Data from Sloan Digital Sky Survey (Skrutskie et al., 2006).

Investigations of objects in the solar neighbourhood, with distances from the Sun up to a few parsecs for fainter objects to hundreds of parsecs for more luminous stars, selective or exhaustive, provide data of fundamental importance concerning basic stellar parameters. These qualities can concern special types of objects but may also describe variations of them as functions of effective temperature, absolute magnitude or surface gravity, abundance of heavy metals, place of origin, population characteristics or kinematics.

The understanding of galactic structure, its origin, development and stability are of high importance for insight into the formation and development of galaxies. In this context, the structure of our own galaxy provides fundamental information. However, its delineation and explanation are challenging undertakings. The challenge has encouraged a number of survey and search programs, as described by Garzón et al. (1993, 1994), Persi (1994), Vallée (2005) and Witham et al. (2008).

In the quest for insight into the galactic evolutionary scenario, obtaining observational data regarding the sub-systems of the Galaxy is a challenging observational target. A number of important questions remain open in spite of substantial systematic studies of these systems in the Galaxy. Not least are conclusions regarding the dependence of the average sub-system abundance of heavy elements on age a question of considerable debate. Included is the relation between not only hydrogen and the metallicity elements but also the relationship between these latter elements and the alpha-process elements.

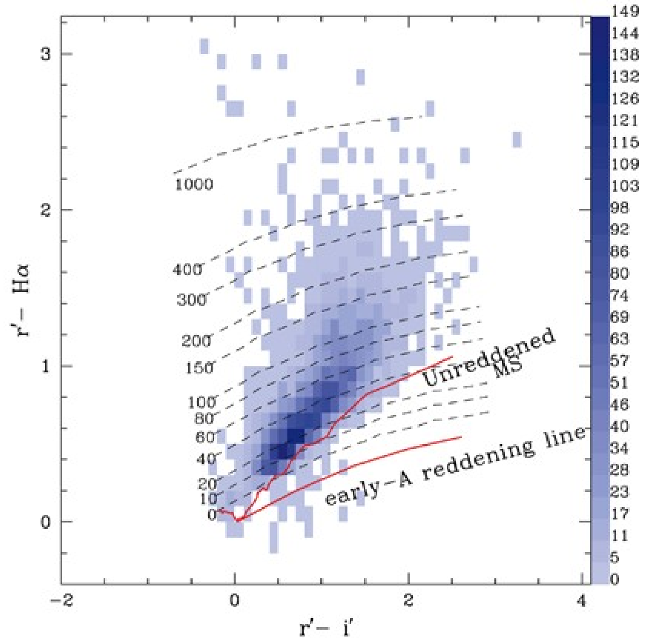


Figure 37. Distribution of Hα emitters in the (r' - Hα) versus (r' - r) plane. The shade of blue indicates the density of emitters as defined by the right-hand scale. Dashed lines represent lines of constant Hα equivalent width in Å (Witham et al., 2008).

Reference can be made to Bensby et al. (2003), Bensby and Feltzing (2006), Feltzing et al. (2007) and Bensby et al. (2007, 2009), Prochaska et al. (2003), Idiart and Thévenin (2000), Zhao et al. (2001), Koch and Edvardsson (2002), Qiu et al. (2002), Pont and Eyer (2004) and Koch and Grebel (2004).

Stars as well as stellar clusters and associations give us essential pictures of the Galaxy. The interstellar medium tells another and complementary story. In this latter case, gas and dust represent, again, different aspects, both highly important for a comprehensive understanding of

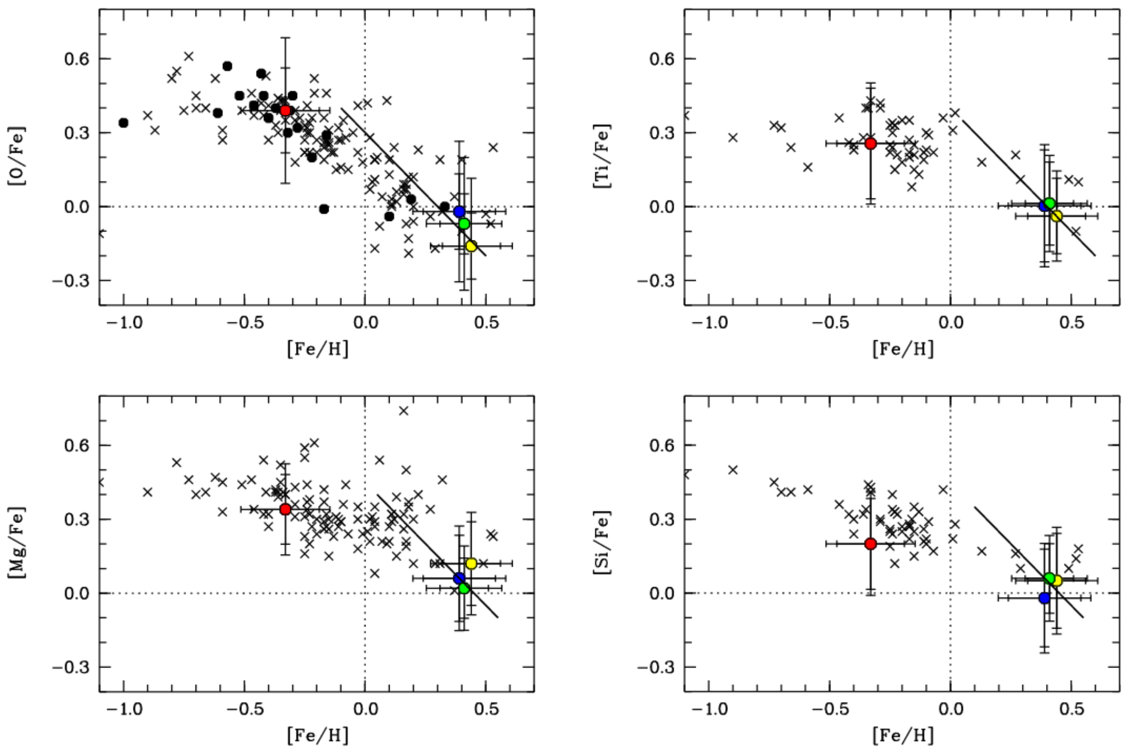


Figure 38. Abundance trends in the galactic Bulge based on giant stars (Bensby et al., 2009).

the Galaxy. The interstellar medium is as dilute as important for the life-cycle of stars and, thus, for the evolution of the Galaxy. In terms of mass, the interstellar gas is much more important than the corresponding dust. The dominant part of the interstellar gas is hydrogen, followed by helium. However, while sparsely represented, some of the heavier-element gas serves as excellent optical-visual-red tracers of the gas. Also the interstellar dust does, in spite of its relatively low abundance, manifest itself rather clearly in the same wavelength region.

Highly significant contributions regarding both gas and dust in the Galaxy can be made through observations in the optical-visual and adjacent wavelength regions. Corresponding tools are spectroscopy and photometry. Concerning the two manifestations of the interstellar medium, observational methods are rather different.

The interstellar gas is a diversified medium. In the optical-visual-red wavelength region, favorable observing conditions are available for calcium, sodium and potassium. Spectral lines of these elements, observed against background stars with suitable spectral continua and brightness, have also been studied for a range of purposes. In general, such studies, to prove optimum useful, have to rely on high spectral resolution. Regularly, spectral resolutions corresponding to R around 5x104 and even higher have been employed, depending on the spectrographic equipment available but also on the brightness of the background sources.

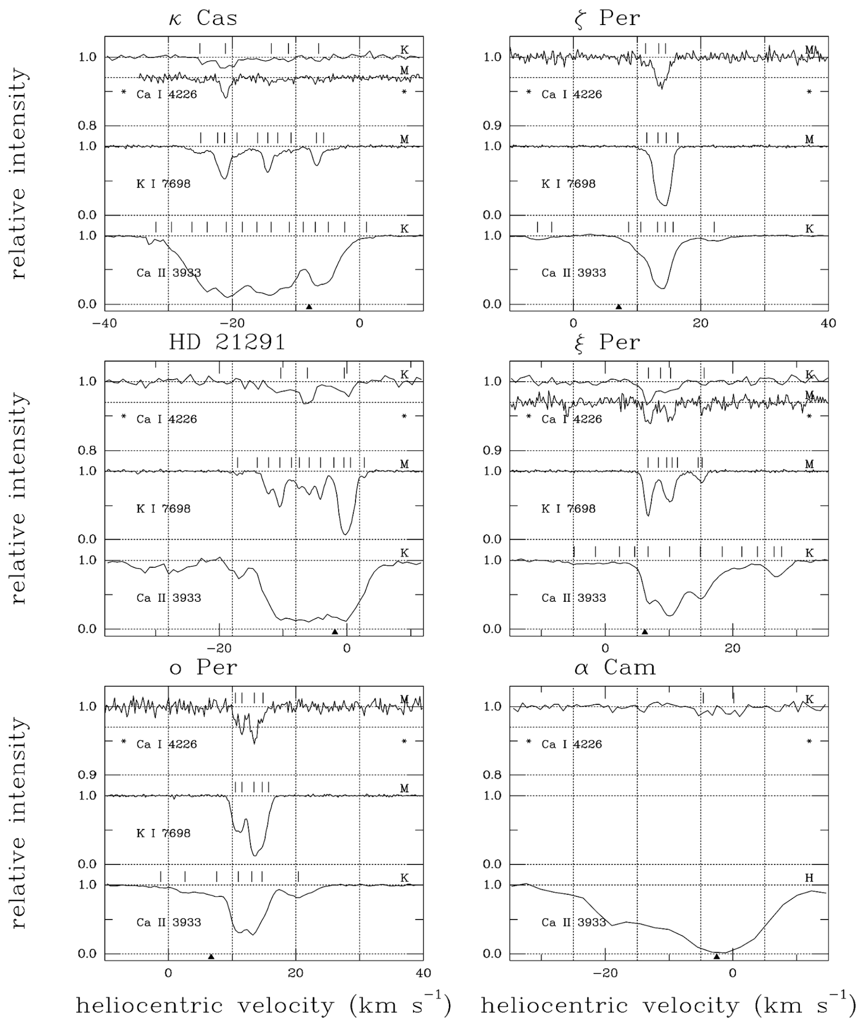


Figure 39. Profiles of interstellar lines of CaI, KI and CaII (Welty et al., 2003).

The interstellar-gas tracer element most commonly used is sodium. The reason is the strength of the D1 and D2 lines. This strength favours observations of thinner gas clouds, work over larger distances and employment of background stars of more modest brightness. At the same time, it creates difficulties in opposite conditions, with saturation a significant problem. In these cases, the corresponding lines of calcium and potassium are interesting replacements.

Sodium-line studies of interstellar gas have been made both in terms of large scale galactic surveys (Maurice et al., 1985; Ardeberg et al., 1992) and as more detailed investigations of the local interstellar medium. In the latter case, in some programmes, rather large spectral resolutions have been employed. Reference is made to Blades et al. (1980) and Welty et al. (1999, 2001, 2003). Further, reference is made to Frisch (2001). All these programmes have been conducted also with telescopes with apertures well below 3.4 m. In this context, it is interesting to note some early and very ambitious projects regarding construction of spectrographs allowing work at spectral resolutions of, respectively, 3x103 for the Mt Stromlo 1.9 m telescope (Butcher, 1971), 6x105 for the McDonald 2.7 m telescope (Lambert et al., 1990) and 106 for the Anglo-Australian 3.9 m telescope (Diego et al., 1995).

The interstellar medium manifests itself also through a number of diffuse interstellar bands. More than 300 such bands have been identified. The origin of these more or less broad absorption features has long been unknown, and only recently has it been possible to study them at higher spectral resolution and to identify sub-structures. Reference is made to Ehrenfreund (1999), Fossey and Crawford (2000), Galazutdinov et al. (2002), Sollerman et al. (2005), Holmlid (2004, 2008) and Sarre (2006). With a 3.4 m telescope, highly valuable contributions can be made to our understanding of the diffuse interstellar bands.

Figure 40. Pipe Nebula with marking of field studied as reported in following picture (Lombardi et al., 2006).

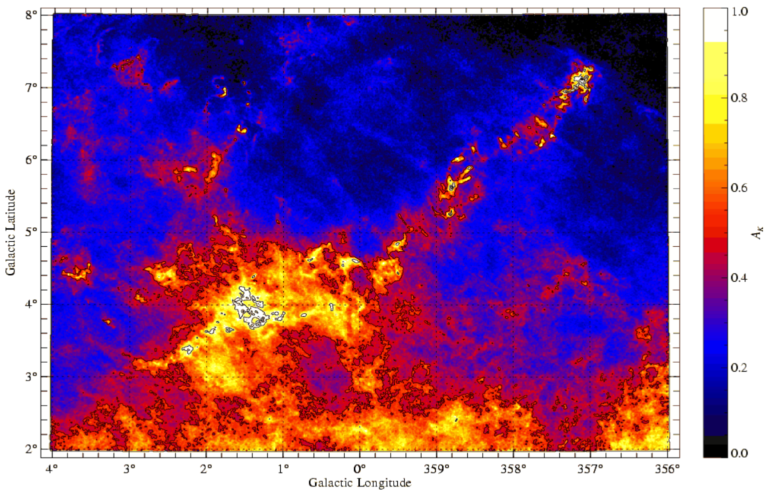


Figure 41. Piper Nebula interstellar extinction over the field shown in previous figure (Lombardi et al., 2006).

Dust in the Galaxy, while not abundant by mass, has a rather obvious effect on observations of stars. It causes extinction of the light. As the extinction varies notably with wavelength, there is also an effect on the spectral energy distributions of the objects observed. The effect increases with wavelength and, thus, causes what is labeled reddening of starlight. The galactic distribution of interstellar dust is notably patchy (Mathis, 1990; Lombardi and Alves, 2001; Krugel, 2002; Draine, 2003, 2004; Lombardi et al., 2006). Nevertheless, the amount of reddening is, normally a clear function of distance. Interaction of interstellar dust and galactic magnetic fields causes alignment of dust particles (Krügel, 2003). This, in turn, implies that the interstellar dust, in addition to extinction and reddening, gives rise to polarization of light, an effect readily observable in many parts of the Galaxy.

Much of the current discussion has had its focus on wavelengths representing the optical-visual and closely adjacent parts of the spectrum. Nevertheless, a 3 m class telescope can be employed also for investigations at longer wavelengths. In the near infrared part of the spectrum, vast possibilities are present and comparatively little has so far been made. The corresponding work with and results of the Two Micron All Sky Survey (2MASS) project are clear examples. With two telescopes, one in the northern, the other in the southern hemisphere, a large survey program has been undertaken in three photometric bands. These bands are the J and H bands at 1 250 and 1 650 nm and a modified K band at 2 170 nm. The results obtained have, in a large number of manners, served for cutting-edge research programs. See Skrutskie et al. (2006).

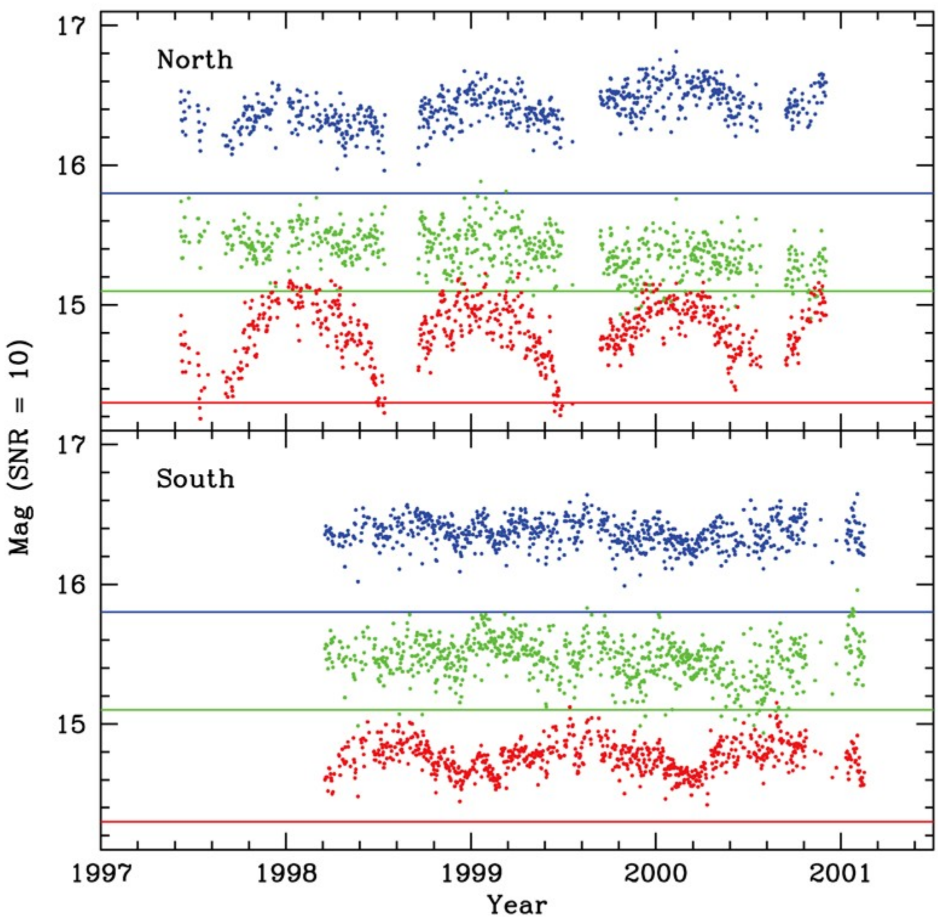


Figure 42. Average nightly sensitivity levels in the J, H and (modified) K bands for the 2MASS observations obtained in the northern and southern hemispheres (Skrutskie et al., 2006).

Galaxies

Over the latest close to hundred years, galaxies have been the subject of vast efforts of many astronomers, not least regarding large-scale observing programmes. Huge amounts of observing and analysis have gradually opened the world of galaxies and its actors. Studies have been made of different types of galaxies, of galaxies at different distances and of galaxies in various degrees and phases of interaction (González-Delgado et al., 2001; Bergvall et al., 2003; Sánchez et al., 2005; Wolf et al., 2005, Ascaso et al., 2009; Aguerri et al., 2009). However, while our general knowledge of galaxies has grown very much, our insight into their formation and evolution has remained sketchy at best as has our understanding of the consequences of galaxy interaction. Simply, we are surrounded by an impressive variety of galaxies, spiral galaxies, elliptical galaxies and irregular galaxies with vastly different sizes and masses, the low-mass galaxies existing in very large numbers, and we do not know from where all these galaxies come or how they relate to each other.

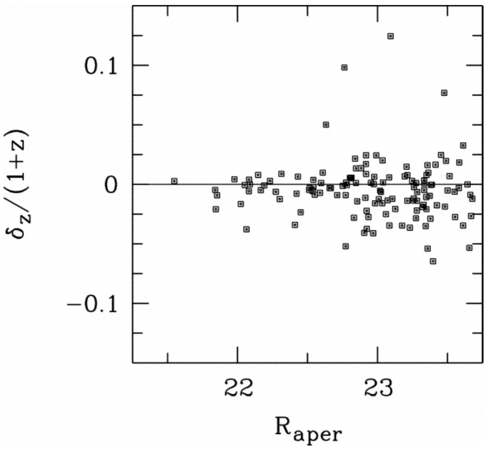


Figure 43. Redshift errors for galaxy sample from the COMBO-17 Survey of galaxies obtained with the 2.2 m MPG/ESO telescope at La Silla (Wolf et al., 2005).

Remarkably, our understanding of the evolution of galaxies remains poor even concerning our closest neighbor galaxies, members of the Local Cluster of galaxies (van den Bergh, 2000). Above, comments have been given concerning the similarities and differences between the Galaxy and M 31. Unsatisfactory in itself, this uncertainty also has an unavoidably negative effect on our understanding of other galaxies, in the Local Cluster of galaxies (van den Bergh, 2000) as well as beyond.

A question of fundamental importance but without any solid answer regards the formation relation between galaxies with different masses, from small dwarf galaxies to those most massive. The scenario of hierarchical formation of massive galaxies (Blumenthal et al., 1984) sees giant galaxies building up due to the merging of smaller galaxies. The hierarchical scenario is based on a large amount of observational evidence (Fontana et al., 2003; Eisenstein et al, 2003) and counts on solid support (Somerville et al., 2004). Further, concerning clustering of galaxies, the hierarchical scenario is strengthened (Kauffmann, 1999; Spergel et al., 2003). However, recent observations (Glazebrook et al. 2004; Cimatti et al., 2004) of galaxies that are, at the same time, both very old and very massive are not trivially compatible with hierarchical growth of galaxies.

Obviously, much work, not least observational studies, remains before we can get a consistent picture of the formation and evolution of galaxies. In this work, observations with a 3 m class telescope can play an important role. Examples are observations of dwarf galaxies in the Local Cluster of galaxies and studies of blue compact galaxies, the latter hosting highly active star-formation processes (Östlin et al., 2001; Bergvall and Östlin, 2002; Bergvall et al., 2003; Östlin et al., 2004; Zackrisson et al., 2005a, 2005b; Östlin et al., 2007; Cumming et al., 2008).

Both types of galaxies define objects that are both important from evolutionary aspects and, when situated in the nearby part of the universe, rather reasonably accessible for population and other studies. Reference is made to Belokurov et al. (2007). In general, studies of the evolution of galaxies is a field of vast interest (Zackrisson et al., 2001). Important from many points of view, star-burst mechanisms (Bergvall and Östlin, 2002; Bergvall et al., 2003) merit further detailed investigations.

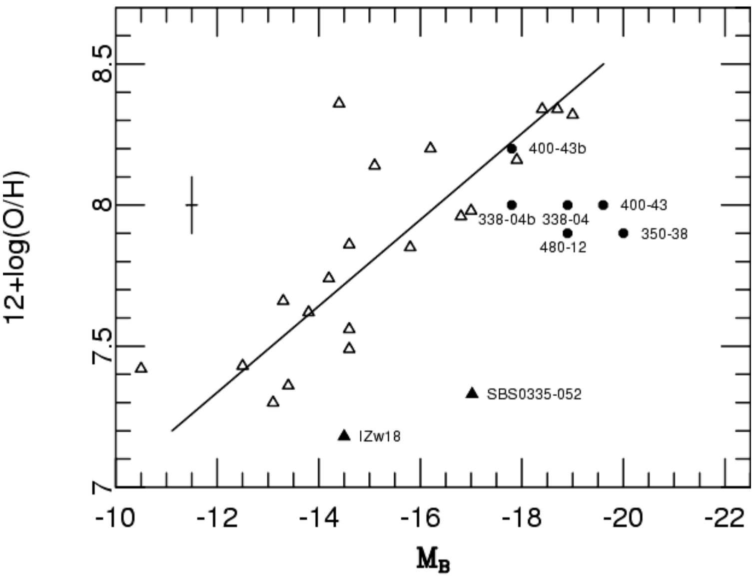


Figure 44. Oxygen abundance as a function of absolute B magnitude with data from Skillman (1989). See Bergvall and Östlin (2002).

While studies of stellar clusters are fundamental for our insights into stellar evolution, data for such clusters are of highest value also regarding external galaxies and their evolutionary status. As contrasted to stars in the general galactic field, members of stellar clusters can be regarded as coeval and having a common initial abundance of heavy elements. Thus, the reliability of the determination of masses and ages is highly enhanced. Corresponding emphasis and development of observational tools have been reported and commented by Chabrier (2003); Ardeberg and Linde (2006a, 2006b) and Cervantes and Vazdekis (2007).

Also regarding the interstellar medium in the most nearby galaxies, highly valuable studies can be made with a 3 m class telescope. Such investigations have, with telescope apertures from 1.5 to 8 m, been made not least of the two Magellanic Clouds. Reference can be made to Ferlet et al. (1985), Maurice and Silvy (1993), Vladilo et al. (1993), Heckman and Lehnert (2000), Junkkarinen et al. (2004), Sollerman et al. (2005), Cox and Spaans (2006), Welty et al. (2006), York et al. (2006) and Cox et al. (2007).

A number of dwarf galaxies are positioned at distances from the Galaxy that are smaller than, similar to or slightly larger than that of the Magellanic Clouds. Among such galaxies are the Bootes, Sculptor and Sagittarius dwarf galaxies, Ursa Major II and Ursa Major I as well as the Fornax, Sextans, Ursa Minor, Draco and Carina dwarf galaxies. Depending on the site, a subset of these galaxies can be investigated for content of interstellar medium. In the case of discrete lines, the normally pronounced differences in line-of-sight velocities of the local galactic and the nearby-galaxy interstellar media support safe identification of the lines to be measured.

A 3 m class telescope with reasonably large field of view is an important tool for surveys of galaxies. Repeatedly, and with telescopes with similar and smaller, and even much smaller, apertures, such galaxy surveys have proven extremely useful and valuable. Reference is made to York et al. (2000), Colless et al. (2001), Jones et al. (2004, 2009) and Lawrence et al. (2007). Interesting new survey work could be based on different spectral resolutions, deeper

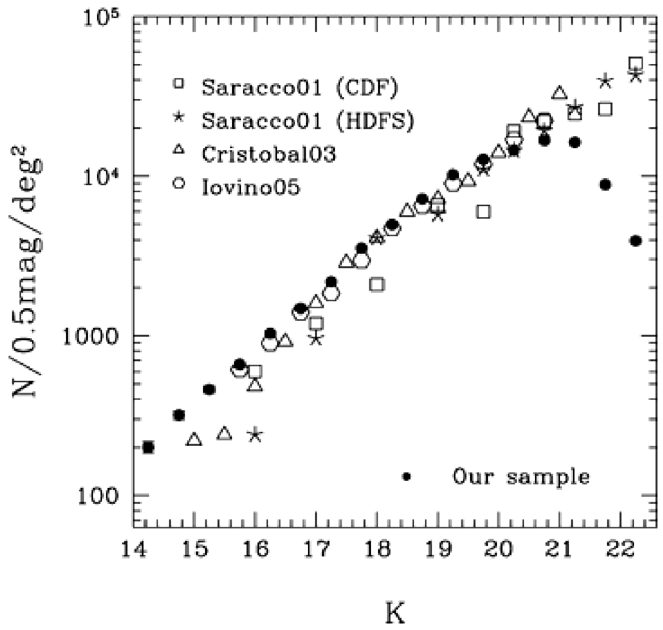


Figure 45. Number counts resulting from 6 hours of galaxy observations with the 3.8 m United-Kingdom IR Telescope, comparisons with results from the literature included (Lawrence et al., 2007).

exposures as well as other and specially selected fields. Properly designed and carried out, such surveys will provide highly valuable material for further studies of galaxies.

Extremely interesting results can be obtained from surveys of galaxies based on spectrograms of very low resolution. Such a survey will, unavoidably, allow less detailed conclusions. On the other hand, it can reach galaxies with much higher z values. Conducting such a survey with narrow-to-intermediate-band photometry will offer special possibilities to reach very faint and distant galaxies. With a generous, more than a dozen, number of well-defined and adequately positioned photometric pass-bands corresponding to R of the order of 50 and generous exposures, possibly combined with data from broad-band photometry, a wealth of new results can be obtained. An excellent example is the COMBO-17 survey of galaxies made with 17 narrow pass bands, the observations carried out with the MPG/ESO 2.2 m telescope at La Silla. Reference is made to Wolf et al. (2001, 2003, 2005), de Zeeuw et al. (2002), Emsellem et al. (2004), Kuntschner et al. (2007), Moles et al. (2008), Benítez et al. (2009) and Cristobal-Hornillos et al. (2009).

Employing photometric low-resolution spectral criteria allows surveys down to faint galaxy magnitudes. This can be used in surveys and investigations of clusters of galaxies. Such studies are highly useful for evolutionary studies of clusters of galaxies. Very interesting results of this type have, with such tools, been obtained with telescope apertures smaller than 3 m (Fasano et al., 2000, 2006).

While the survey-capacity of a 3 m class telescope is beyond doubt, also more detailed studies of galaxies of special interest can be successfully made with such a telescope, and even with telescopes with smaller apertures. Evidence is massive that such work is not limited to brighter galaxies but is of high value also for fainter objects. Reference can be made to Bergvall (1984), Bergvall and Johansson (1985), Bergvall and Rönnback (1995) and Bergvall et al. (1999).

Gamma-ray bursts (GRBs) are, so far, the most luminous events known (Klebesadel et al., 1973; Hurley, 1992; Fishman and Meegan, 1995; Horvath, 1998; Katz, 2002; Fan and Piran, 2006). These notably transient phenomena emit flashes of gamma rays, parts of exceedingly energetic explosions. Hosts of these events are galaxies, all of which so far identified are situated at very large distances. The GRB emitters are, clearly, highly exceptional objects. Still, so far, we can only speculate regarding the true nature of the GRB engine, or the true natures of the GRB engines (Woosley and Bloom, 2006; Wozniak et al., 2009; Virgili et al., 2009). Data from the Gamma-Ray Large Area Space Telescope (GLAST) and the AGILE x-ray and gamma-ray spacecraft will, hopefully, proper time given to the monitoring of the relatively scarce GRB events, provide break-through observational contributions. An exceedingly valuable contribution to the understanding of the nature of GRBs can be expected from successful timely-launched follow-up observations of GRB events. Such observations could, potentially, be made with a 3 m class telescope. In practice, imaging, photometry and polarimetry should be attempted. The field of view should be of generous size (Hurley et al., 1986), ideally of the order of 10x10 square arcmin.

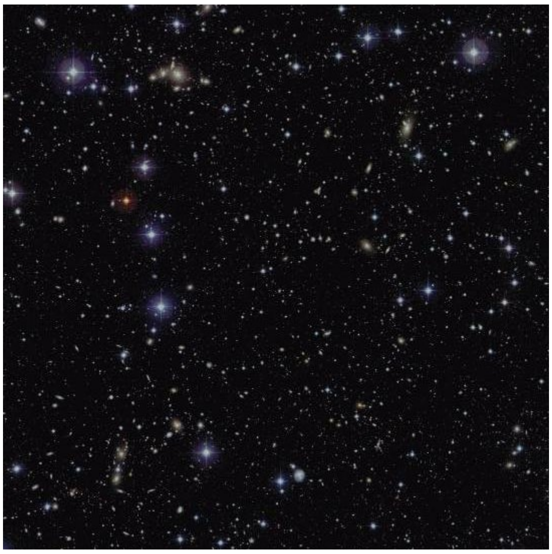


Figure 46. Cluster field Abell 901/902 as obtained in the COMBO-17 galaxy survey program (MPIA)

The bursts of energy observed and followed cover a considerable time scale. While the most short-lived events cover only some milliseconds, other similar occurrences can last up to several minutes and even more than half an hour. Anyhow, flashes with durations of from one to ten seconds may be seen as dominating. Thus, the corresponding frequency of detector read-outs should be high, or above 100 Hz, preferably up to 1 kHz.

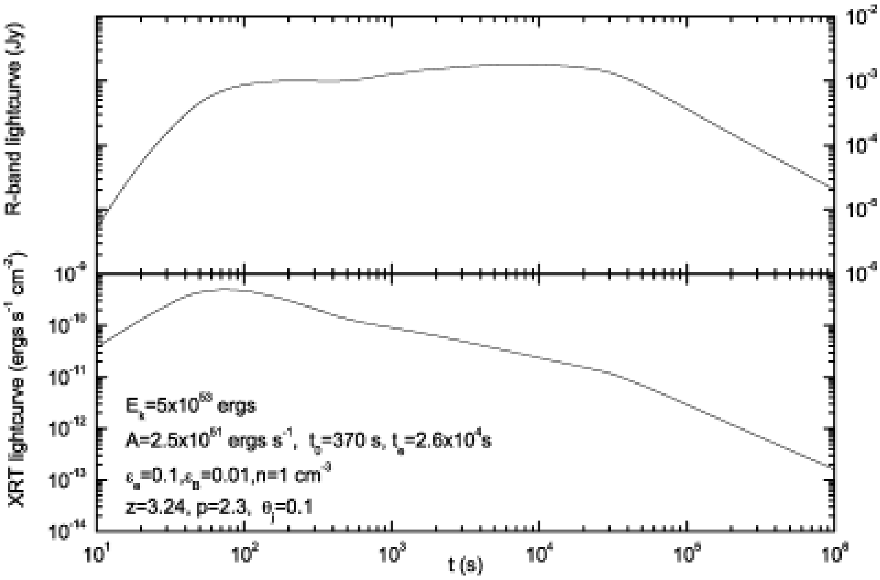


Figure 47. The GRB x-ray, 0.2 – 10 keV, afterglow light-curve plus the R-band light-curve for an energy-injection model (Fan and Piran, 2006).

While the field of view and read-out frequency required can be achieved with a 3 m class telescope, there is another demand defined by the limited duration of the GRB events. To be really meaningful, on-line alert lines have to be constantly open. Further, the follow-up observations have to be initiated as quickly as possible, in practice within seconds. This, in turn, in addition to the necessity of immediate unconditional closure of any observations in progress, sets hard demands on fast positioning.

In practice, both the telescope and the enclosure have to be able to change position, over tens of degrees, within seconds. Thus, slewing speeds have to be of the order of several degrees per second. Importantly, it defines rather extreme requirements, not only on the slewing speed but also concerning the acceleration and deceleration of both telescope and enclosure. Accordingly, while scientifically highly interesting and potentially awarding, a priority regarding GRB follow-up observations calls for serious discussions of mechanical design. Possibly, a strategy could be to attempt follow-up studies only of GRBs with reported positions reasonably close to current program telescope positions.

Follow-up work

A number of ground-based telescopes and space missions with special features and/or survey programs will set the scene for interesting follow-up studies with a 3 m class telescope with high image quality. Such investigations can, on the one hand, be made as complements to the survey programs, on the other hand, for a number of or for classes of objects, lead to projects in their own scientific right. Among ground-based facilities of special importance, the existing VLs and the ELTs in progress are of high relevance. Corresponding importance can be attached to the space programs of Gaia, SOFIA, eROSITA, JWST and Darwin. While collaborative observing programs with VLT and ELT teams seem rather obvious, some comments seem proper regarding space missions to be launched in the near or reasonably-near future.

Gaia mission

Providing high-precision space astrometry data, the Gaia mission, a more sophisticated follow up program of the Hipparcos mission, plans for launch in 2013 and a total mission time of six years. The data provided will be of a precision far higher than anything so far existing. In addition, the mission will cover a number of stars incomparably higher than any similar program conceived (Dollet et al., 2004a, 2004b, 2004c; Mignard, 2005a, 2005b). In addition to the unique astrometric data (Mignard, 2003, 2005a), Gaia will obtain measurements in several intermediate-width photometric bands and low-resolution spectroscopy. Astrometry and photometry should reach a visual magnitude of around 20, while the spectroscopy will be limited to magnitude 17. See also Tingley (2009) and Tingley et al. (2009).

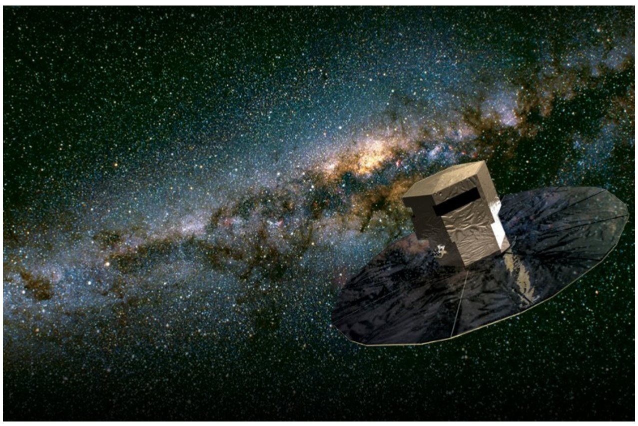


Figure 48. Gaia and the Galaxy (European Space Agency).

The primary scientific aim is high-precision distances, movements and distribution of around 10^9 stars in the Galaxy. The most central question to be addressed concerns the formation and evolution of the Galaxy but also of its member stars (Prieur et al., 2002; Kervella et al., 2006). A connected problem is the influence on this formation and evolution exerted by other galaxies in our galactic neighborhood. Other key questions of the Gaia mission are the frequency of planetary systems orbiting stars in the Galaxy and the distribution of dark matter. Nevertheless, Gaia data will be of excellent value also for objects in the solar system (Crosta et al., 2006; Mignard et al., 2007; Tanga et al., 2007; Zwitter et al., 2007; Delbo et al., 2008), even regarding near-Earth objects (Mignard, 2002). With a data production more than impressive, the Gaia mission will provide a huge list of objects, most of them previously unknown. For full scientific return, follow-up observations with ground-based telescopes are required (Hestroffer et al., 2008). An obvious and valuable contribution concerns determination of physical parameters of stars, for some of them in the form of spectral analysis, for other stars via spectral classification and photometry, as well as of their radial-velocity data. This will be the case for huge numbers of stars of all sorts of types. The combination of precision distances, tangential and radial velocities, spectral analysis and photometry will set the scene for entirely new insights into the world of stars and stellar evolution as well as concerning the structure and dynamics of the Galaxy.

A very important aspect of follow-up observations concern planets and planetary systems. The avalanche of new planetary systems provided by the Gaia mission will need substantial follow-up observations, not least concerning central stars. Such programs are of vital research interest. A 3 m class telescope with good image quality is an excellent tool for substantial scientific contributions, and especially so if adequate well-designed auxiliary instrumentation and generous time scheduling can be provided. A follow-up program with such a telescope will, in addition, provide ample material for identification and continued investigations of objects of special interest.

SOFIA

The Stratospheric Observatory for Infrared Astronomy (SOFIA), developed by NASA, is an airborne observatory, intended as a complement to the Hubble, Spitzer, Herschel and JWST missions as well as to ground-based VLTs and ELTs. A modified Boeing 747 SP airplane carries a 2.5 m telescope intended for coverage of light from visual to far-infrared wavelengths with special emphasis on the wavelength region from the mid-infrared to sub-millimeter. Routine operation is foreseen from 2010. The mission is programmed for an operation time of 20 years (Erickson, 1995). See also Schubbach et al. (2003), Dreger et al. (2003) and Kunz (2003).

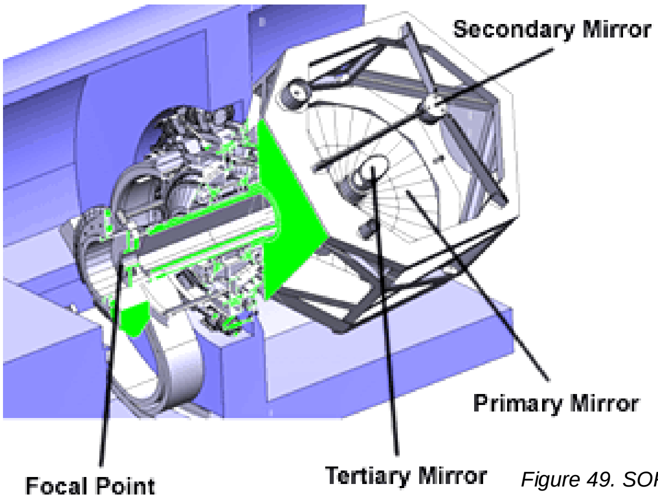


Figure 49. SOFIA telescope concept (SOFIA Science Center).

The host airplane will, be flown at altitudes in the range 12 000 to 13 700 m. Accordingly, atmospheric water vapor will be close to fully absent. This will give the SOFIA mission pronounced advantages at longer wavelengths, a fact well taken into account in the definition of the SOFIA science case. One consequence is that high scheduling priority will be given to observations at wavelengths longer than those in the near-infrared part of the spectrum.

With its special wavelength coverage, advantages and priority setting, SOFIA will provide high numbers of new exciting objects. One example is detailed investigations of Kuiper-Belt Objects (KBOs) and their physical parameters. Importantly, SOFIA will provide data on KBO occultation of stars with a signal-to-noise ratio far better than that of ground-based telescopes. Such observations will be used to determine KBO sizes and compositions as well as the structure of their atmospheres. In a similar manner, SOFIA data will add long-wavelength results to our basis of stellar observational results, providing possibilities for large advance in our understanding of stellar atmospheres. Reference is made to Kärcher et al. (2008).

Not least will data resulting from SOFIA observations of planetary systems in different stages of evolution contribute to the insight into the coupling between the stellar and planetary evolutionary processes. The understanding of the development from circum-stellar shells to corresponding discs will be greatly enhanced as well as the gradual evolution of these discs into planets. Further the wavelength range of priority is excellently suited for surveys for organic materials and, thus, for bio-signature searches (Selsis et al., 2005; ESF, 2009).

Giving high priority to observations at higher wavelengths, the SOFIA mission will, to be optimally productive, require support data at shorter wavelengths. Imaging, photometry, spectroscopy and polarimetry at these wavelengths will be in high demand. Such data can be provided from observations with a 3 m class telescope. Many of the objects observed will, no doubt, merit further studies.

eROSITA

A cutting-edge x-ray facility, the extended ROentgen Survey with an Imaging Telescope Array (eROSITA) has as its leading scientific driver a survey for black holes and dark matter, not least in clusters of galaxies. Using seven electronic eyes with aperture 36 cm, it will be launched in 2012. The satellite will be placed in an orbit around the second Lagrange point of the Sun-Earth system, L2. As viewed from the Sun, L2 is located approximately 1.5 Gm be-

Figure 50. eROSITA x-ray imaging telescope array (German Aerospace Center).

yond the Earth. All-sky observations with eROSITA will last seven years. Reference is made to Meidinger et al. (2008), Misaki et al. (2008), Friedrich et al. (2008) and Fürmetz et al. (2008).

Puzzling, there is massive evidence that the expansion of the universe, rather than slowing down as a reaction to its own gravity, is in acceleration. The reason for this strange behavior is referred to as dark energy, the explanation of which is at best an educated guess. It is now hoped that the eROSITA mission will provide data helpful for a more solid insight into the physics of the universe. Advances hoped for include mapping of x-ray sources, active galactic nuclei, black holes, large-scale structure and clusters of galaxies.

The eROSITA observing program includes 105 clusters of galaxies. The number and distances of the clusters will provide material of unprecedented quantity and quality for studies of the large-scale properties of the universe and their evolution with time. Also, the observational material obtained should provide a basis for a search for the nature of the baryonic acoustic oscillations. See Meidinger et al. (2007).

In addition, it is expected that the eROSITA data will enable identification of millions of active galactic nuclei (AGNs). At the same time, observational material should provide a favorable possibility to study the long-range growth of black holes. Further, it seems beyond doubt that the program will result in the discovery of vast numbers of exotic objects and possibly also in the detection of new properties of the universe. Both the size and the nature of the eROSITA project define the interpretation of its results as a highly challenging undertaking. This challenge is strongly emphasized by ambitions to provide data analysis in near real time (Kreykenbohm et al., 2009).

Prime targets of the clusters of galaxies are the clouds of high-temperature gas collected at the cluster centers. The goal is the distribution of the clusters of galaxies in space as well as the time variation of this distribution. An estimate of the part of the total universal energy density contributed by the dark energy will be attempted. Further, the time variation of this part will be investigated as a function of cosmic time. Ultimately, we want to understand when and how our universe was created. These questions being, to some degree, answered, we should also be able to predict the future of this evolution.

Explicitly designed for observations at very short wavelengths, eROSITA will report on its targets based solely on their high-energy ingredients. At the same time, the number of objects resulting will be exceedingly high. Nevertheless, to be optimally useful, this material requires follow-up observations of high quality. While large-scale characterization of the objects and measurements of their z values will have to be handled with the help of intermediate-band photometry, there is an urgent need for spectroscopy of large numbers of objects.

Red-shift data based on spectroscopy must be made for many and carefully selected clusters of galaxies with a z range as large as possible. With high image quality, adequate spectroscopic instrumentation and generous allocation of observing time, a 3 m class telescope should allow such observations of clusters with z values 0.5 and higher, as demonstrated by the corresponding follow-up observations of ROSAT (Briel et al., 1988, 1989; Barstow and Sansom, 1990) sources. Reference is also made to Danziger et al. (1990). For the purpose discussed, it seems a good idea to promote a multi-object spectrograph facility with a reasonably large field of view. Photometric observations can, with a 3 m class telescope, be made for large numbers of objects as demonstrated, in connection with the ROSAT survey, by Fleming (1998). Valuable programs can include specially selected objects but also survey regions, in both cases aiming at detailed data to serve as calibration and interpretation assistance of the analysis for the analysis of the more massive body of data.

James Webb Space Telescope

The James Webb Space Telescope (JWST), partly a follow-up project to Hubble Space Telescope (HST) (Feinberg and Geithner, 2008) scheduled for launch in 2014, is a large space telescope, optimized for observations at infrared wavelengths (Gardner et al., 2006). With a 6.5 m folding-out primary mirror, it will, in order to achieve cooling to a few tens of degrees K, orbit Earth at the Lagrangian L 2 region, at a distance of $1.5x10^6$ km (Clampin, 2008; Arenberg, 2008). Prominent targets are planetary systems and the origins of life, the birth of stars and proto-planetary systems, the evolution of galaxies and the end of the dark ages. Reference is made to Gardner et al. (2004) and Gardner (2008).

Search for signs of the origin and early development of life in our sense is an important JWST program. It will include observations of numerous exo-planetary systems (Greene et al., 2007). The survey will extend to distant systems (Balzano et al., 2008) but will also include members of our own solar system. Physical and chemical properties and processes will be investigated and analyzed for life signatures. See also Bounama et al. (2007) and Lunine et al. (2008).

A related high-priority program concerns processes leading to the birth and early development of stars. An essential part of this program will be studies of the early phases of developments leading to the formation of planets (Krist et al., 2007). Circumstellar shells and discs will be essential targets (Makidon et al., 2008). The investigations will include processes in early phases of the universe.

Study of processes leading to the assembly of galaxies is another program of special importance. The corresponding developments are still largely not understood. Early phases of the evolution of various types of galaxies will be investigated. High-priority targets are large-scale galactic structures, spiral arms, active nuclei and stars as well as important ingredients of the inter-stellar medium, gas and heavy elements. Dark matter will be a target of special interest.

The end of the dark ages, the first light and the reionization are fundamental cosmological processes observed but not understood. The aim is to investigate the earliest objects in the universe and to follow the development of ionization. Cosmological parameters and fundamental physics will be studied. The properties of JWST make it an ideal space telescope for studies of the nature of these targets and developments.

Figure 51. James Webb Space Telescope model (National Aeronautics and Space Administration).

For these purposes, JWST will have four specially designed instruments. Their prime spectral coverage will be from near infrared to mid infrared wavelengths. A fine guidance sensor will include a dedicated guiding unit and a tunable-filter camera (Doyon et al., 2008). Dedicated to work at near infrared wavelengths are a camera and a spectrograph. Finally, a special-purpose instruments will be used for studies in the mid infrared spectral range.

Large efforts are made to prepare outlines of collaboration between research groups using JWST and ground-based facilities. The three ELTs now in progress are seen as prominent actors as are the VLTs. Once such collaborative programs produce results, there will be a pressing need for follow-up observations with smaller yet powerful telescopes, not least at optical-visual and adjacent wavelengths. In this context, a high-quality 3 m class telescope makes an important partner. Targets will be detailed observations, imaging, photometry and spectroscopy, of selected objects as well as more exhaustive studies of well-defined samples. Prominent parts of these studies will probably concern exo-planetary systems and star-forming regions.

Darwin spacecraft

The Darwin spacecraft is part of the European Space Agency (ESA) program. It has a clear prime class of targets (Cockell et al., 2009). It will study exo-planets as Earth-like as possible. The real goal is identification and analysis of finger-prints of life like ours in various forms of development (Ford et al., 2001; Des Marais et al., 2002; Kiang et al., 2007a, 2007b). More precisely, Darwin will aim at detection of atmospheres the contents of which can be taken to indicate the presence of life. To increase its ability, the spacecraft will concentrate its efforts to the 103 most nearby stars. These will be investigated for presence of smaller, rocky planets.

Typical constellations of stars and Earth-like planets have very high contrast ratios, At visual and adjacent wavelengths, they are, normally, at best, in the range 10^9 to 10^{10}. At longer wavelengths, contrast ratios get less daunting. Aiming at star-planet contrast ratios as moderate as possible, the Darwin project will employ light with wavelengths in the mid infrared part of the spectrum (Labadie et al., 2005). This is also a wavelength region favorable for identification of signatures of life. In mid infrared light, star-planet contrast ratios for Earth-like planets should be around 10^6 only. See also von Bloh et al. (2009), Whitmire and Matese (2009) as well as Smith and Scalo (2009).

Figure 52. Darwin Spacecraft (European Space Agency).

At the wavelengths discussed, Darwin will have decisive advantages compared to ground-based telescopes. Most of this light is blocked by the Earth's atmosphere. In addition, the emission of the atmosphere is high, and so is the emission of the ground-based telescopes, as they have temperatures around 300 K, while Darwin will have a temperature of just around 40 K and the detector only 8 K.

Life activity will result in a number of predictable bio markers. Flora produces oxygen, while fauna expels carbon dioxide and methane. These gases mix with water and water vapour. In the mid infrared part of the spectrum, they have absorption lines the strengths of which should be observable for the nearby objects targeted. See also Selsis et al. (2002).

Darwin will comprise four or five free-flying space-telescope units. All of them will have primary mirrors with a diameter of 3 m. They will fly to form an interferometer, all located at the Langrangian L 2 point. The central unit, the principal part of the combined spacecraft, will include equipment for beam combination. See also Ruilier et al. (2007) and Wallner et al. (2007).

The constellation will provide interferometry with high spatial resolving power. To minimize the disturbing light from the central star, signal-delay techniques or nulling interferometry will be employed (Ollivier et al., 2001; Vosteen et al., 2005; Vosteen and Ahlers, 2005; Peters et al., 2007; Rouan et al., 2007; Buisset et al., 2007). Further, it will have cameras and spectrometers. A successful Darwin mission requires several technological advance of break-through nature. Launch of Darwin is currently scheduled for 2016 or later.

Terrestrial Planet Finder

The Terrestrial Planet Finder (TPF) mission is a National Aeronautics and Space Administration (NASA) project. It has obvious similarities to ESA's Darwin spacecraft mission (Des Marais et al., 2008). Featuring three to four spacecraft telescopes flying in precise formation, the TPF Interferometer relies on sophisticated interferometric techniques. The unit telescopes should spread out over distances of approximately from 40 to 400 m, depending on the final choice of configuration. The unit telescopes have aperture of three to four metres. They are optimized for observations at infrared wavelengths. Reference is made to Arenberg et al. (2007) and Lawson et al. (2007).

The TPF Coronagraph is, tentatively, based on a four by six meter light collection telescope. Emphasis is on light of visible wavelengths. A central disc will block the light from the central star, a task supported by further specialized arrangements. Not least will external occulters be used (Hunyadi et al., 2007a, 2007b; Cady et al., 2007). This should ensure proper access to the planetary light and its investigation. The TPF targets are the origins of stars, planets and life. More specifically, the combined TPF should be employed to determine planetary characteristics such as distance from the central star, size and temperature. The ultimate goal is to find and investigate Earth-like planets in habitable zones. However, to promote optimum understanding of the Earth-like planets, also larger members of the planetary systems will be studied.

For all these planets, spectroscopy will be used to identify, study and analyses the contents of the atmospheres. Large efforts will, especially in the case of the Earth-like planets, be made to determine the relative amounts of gases like carbon dioxide, water vapor, ozone and methane, all in order to assess the degree to which life in our sense could be supported, in the past and/or present and/or future. Currently, no TPF launch date is available.

Iran and astronomy

from educational telescopes to a modern observatory

Iran has a brilliant historical background in sciences. This is especially true concerning astronomy, a field of science that has, for centuries, enjoyed an especially favourable treatment by Iranian governors. In the pre-Islamic as well as in the early Islamic era, Iranian astronomers were rather generously treated by the country's heads of state. At this time, Iranian astronomy had a leading international role. It was also highly popular among Iranian citizens. One of the results was that Iranian astronomy and astronomers occupied leading roles on the international science arena.

Further, it is of interest to refer to the glorious past of the Islamic world as a whole regarding science or, rather, science philosophy. When the Greek state and civilisation lost its hegemony, in the second century of the Western calendar, an époque in critical thinking came to an end. The Roman empire, taking over, added little in this respect. The following huge victories of Christianity were worse still. The catholic church banned virtually all attempts at research that were, or even could be suspected of being, in conflict with the texts in its holy Bible. The impact of the migration events brutally crushed what was left of heroic attempts at scientific activity. The Greek, and world, cultural heritage was saved by Islamic powers and rulers, being much more open-minded than their catholic counterparts.

Much later, starting in its fifteenth century, the Christian world, under clear pressure, adopted a gradually more open and liberal attitude towards science. At about the same time, and non-trivial to explain, the Islamic world started moving in the opposite direction. The latter movement still has its repercussions on the attitude concerning science in Islamic states. Trying to understand and overcome the resulting dilemma between the Western and Islamic research communities is as difficult as important (Mansouri 2003-2005).

In the beginning of the twenty-first century according to the Western calendar and by the end of the fourteenth century following the Iranian calendar, popular Iranian support of astronomy is as solid and enthusiastic as ever with Iranian amateur astronomy showing high and impressive activity.

Figure 53. Iranian astronomers established large observatories like Ulugh-Beg Observatory in Samarkand (today, Uzbekistan) or Maraqeh and developed instruments such as the astrolabe to a high degree of accuracy (middle) and large Sextants (right, Remains of the Ulugh-Beg sextant on Samarkand).

In addition, mass media in the country, not least its national television organisation, tend to abound in articles and programmes around astronomy of all kinds. National budgetary support of research in astronomy is, however, very limited, as it unfortunately is in many other comparable countries. As a result, Iranian astronomers have pronounced difficulties maintaining national astronomy at its previous internationally privileged position. Rather, today, Iranian astronomy is close to absent on the international, and, to an unfortunate extent, even on the regional, research arena.

Still, today, Iran has a number of professional astronomers. They are, however, quite limited in number for a population exceeding 70 million inhabitants. While often personally scientifically successful, they have a hard time living up to their own ambitions and especially so as a modern research community following and influencing the rapid global advance of the frontier of observational astronomy.

To a major extent, the troublesome situation of Iranian astronomers is due to the restrictions regarding funding. No doubt, Iran, with its vast territory and desert-region mountain areas under uncommonly clear skies can provide a number of favourable sites for a modern observatory dedicated to astronomy at visual and adjacent wavelengths. However, the existing Iranian professionally working facilities for such observations are not only very few. They are also modest at best.

Table 2 gives an account of existing Iranian observatories professionally managed. They all belong to universities, a fact in itself rather positive. Nevertheless, the apertures of the existing telescopes define them as educational facilities at the very best. Moreover, the telescopes are not located in the best of places for observational astronomy. For these reasons, also some ambitious efforts regarding instrumentation remain, largely, just ambitions. While attempts at serious, even heroic, scientific use are made, the results are, unavoidably, limited. To be able to obtain competitive observational data, Iranian astronomers have to compete for observing time at foreign observatories without the ability to pay back in any reasonable terms. The sense of frustration in the Iranian community of astronomers is easily explained.

Location	Main telescope	Instruments
Tabriz University	60 cm Ritchey-Chrétien	Photometer, CCD, spectrometer
Shiraz University	50 cm Cassegrain	Photometer, CCD , spectrometer
IASBS, Zanjan University	35 cm Schmidt-Cassegrain	Photometer, CCD
Ferdowsi Univ., Mashad	35 cm Schmidt-Cassegrain	Photometer, CCD

Table 2. The telescopes currently dominating the national Iranian observational university research in astronomy at visual and adjacent wavelengths. Host universities are noted as are instruments available.

It appears important to note that Iran as a potentially important player on the international astronomy scene can rely not only on rather favourable weather and topographic conditions but also on further supportive geographical circumstances. While the range of latitudes is if not ideal anyhow quite convenient, the corresponding longitude range situates Iran in an interval in which the international need is large for observations being part of programmes in terms of uninterrupted monitoring and targets-of-opportunity observations. However, a corresponding partnership calls for a powerful telescope of modern type. The need for such a telescope can be further emphasised from an overview of the current telescope facilities present and in progress in the longitudinal, as well as latitudinal, regional neighbourhood of Iran. Such an overview is illustrated in Table Y. The lack of powerful modern telescopes is evident. The only possible exception concerns Iraq and its Erbil observatory. However, current reports refer to a facility considerably damaged and with no major telescope present .

In the past five years, Iranian astronomers have staged an intensive and enduring campaign to acquire a modern national observatory, referred to as the Iranian National Observatory, or INO. Initial planning has, gradually, matured. Today, there is full consensus in the Iranian community of astronomers regarding the full suitability of a 3 m class modern telescope as the highest priority for INO. Also concerning auxiliary instrumentation, national discussion is converging. Moreover, and most importantly, the plans have received support from the government and adequate funding is forthcoming. This opens the possibility of a long-wanted and well deserved revival of internationally serious observational astronomy in Iran and entirely new research opportunities for its community of astronomers.

Country	**Facilities** (Main telescope and its aperture)
Armenia	Byurakan Astrophysical Observatory, 2.6 m
Azerbaijan	Shamakhi Observatory, 2.0 m
Egypt	Kottami Observatory, 1.9 m
India	Vainu Bappu Observatory ,2.3 m and 1.2m Hanle observatory ,2.0 m, and 3 m under construction
Iraq	Erbil Observatory, 1.2 m (3.5 m telescope available?)
Jordan	1.5 m under construction
Tadjikistan	Sanglok Observatory, 1.0 m
Turkey	Bakyrlytepe Observatory, 1.5 m
Turkmenistan	Dushak-Erekdag Observatory, 1.0 m
Uzbekistan	Maidanak Observatory, 1.5 m

Table 3. Most prominent observational facilities for astronomy at visual and adjacent wavelengths and in the longitudinal and latitudinal vicinity of Iran.

With the highly encouraging prerequisites for INO, the discussion regarding a modern 3 m class telescope, while in all essentialities of a rather generic nature, will, in a number of manners, be centred on the Iranian telescope project. It will concern the telescope, the main INO research facility, its optics and mechanics as well as its active and adaptive optics systems. Further, it will include the corresponding telescope enclosure and the adhering infrastructure. In addition, site evaluation and site selection for INO will be discussed.

An Adaptive-Optics Laboratory

Adaptive optics (AO) is an advanced technique in vigorous development. As noted and discussed in the present section, the field has experienced forceful advance, amply detailed in a large amount of reports. Still, much remains to be developed, conceptually as well as regarding practical installations and exploitation. This is true for the whole range of telescopes for which AO systems are contemplated, in design, under production and in a phase of commissioning. Not least is such development work highly valuable for more complex AO configurations. One example receiving strong world-wide attention is that of multi conjugate adaptive optics (MCAO).

While high promises are due for MCAO systems, corresponding techniques are still in an early phase. This has motivated the establishment of the Lund Observatory Adaptive Optics Laboratory (LOAOL) as outlined by Owner Petersen and Knutsson (Knutsson, 2008). LOAOL is since 2008 equipped with a post-focus MCAO system, in practice realized as a dual-conjugate adaptive-optics (DCAO) installation. The reason for the choice of a dual conjugate rather than a true multi conjugate system is the relatively limited gain offered by the more extended system and the higher complexity and noise level of the latter system. The DCAO system is fed by a 14 inch Schmidt Cassegrain Telescope. The complete installation is optimized for development and evaluation purposes.

Profiting from the installations of Knutsson, we departed from the proven facilities of the LOAOL single-conjugate adaptive-optics (SCAO) system and worked on a scheme of further development, including DCAO experience. We used the summer season of 2008 for our work. This included studies of the effects of both SCAO and DCAO. Both point sources and extended objects, simulated as well as on-sky targets, were used for our studies of the effects of atmospheric turbulence and their compensation in SCAO mode and for DCAO we had just some simulation because of LAOL astronomical and optical limits.

Lund's climate, sky and atmospheric conditions

The observing conditions of Lund are rather typical for its climate region. Clear nights are limited in number and the atmosphere has the problems to be expected from a northern town close to sea level. Still, for AO experimental work approximately 80 nights per year are useful. The effective wavelength of the LOAOL arrangement is 750 nm and the corresponding typical r_0 value is around 7 cm at λ = 550 nm (Knutsson, 2008).

Figure 54. Lund landscape seen from the top of the Lund Observatory 1.5 m telescope tower.

LOAOL configuration

The concept and configuration of the LOAOL instrumentation is demonstrated in Figs. 55 and 56. To enhance flexibility and stability of arrangements, all components have been mounted on a horizontal optical table. For the tracking of celestial objects, a siderostat has been used. The tracking mirror of the siderostat has a clear aperture of 600 mm, while the corresponding secondary mirror, providing a static output beam, has a clear aperture of 380 mm. At the latitude of Lund, 55° 42', this implies a largest diameter of the output beam of 335 mm.

Figure 55. LOAOL components, including Lund Observatory siderostat (down right)

The siderostat output beam is directed to the fixed light collector, a Schmidt-Cassegrain telescope with a clear aperture of 356 mm. As this is slightly larger than the output beam from the siderostat, the pupil is somewhat obscured. The Schmidt-Cassegrain telescope delivers an f/11 beam to the experimental setup. This includes a tip-tilt mirror, two deformable mirrors (DMs), a wavefront sensor and a science camera. With the help of a folding mirror, a reference arm can be introduced in front of the wavefront sensor and provide a wavefront reference. Also, a calibration arm can be introduced for calibration of the response of the tip-tilt mirror as well as of the two deformable mirrors. For further details, see Knutsson (2008).

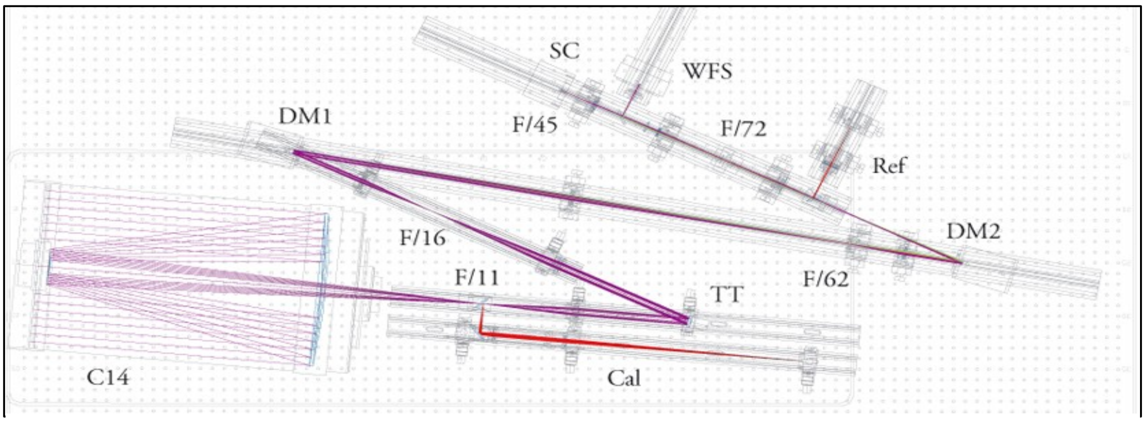


Figure 56. LOAOL conceptual configuration and light- path (Knutsson, 2008).

LOAOL can, alternatively, be used in single-conjugate or dual-conjugate mode or, as a third possibility, in a low-order mode, including mainly tip-tilt corrections. In our experimental, on-sky work, we have made use of all these three options. The present report concentrates on the use of the dual-conjugate mode, albeit including comparisons with the performance of the corresponding single-conjugate mode of operation..

Simulations

As a first approach, we made simulations of atmospheric turbulence representing some different turbulence conditions. We employed phase patterns imprinted on transparent film. Attached to motor-driven wheel and placed in front of the deformable mirrors, they were used to simulate the effects of atmospheric turbulent layers.

The system has a field of view of 20 by 20 square arcsec. In our experiments, we wanted to fill this field to various degrees. For this purpose, we produced a number of different film slides and cover plates with different pin holes.

First, we made simulations concerning point-source objects. Our results showed that under controlled laboratory conditions, an SCAO system can, over a small field of view, improve a non-ideal image quality to a corresponding quality limited by effects of diffraction only. However, with this system, corrections over a larger field of view are not possible. An example of our SCAO simulation results is given in Fig. 57.

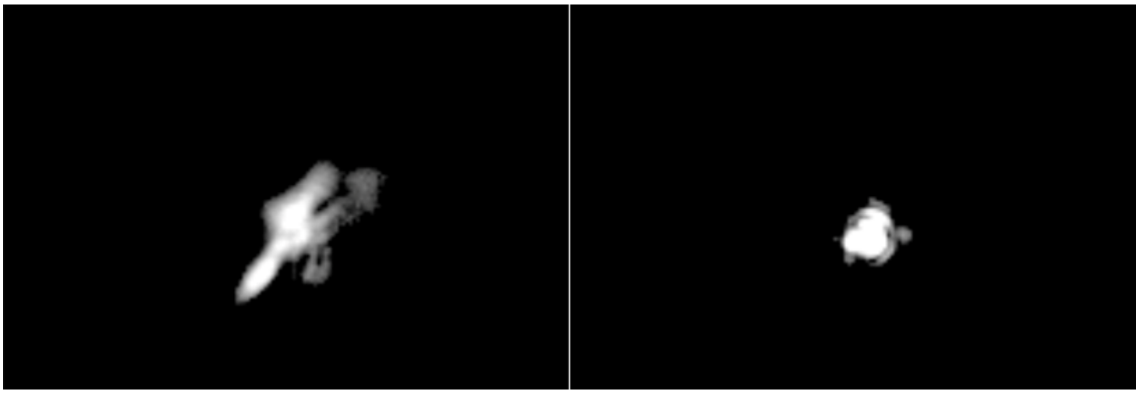


Figure 57. Simulated SCAO corrections of point-source object. Left-hand box shows object without correction, right hand box with correction.

In a following step, our simulations were continued to probe the efficiency of the DCAO mode. For this purpose, we placed a set of plates with four or more pinholes, in different pattern, as object and two different phase screen as air-turbulence simulator for two different altitude atmospheric layer in front of each DM. The system successfully improved the image quality of the pseudo-extended object, although with some remaining tip-tilt effects. This is illustrated in Fig. 59.

We tried to eliminate or at least decrease the tip-tilt effect. With this intention, we used turbulence emulators made for different r_0 values. Also, we varied the pattern speed, v_0. However, while we could decrease the effects of tip-tilt, we were not able to remove them completely. We conclude that complete removal of the effects needs addition of one or more conjugate planes in the AO system. In addition, we note a limited practical freedom concerning the location of the phase screens, Further, in practice, in dual-conjugate AO, we saw a clear and significant effect of the compatibility between the pattern chosen for calibration and the shape of the object to be observed.

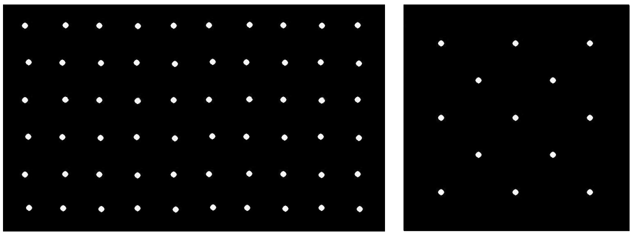


Figure 58. Two different calibration patterns used for calibration of the AO system in DCAO mode and work with high contrast objects. Experiments showed that a dense periodic pattern (left) can provide a better result for image correction than a less compact system (right), also for objects with low contrast.

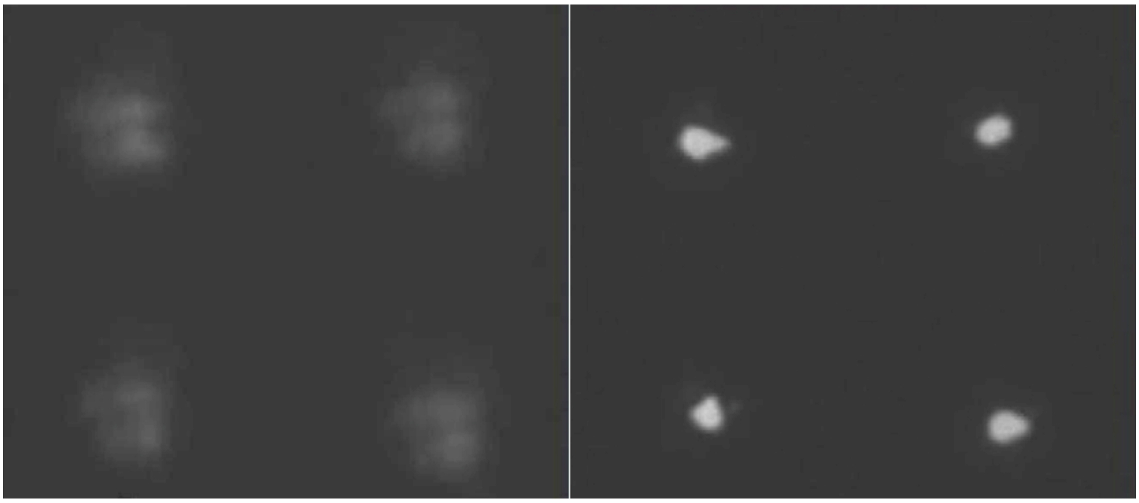


Figure 59. Simulated DCAO corrections of a pseudo-extended object. Left-hand box shows object without correction, right hand box with correction.

While admittedly more complex than SCAO corrections, DCAO corrections merit high attention, as there is a wealth of highly interesting extended astrophysical objects. Also, for such purposes, efficient MCAO reconstruction matrices have been developed. However, they depend on reference objects with high contrast images, such as brighter stars. Thus, successful MCAO, or DCAO, correction over an extended feel requires identification of a high-contrast reference object in or at least vey close to the field for which correction is needed. In practice, this is often either difficult or entirely impossible. In this case, an alternative is the use of a region in the extended object presenting high local contrast.

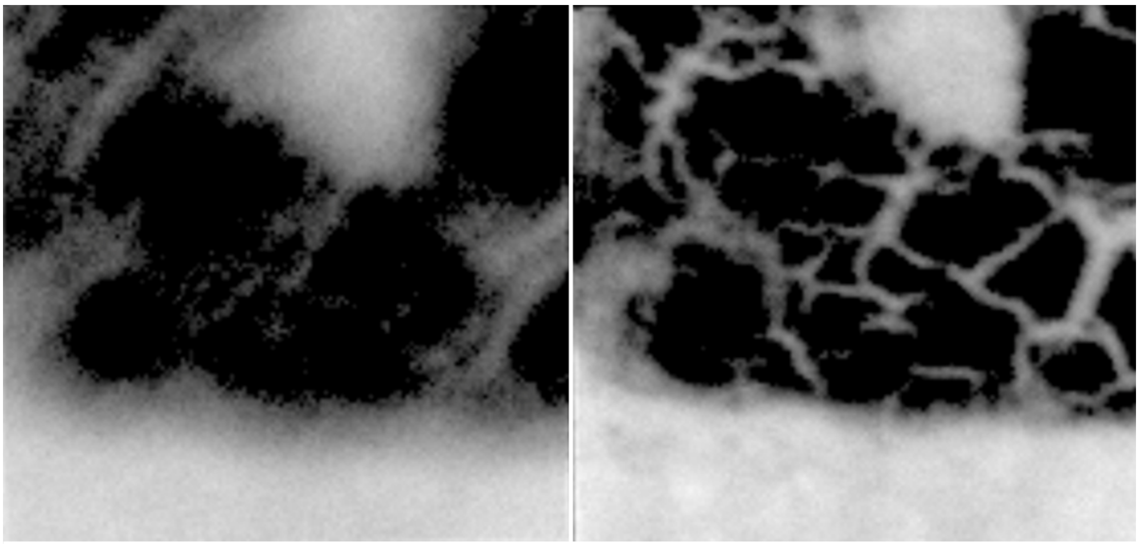


Figure 60. Central part of extended object corrected with SCAO system. Left-hand box shows object without correction, right hand box with correction.

To simulate an extended object, we used a screen made from a lead-pen trace on white paper. With this object, we first tried SCAO correction, using the central region of the object. Here, we adopted as reference object a part of the image presenting high local contrast. Closing the AO loop, we could note a rather strong improvement of the image quality in the centre of the field. This is shown in Fig. 61. As expected, in parts of the image outside the central field, only marginal image-quality improvement was noted.

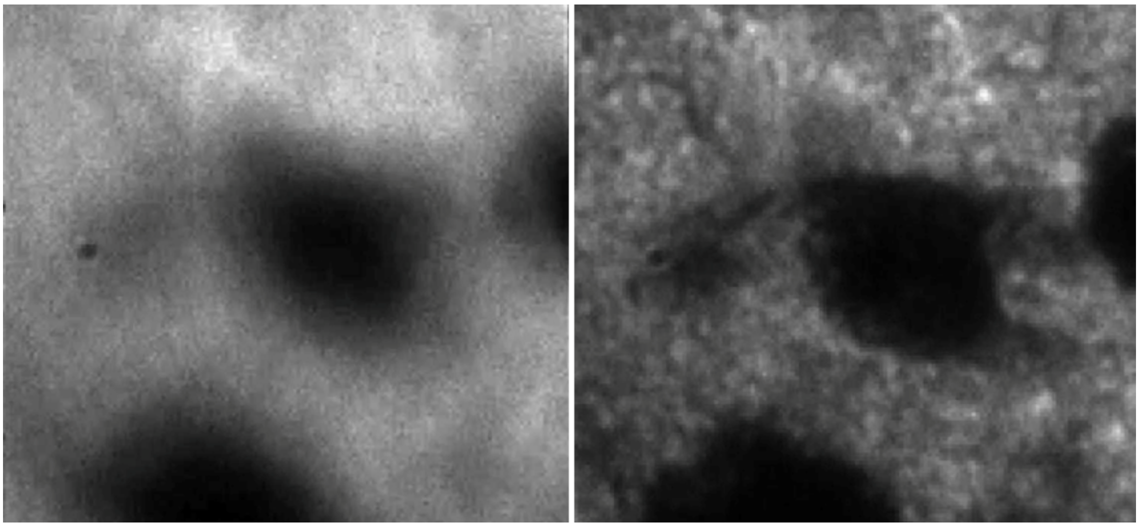


Figure 61. Extended object corrected with DCAO system. Left-hand box shows object without correction, right hand box with correction.

For DCAO correction of the same image, we used a more extended field for reference. We applied two turbulence emulators in two different conjugate planes, in front of the DMs, and assigned five reference areas on the image, all with high local contrast. We could close the AO loop and obtained a well-corrected image. The texture of the paper clearly appeared in the corrected image and the contrasted feature details covered the entire image field. At the same time, instability in the outermost parts of the field are present, calling for at least one further conjugated plane for additional improvement.

On-sky observing results

The combination of the siderostat, the Schmidt-Cassegrain telescope and the AO systems presented some practical problems. First of all, the siderostat is not intended for work of the present nature and gives, in its present position, access to a limited part of the sky only. The small field of view of the AO system implies, for smooth work, high requirements on both pointing and tracking. These needs are not well matched by the siderostat.

Additional problems are due to the fact that the optical axis of the AO system does not coincide with siderostat collimation, making target identification, capturing and tracking difficult. Also, once captured, it is difficult to maintain an object in the AO field more than 20 seconds. Further, with the light collection power available, reference objects have to have a brightness corresponding to at least V = 3, or the AO system is disabled due to photon starvation.

Given the practical limitations described, we concentrated our AO work to observations of bright stars. Of those available within the field provided by the siderostat, we worked with α Aquila (Altair) and ε Pegasi (Enif). They have V magnitudes and spectral types of 0.77 A7IV-V and 2.38 and K2Ib respectively. In both cases, the objects were used both as reference and target objects.

Altair

The first object used, Altair, is bright enough to allow high signal-to-noise ratios both for open -loop and closed-loop operation of the AO system. Closing the loop meant a large increase in contrast and Strehl ratio as well as a corresponding decrease in FWHM. Fig. 62 shows the Altair image before (left) and after (right) closing of the AO loop. Fig. 63 and 64 illustrates the corresponding effect on the image profile. After closing the AO loop, the relative intensity that refers, directly, to the strehl ratio goes up (Fig. 63) and FWHM goes clearly to smaller values (Fig. 64).

Figure 62. Images of Altair observed with the SCAO system. Left-hand box shows the image with open loop, right-hand box with closed loop.

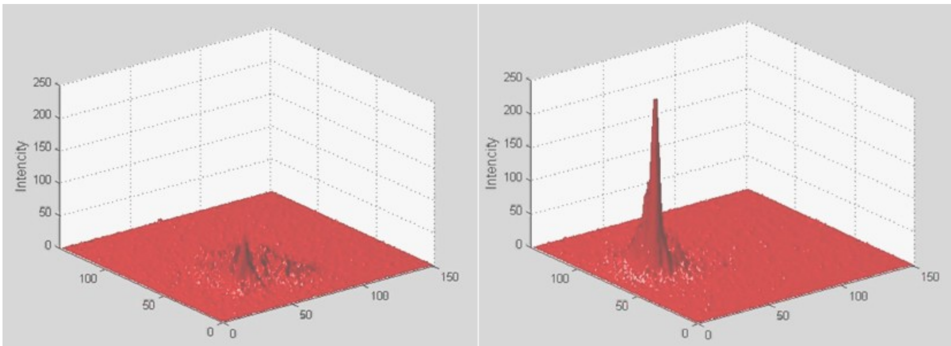


Figure 63. Point-spread function for Altair with open (left) and closed (right) SCAO loop. Image-plane scale is given in pixels. One pixel corresponds to 0.018 arcsec.

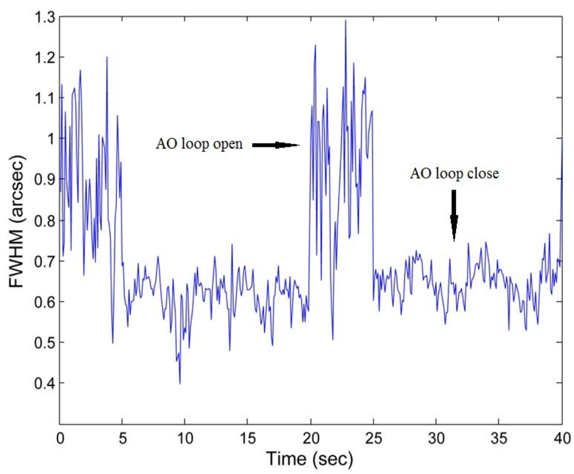


Figure 64. Variation of FWHM for Altair

Enif

The second object used for the SCAO study, Enif, is considerably fainter than Altair. This has a clear effect on the signal-to-noise ratio obtained and the operation of the AO system. Nevertheless, it was possible to close the SCAO loop. At the same time, the results obtained show, as illustrated in Fig. 65, that the brightness of Enif is somewhat low for its use as an AO-system reference object. Given the modest value of r0, this is very much in line with experience obtained at larger telescopes (Ardeberg and Andersen, 1994). The effect of loop closing is demonstrated in figs. 66 and 67 for the peak intensity and the FWHM respectively.

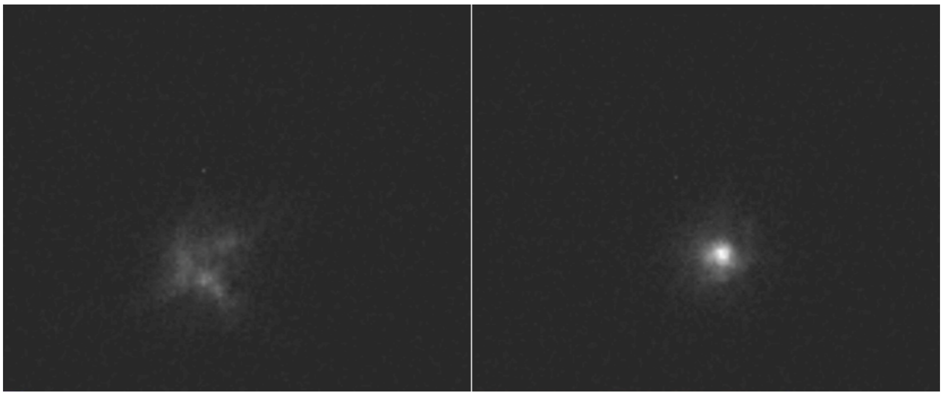


Figure 65. Images of Enif observed with the SCAO system. Left-hand box shows the image with open loop, right-hand box with closed loop.

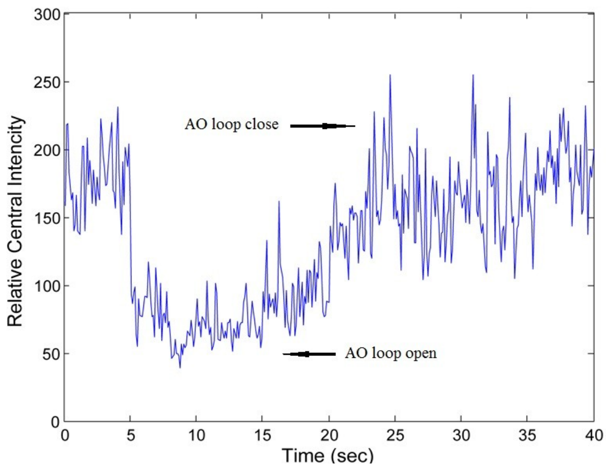


Figure 66. Variation of peak intensity for Enif image with SCAO loop opened and closed.

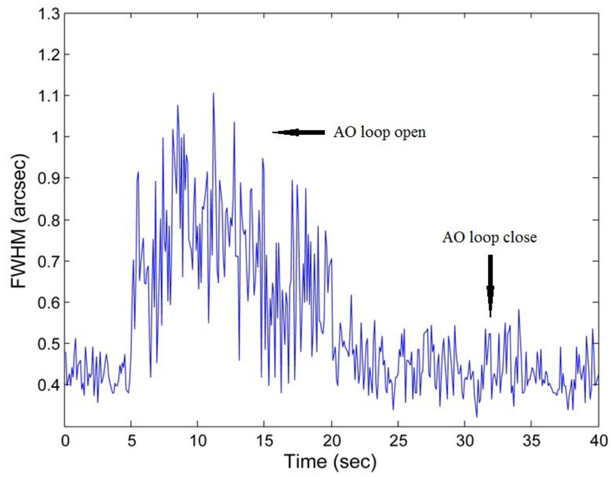


Figure 67. FWHM for Enif and its variations with SCAO in open and closed loop.

Site

Not so long ago, site selection was a comparatively uncomplicated task. The requirements emphasised a mountain reasonably high and with a benign climate offering a conveniently large number of nights free, or reasonably free, from clouds. If, in addition, the mountain was located at a convenient, not too large, distance from the home institute and offered a reasonably easy access and abundant local supply of drinking water, it was seen as highly attractive as an observatory site.

Today, serious site selection for observatories intended to work at visual and adjacent wavelengths is much more demanding. The assessment work required is very much more detailed. Many more parameters have to be taken into account and their evaluation demands considerable efforts. As a result, site evaluation and selection for more ambitious observatory projects is today a major undertaking.

Site Parameters

Site quality cannot seriously be assigned a unique label. To a very large extent, it depends on its future use and on observing priorities. However, discussing observations in the visual and adjacent wavelength regions, there is today a dominating desire for high image quality and possibilities to reach faint objects over the wavelength range accessible with most modern telescopes, or from the ultraviolet-blue to the near infrared part of the spectrum. Accordingly, there is a number of site-quality indicators that play a major role and are assigned high weight. Prominent among them are photometric sky quality, atmospheric turbulence, atmospheric content of water vapour, sky brightness, content of dust in the atmosphere, atmospheric transparency, wind conditions, temperature variations and local humidity level.

Other, somewhat less prominent albeit still important, parameters concern the height of the summit above the prevailing inversion layer and the contrast of its peak relative to its surroundings. Adequate turbulence monitoring will reveal problems in these aspects. Low seismic as well as micro-seismic activity is more than convenient and especially so if interferometry is intended. Low frequency of air traffic is an important asset as is a reasonable distance to urban areas. A reasonably easy access has positive implications for the cost of both installations and operation. Reference is made to Ardeberg (1983, 1986, 1987) and Ardeberg et al. (1986).

Photometric sky quality

Clouds affect all sorts of observational activities at visual and adjacent wavelengths, imaging, photometry, spectroscopy, polarimetry and astrometry. In some cases, clouds decrease the efficiency of observations, in other cases, they ruin their quality. The number of nights free from clouds is therefore a parameter of fundamental importance. While many traditional observatories offer little more than some dozens of cloud-free nights per year, this is far from acceptable for installations of new observing facilities. The best records available show more than 250 photometric nights per year, with a photometric night defined as one with uninterrupted clear sky over at least six consecutive hours. In this context, normally allowance is made for horizontal clouds up to seven degrees above the horizon.

Assessment of photometric sky quality can be made in a number of manners. Methods available include cloud detectors working, mainly, at near-infrared and/or infrared wavelengths, cloud-survey radiometry, radiometric cloud-mask operation, optical-thickness monitoring, autocorrelation methods, monitoring of selected objects, image evaluation and satellite cloud surveys. Various applications of fish-eye sky-patrol-type lenses are common. In addition, conventional ocular sky inspection is a method still in abundant use. The latter method gains considerably in reliability with a split test involving comparison of the results obtained at the epochs of bright and dark moon (Ardeberg et al, 1986).

Photometric sky quality is a function of many parameters. It varies with the time of the day, with season and from year to year. The variations range from only marginal to highly important. While some sites, albeit not many, offer conditions more or less always equal, other sites, even rather favourable ones, can show variations from, say, around and more than 80 % photometric nights in some periods to less than, say, 30 % in other periods.

Large-scale variations can be of a more or less regularly cyclic type or erratic or combinations of both. Periods can include from single years to decades and more. They can also combine two or more periods. Long-period variations are in many cases significantly influenced by large-scale climatic phenomena, such as El Niño and La Niña, both semi-regular with primary periods below a decade, and El Invierno Boliviano, the latter often concurrent with El Niño.

The periodic nature of photometric sky quality requires special attention regarding its assessment. Prudent site evaluation should include time spans larger than, preferably much larger than, the climatic cycles known to influence the sky conditions of the sites in question. It should also include all seasons and the complete diurnal cycle. Unfortunately, too many site selections have resulted in disappointments due to assessment times of too short durations.

Seeing

In astronomy, the term seeing normally is understood as the combination of image degradation and scintillation, both to a smaller or larger extent imposed on the image of celestial objects by the Earth’s atmosphere and its turbulence. When observed in higher temporal resolution, the images of point-source objects, such as stars, are composed of rapidly varying patterns of speckles. With gradually decreasing temporal resolution, the speckle pattern turns into a blurred over-all image, often called a seeing disc. The de-facto resolution of this disc is far less favourable than that of the speckles.

In addition to the degradation of image resolution, the Earth’s atmosphere causes irregular luminosity variations. For apparently brighter stars, these brightness fluctuations are readily observable also with naked eyes. The effect is commonly called scintillation or twinkling.

The image quality exerts dominant influence on a large range of parameters influencing the results of observing at visual and adjacent wavelengths. In case of isolated celestial objects, it determines the speed and/or limiting magnitude of imaging, photometry, spectroscopy and polarimetry. For crowded-field studies, it determines the number of objects distinguishable and observable, the quality of the data determined as well as the limiting magnitude and/or observing speed.

Atmospheric turbulence

Heated by day-time solar radiation, the ground releases its excess heat during night time. The rising air, hotter than its surrounding counterparts, spreads and mixes with cooler air. The cooler air, in turn, due to its higher density, makes its way downwards, spreads and causes mixture. The total body of air gets thermally increasingly inhomogeneous and turbulence on a range of scales is produced.

At the same time, the Earth’s atmosphere is affected by winds, varying in space and time. Drifting air masses meet obstructions, in the form of topographic variations, possible constructions and air-masses affected by humidity. The effects of scattered erratic thermal inhomogeneities and air streaming, ordered and disordered, interact and produce further inhomogeneities and turbulence. An illustration of such effects is given in Fig.68.

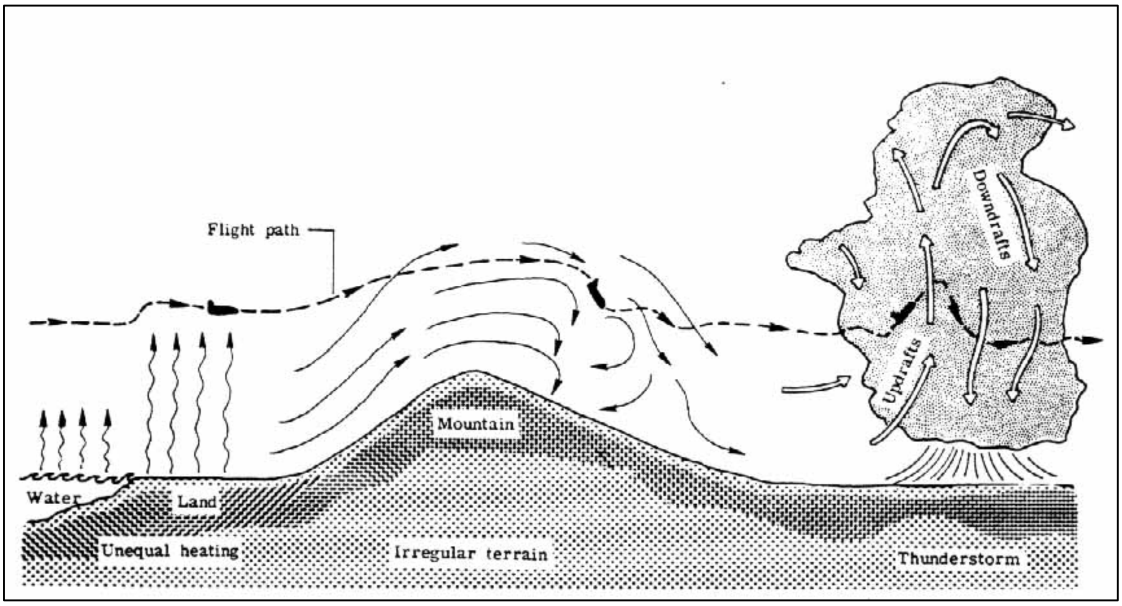


Figure 68. Some aspects of the creation and maintenance of atmospheric turbulence

Thus, air temperature as well as air humidity and movement will vary as functions of location and time. As a result, the density of the atmosphere will be erratically variable along the path of incoming light rays. This, in turn, leads to corresponding variations of the refractive index of the air and, accordingly, varying refraction of the light from the celestial objects. The intrinsically plane wavefronts get distorted. Depending on the scale of these distortions, the results on imaging quality are dominated by either image blurring or image motion, the latter effect often referred to as caused by wavefront tilt.

Let n denote the refractive index of the local part of the atmosphere, T the absolute temperature, p and ν the corresponding atmospheric pressures and vapour, respectively, and λ the equivalent wavelength of observation. For the dependence of n, and thus also of FWHM, on the dominant physical parameters of the atmosphere, we then get (Bely, 2003)

$$n-1=\frac{77.6\times10^{-6}}{T}\left(1+7.52\times10^{-3}\lambda^{-2}\right)\left(p+4810\frac{v}{T}\right)$$

Atmospheric composition, density and kinematics vary with height above ground. As a result, the effects of atmospheric turbulence are different in different layers of the atmosphere of Earth. The uppermost part of the atmosphere, often called the free atmosphere, referring to its relative freedom from direct coupling to ground phenomena, might be seen as reasonably unaffected by topography up to kilometre scales and, thus, similar over a wider region. At altitudes smaller than those of the free atmosphere, atmospheric characteristics are influenced by more local topographic structure. Accordingly, they vary both with azimuth and the speed and direction of the wind.

In the atmospheric boundary layer, the activity is heavily influenced by even rather local topography, also that on observatory scale, including a wide range of installations. Thus, both structures and heat dissipation of such installations are often critical for the outcome of observed image quality. This concerns not least the conditions in the proximity of observing facilities.

FWHM

The image quality observed can be characterised in a number of manners. Among observers, the measure most common is that of the full width at half maximum intensity, FWHM, of the seeing disc. To be an adequate measure of image quality, the FWHM has to be defined from an image with a reasonably large integration time, although, in practice, often some seconds of integration are sufficient to obtain a symmetric, usable point-spread function. For a Gaussian distribution, the FWHM is illustrated in Fig.69.

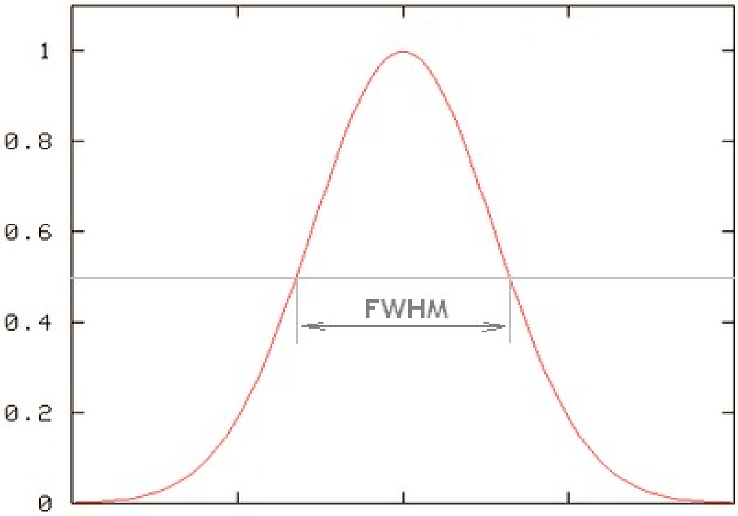


Figure 69. Definition of full width at half maximum intensity, FWHM .

As atmospheric conditions normally are time dependent, FWHM data obtained from shorter integrations tend to give rather variable results. Still, also FWHM data from longer integrations often show significant differences from hour to hour or even over shorter periods. As a rule, the better the conditions are, the more stable are also the FWHM data recorded.

Favourable FWHM data require generally minimised paths through the Earth's atmosphere and selected observatory sites. In practice, high passive image quality demands an observatory with both high altitude and high contrast relative to its more immediate surroundings. Further, a desert-type climate and a regime with low, while not very low, wind speeds tend to be helpful. In the best of ground-based observatories, FWHM values down to or around 0.4 arcsec can be obtained without use of adaptive optics. Observatory sites not generally delivering FWHM data smaller than 1.0 arcsec are today not rated as very favourable for imaging at visible and adjacent wavelengths.

Fried parameter, r_0

Conceptually, the spatial resolution of a telescope is well defined as a function of aperture and wavelength of observation. See above under page 16. Thus, at a fixed wavelength, the spatial resolution is inversely proportional to the aperture. In practice, however, things a more complicated, due to the effects of the Earth's atmosphere and its turbulence. In the absence of adaptive optics, in practice, for larger apertures of telescopes at ground-based observatories, the spatial resolution is independent of the aperture and given by the intrinsic quality of the atmosphere.

The conceptual relation between aperture, wavelength and spatial resolution defines, for any given intrinsic, atmospheric-defined seeing, a lower limit of the aperture, above which the spatial resolution is constant and equal to its intrinsic value, and below which it is inversely proportional to the aperture and gradually less favourable then the intrinsic, atmospherically defined value. This limiting value of the aperture is called the Fried parameter or r_0. Alternatively, r0 can be taken as the typical geometrical scale of turbulence variations or the corresponding coherence length.

As FWHM, r_0 is a parameter highly different between observatory sites but also with time and wavelength. While r_0 values of around 5 cm were, for visible and adjacent wavelengths, only a few decades ago, seen as quite satisfactory, today demands are much higher. To be seen as favourable as a site for modern telescopes, an observatory should show r_0 values around or above 10 cm. At observatories seen as excellent, night-time r_0 is frequently above 15 and even 20 cm. Even r_0 values of 25 and 30 cm are noted, if not regularly, at least over significant observing periods.

r_0 is of special interest regarding the architecture of active-optics systems. As it describes the geometrical scale of the atmosphere, it also sets the scene for the design of the active-optics system. More precisely, r_0 determines the adequate number of and distances between the actuators of a given primary mirror.

Coherence time of atmospheric turbulence, t_0

Adopting an observing frequency compatible with the typical life time of speckles, a spatial resolution limited by effects of diffraction only should be approachable. In practice, this is normally not the case. However, varying the frame rate of observing, we can determine the time scale over which the variations of turbulence become significant. The limiting time resolution so achieved, affected by wind speed, is called the coherence time of atmospheric turbulence, denoted t_0. At favourable observatory sites, and under favourable circumstances, t_0 can range between 5 and 100 ms. See Fig. 70.

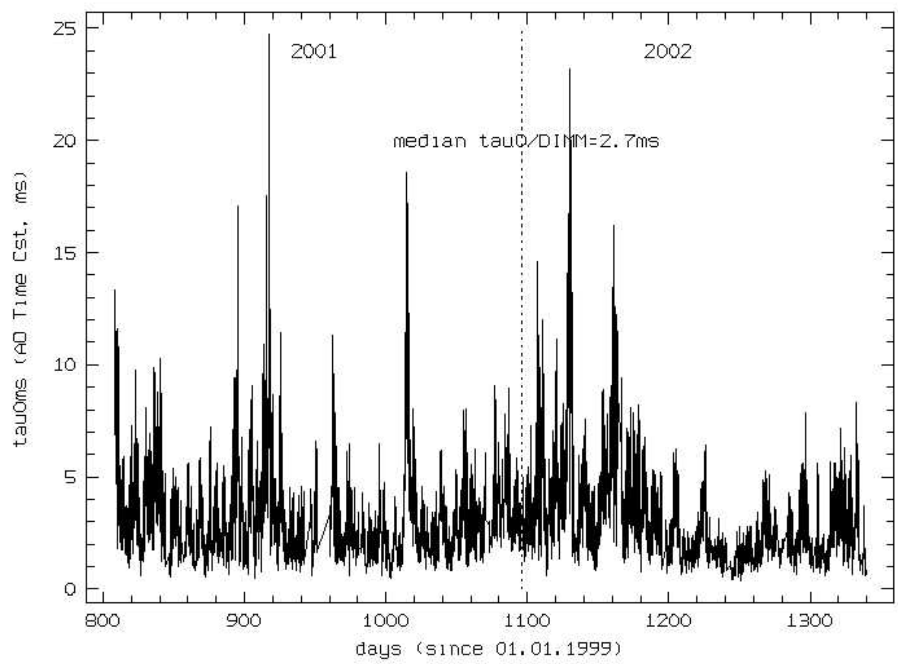


Figure 70. Variation with time of the coherence time of atmospheric turbulence (Tokovinin, 2003).

Both r_0 and t_0 are of highest importance for any system of adaptive optics. As the two parameters describe the structure and coherence time of the atmospheric turbulence, they also define the architecture and lower limit to the bandwidth of the system of adaptive optics.

Isoplanatic angle, θ_0

Given the nature of atmospheric turbulence, the wavefront distorsion of an incoming beam of light varies highly significantly with direction. Thus, a given set of unchanged wavefront data are, in practice, confined to rather small angles of observation. The limiting angle over which the wavefront deviations are non-significant is called the isoplanatic angle, θ_0. At favourable observatory sites and stable atmospheric conditions, and for visible and adjacent wavelengths, θ_0 is typically of the order of a few arcsec. The area included in the circle with θ_0 as radius is, by astronomers, often called the isoplanatic patch. The gradual decrease of image quality from a reference star used for AO correction and outwards is illustrated in Fig. 71.

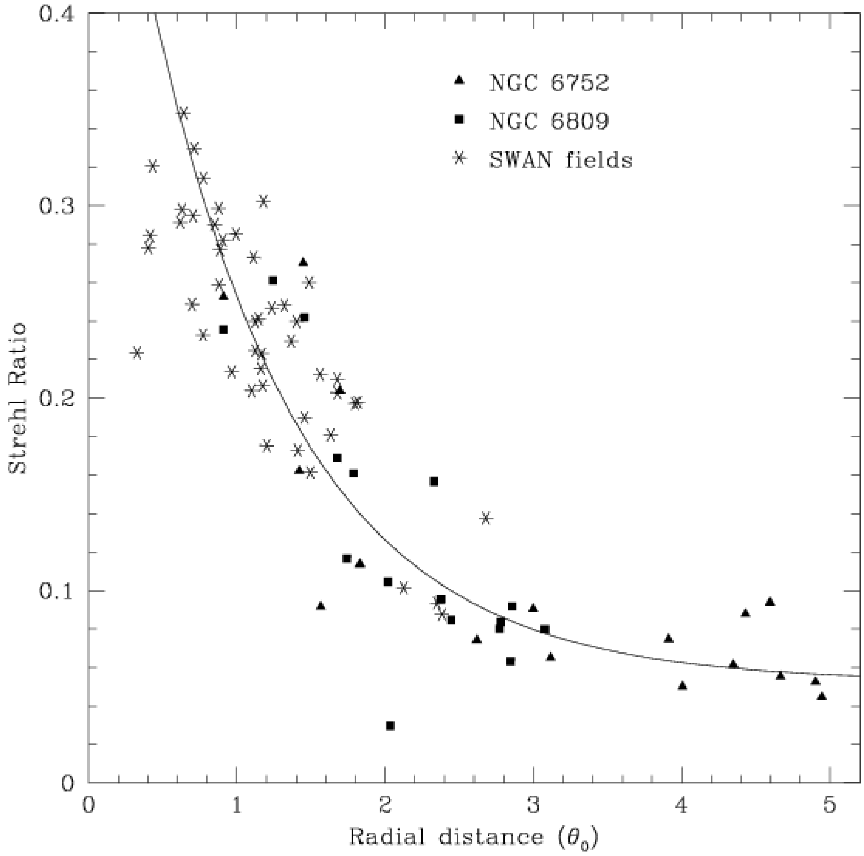


Figure 71. The isoplanatic angle and the variation of the Strehl ratio with angular distance from the reference object (Cresci et al., 2005).

For all forms of adaptive-optics systems, θ_0 offers highly important information. It defines the relation between the distance from the target and reference objects and the quality of the corresponding wavefront correction. These data require careful consideration in any serious design of adaptive optics, single-conjugate, dual-conjugate or multi-conjugate. The dependence of θ_0 on wavelength is considerable. θ_0 is proportional to $\lambda^{6/5}$.

C_n^2 profile

The image degradation affecting ground-based observations is the total effect of many turbulent atmospheric layers along the light path. This accumulated effect is the physically most direct and easily understood of the turbulence parameters in use. It can be described in terms of a turbulence strength expressed as a function of altitude in the atmosphere. The resulting function is the so called C_n^2 profile. The variation of C_n^2 with height above ground is normally considerable. See Fig. 72 for an illustration of this fact.

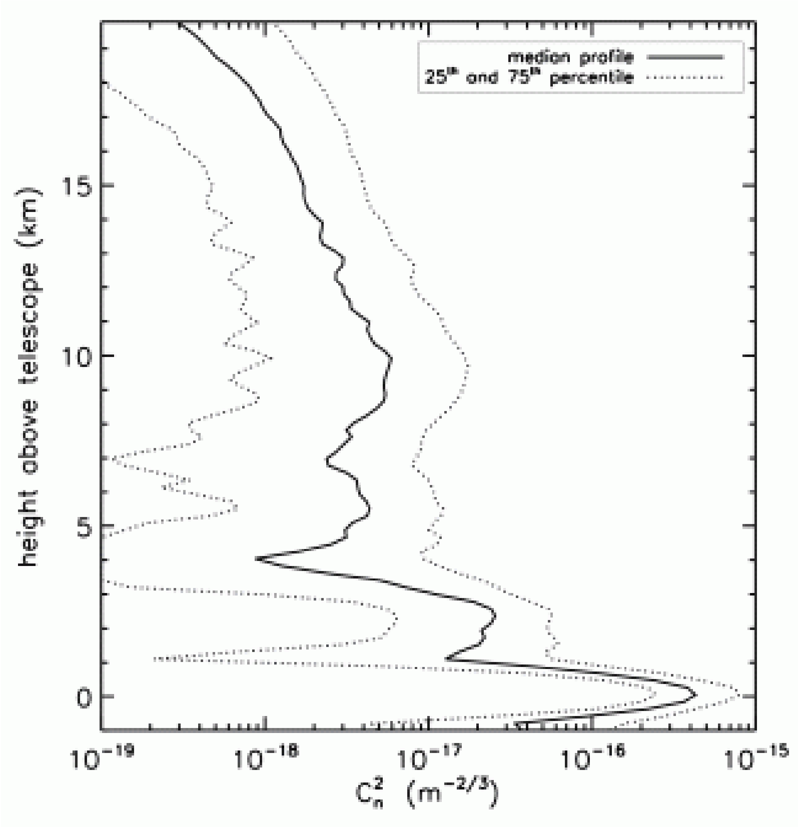


Figure 72. C_n^2 profile over 20 km atmosphere, Masciadri, (Ziegleder, 2003)

There is a rather simple relation between r_0 and C_n^2. Let h denote the height above the primary mirror and $C_n^2(h)$ the variation of C_n^2 with this height. Let further γ denote the zenith angle of the celestial light source and λ the corresponding equivalent wavelength of observation. We get (Bely, 2003)

$$r_0 = \left[16.7\lambda^{-2}(\cos\gamma)^{-1}\int dhC_n^2(h)\right]^{-0.6}$$

Assessment of image-quality conditions

Monitoring, measurement and evaluation of image-quality conditions are processes as challenging as demanding. Many site-evaluation campaigns have dealt with image-quality data of in satisfactory quality, resulting in disappointing results of observatory installations. Assessment of image-quality performance has to be well prepared, performed and evaluated.

Direct image-quality recording

Direct measurements of image quality can be made in many ways. Conceptually, simple monitoring of image quality at high frequency is a natural way to address the task. However, even if image and pixel scales as well as aperture and frame rate are adequate, instrumental stability is always a matter of serious concern. Great care has to be taken to assure that the image-quality performance recorded is a true measure of its intrinsic value and not influenced by vibrations of the instrumentation used. Even highly ambitious constructions, preceded by careful modelling and simulations as well as detailed analysis of the frequency spectra, can, and nearly always do, influence the results of image-quality assessments. Such effects and those of insufficient frequency response have severely limited the value and usefulness of many evaluations of site image-quality conditions.

Trailing of stellar images

Large amounts of image-quality assessments have been based on trailing of stellar images. Not least have such measurements, for practical reasons, used the north polar star as object. As such observations, adequately prepared, can be made with a stationary telescope with modest aperture, prerequisites for stable instrument mounting are in this case uncommonly favourable. In addition, application of the method of star trailing is rather simple, also at sites without any development of infrastructure (Ardeberg et al., 1984). Anyhow, in practice, largely, the star-trail data obtained have had serious shortcomings. Most serious is the fact that it is hard, if not impossible, to separate effects of intrinsic image motion from those produced by the instrumentation.

High-speed image scanning

Multi-slit scanners operating at high frequency are, conceptually, attractive instruments for image-quality assessment. The results are highly useful for both image-quality evaluation and for information on atmospheric extinction and its variations. For adequate results, the method requires, however, a telescope with a relatively large aperture and high stability.

Shearing interferometer

For image-quality assessment, the method of rotational shearing interferometry is uncommonly clever and suitable, at least in a conceptual manner. For various rotation angles, fringe patterns are recorded in the telescope pupil (Roddier et al., 1978; Roddier and Roddier, 1986, 1987). Through adjustment of the maximum shear to prevailing image-quality conditions, optimum use of incoming photons can be assured. The main draw-back of the method is that it is far from trivial to use at remote and undeveloped sites. In total, the use of the method has been rather limited.

Speckle interferometry

A conceptually very direct method for image-quality monitoring is that of speckle interferometry combined with pupil imaging (Labeyrie, 1970; Weigelt, 1983; Ebersberger and Weigelt, 1984; Baier et al., 1986; Weigelt et al., 1986). Correctly handled, the method provides highly attractive data on FWHM, image motion, image profile, speckle life time and isoplanicity plus the distribution of turbulent layers in the atmosphere, C_n^2 and speed and direction of turbulence cells. At the same time, the use of the method has been limited due to the relatively high demands on instrumentation and site infrastructure. In Fig. 73, the non-trivial instrumentation is illustrated.

Monitoring of differential image motion

The principle of dual-aperture recording of image quality for image-quality assessment was introduced by Stock and Keller (1960). Their approach was impressively early but, in practice,

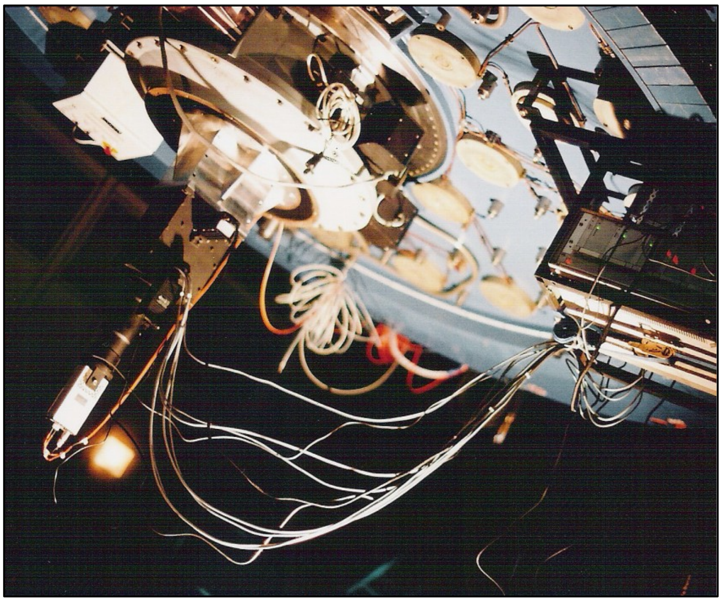


Figure 73. Camera for speckle interferometry (Docobo et al., 2008)

too early for a successful implementation. This was primarily due to the, at that time, limited understanding of the physics of the atmosphere and, also, to the difficulty in meeting the demands on instrumental behaviour.

Since then, analysis of the physics governing turbulence in Earth's atmosphere has been rather successful (Coulman, 1987; Roddier, 1987). This advance, in combination with large improvement concerning instrumentation, has paved the way for highly successful implementation of methods based on records of differential image motion. Early success has incited further work lately resulting in a wealth of exceedingly valuable data for assessment of image quality.

The method of differential image motion monitoring, DIMM, has a number of clear advantages. DIMM observations can, with very good results, be made with telescopes of modest dimensions. In practice, and to some degree depending on site quality, an aperture of around or slightly larger than 30 cm has proven fully sufficient. This is of considerable importance for the practicability of observations at remote sites with limited infrastructure.

At the heart of the DIMM approach is the use of an intermediate pupil-plane image, in which two sub-pupils are defined with masks. Slightly prismatic windows are used to direct the corresponding images onto an intensified CCD detector. The masks can be easily interchanged, thus providing the possibility to adopt the size of the sub-pupils for best possible results. An illustration of a DIMM mask is given in Fig. 74.

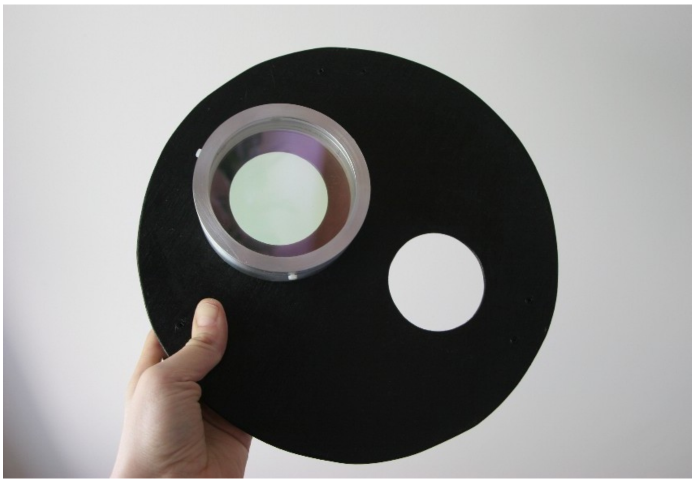


Figure 74. A DIMM aperture plate seen from its front side (Sarazin, ESO).

Small sub-apertures are favourable for two reasons. First, they provide data based on minimised wavefront averaging, thus delivering optimised results on image quality. Second, smaller sub-apertures mean that a relatively small telescope can be sufficient. On the other hand, smaller sub-apertures also imply higher risk of photon starvation and/or restriction to use of very bright reference stars only. Larger sub-apertures, then, imply higher efficiency and a larger sample of reference stars useable but also less sharp and favourable wavefront averaging as well as requirements on larger DIMM telescopes.

Two mutually independent values of r_0 are provided with DIMM observations. One value comes from the differential image motion parallel with the dual-image axis, the other from the counterpart motion perpendicular to this axis. Importantly, both value series of r_0 are independent of mechanical effects coming from the telescope mounting, drive and distortions, all provided that the telescope has a rigidity that suffices for the purpose. The latter requirement is, in practice, rather easy to accommodate. An example of image-quality results obtained from DIMM observations is shown in Fig. 75.

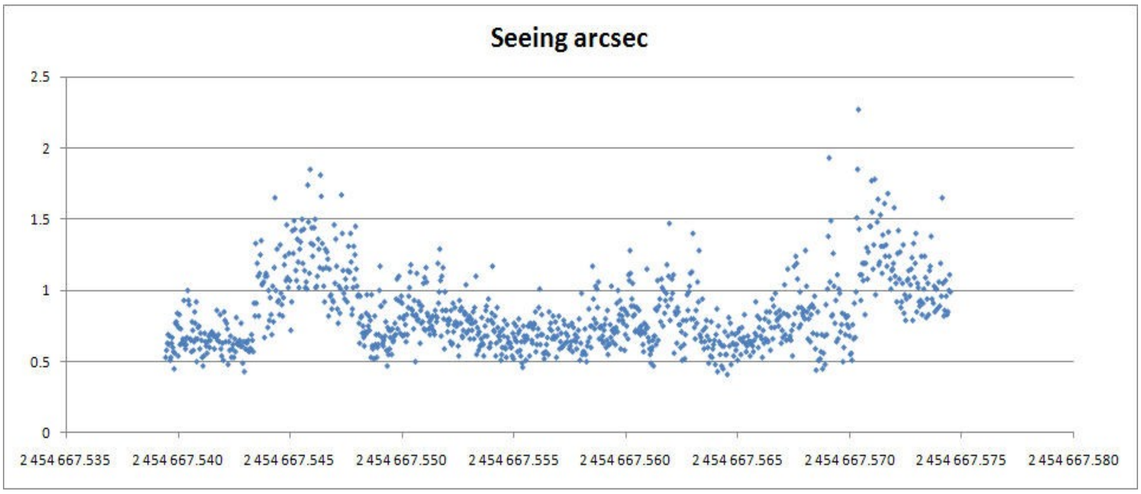


Figure 75. DIMM image-quality data (Sarazin, ESO).

In addition to the dual-aperture approach, the full free aperture of the telescope can be used for recording of image profiles for images of a very wide range of qualities, in practice from rather poor to excellent. This method provides an independent check of the image qualities obtained. The precision obtainable with the DIMM dual-aperture approach is of the order of 0.1 arcsec, provided that the photon beams are adequately rich.

As it is of high importance to be able to freeze image motion, exposure times have to be limited. In practice, they have to be restricted to at most 10 millisec. It is of advantage, if even shorter exposure times can be used without introduction of significant effects of photon starvation. Clearly, the requirements on bright reference stars as well as on detector sensitivity and speed are high as is proper choice of the size of the sub-apertures, while, as noted above, a larger DIMM telescope is not a proper solution. The demand on site infrastructure is neither excessive nor negligible.

DIMM data have been highly useful for site evaluation for VLTs and are now rather important for corresponding assessments of sites suitable for installation of ELTs. This has, in a forceful manner, favoured advanced development of the technique. Much dedicated work has provided DIMM instruments and data of very high quality. Reference is made to the early work of Sarazin (1986), Forbes et al. (1986), Dunn (1987) and Merrill and Forbes (1987).

Periodic variations of image-quality conditions

The influence on image quality of atmospheric turbulence is due to a complicated interaction of many factors. Rising air mixing with cooler air, winds in several atmospheric layers, intermixing of layers, composition differences, temperature inhomogeneities, small-scale and large-scale motions and a range of turbulent actions and cells. While the inner scale of atmospheric turbulence goes down to a few millimetres, the corresponding outer scale can, according to a multitude of estimates using many different methods, be of the order of metres, tens of metres and even up to and beyond 100 metres.

Given the nature of atmospheric turbulence, it is hardly astonishing that its influence on image quality varies greatly both with place and time. This has many important implications. For adequate and reliable results, measurements and analysis of atmospheric turbulence have to be optimised for the place and time at hand. In practice, different places require different approaches and so do different seasons of the year and even different parts of the diurnal cycle.

Experience clearly demonstrates that the atmospheric turbulence above two, both good or even excellent from the point of view of image-quality records, observatory sites can act and influence observations rather differently. Geographic position, not least in terms of latitude and land-mass quality, altitude and contrast relative to the surrounding landscape are obvious reasons as are over-all wind regimes. In addition, the contrast situation is, very often, strongly coupled to both the strength and the direction of the prevailing wind.

At a given site, the impact of atmospheric turbulence often varies with season in a rather pronounced manner, absence of such variations being an exception. The same is, often to an impressive effect, true for the effects recorded at night and in day-time. While all these differences can be rather well explained and understood, they require great flexibility of approach when sites are tested and evaluated for observatory suitability.

An effect worth very special attention is that of seasonal variations of the nature and strength of atmospheric turbulence. This type of variations means that site evaluation for image quality has to comprise all seasons of the year. A number of climatic factors causing long-term variations require further extension of site evaluation periods. Ideally, such evaluation should cover several years of uninterrupted monitoring. This will to a large extent improve the validity of the results of site evaluation although, due to climatic large-scale instability, even long-term monitoring campaigns imply no guarantee regarding future behaviour of the sites investigated. It should be added that inter-comparison of two summits of similar height, general topographic nature and contrast relative to the nearby surroundings as well as close to each other can be quite meaningful even if extended only over a shorter interval of time, say even somewhat less than a year.

Ground-layer turbulence

The ground-layer turbulence and its dependence on height above local ground is of high interest not only as one, important, contributor to the integrated effects of seeing, but also for the more detailed planning for the installation of telescopes. Two important choices for telescope installation at a site are, normally, heavily dependent on the behaviour of ground-layer turbulence. These decisions concern the sub-site location and the height above ground of the telescope.

The ground-layer turbulence is, in turn, very much influenced by local topography, natural and human-made, as well as by wind and ground-to-atmosphere relations and interplay. Thus, clearly, the choice of sub-site location and of the height above ground of the telescope installation can, adequately, be made only with extended consideration of the behaviour of the ground -layer turbulence. These facts make a detailed study of summit ground-layer turbulence a rather important part of site preparations.

Moreover, adequate investigation of the behaviour of the ground-layer turbulence above the site summit is highly important and useful for the final total layout of the observatory. The results of this investigation will, after analysis, show the nature of the wind pattern and thermal flow over the summit. This provides rather valuable data for the planning of observatory installations in a manner securing best possible conditions for high image quality. In parallel, the flow data are indispensable for considerations of and possible decisions on remodelling of the summit in order to improve conditions favouring high image quality. This option is often given insufficient attention. In many cases, even a relatively minor adjustment of summit topography can imply remarkably increased image-quality conditions. Naturally, this is especially true regarding dominant wind directions.

A practical yet highly satisfactory way to efficient studies of local patterns and peculiarities of the ground-layer turbulence is to probe it with microthermal sensors. The idea is to study the microthermal noise with respect to the lower atmospheric sheet covering the summit(s) considered for telescope installation. An investigation is made of the temperature-structure coefficient, C_T^2, and its smaller-scale variations with place and height above ground.

Over the summit place(s) intended for observatory installation(s), a number of masts are erected, extended in height to be compatible with the estimated total height of the local ground -layer-induced turbulence. Normally, to guarantee fully adequate information on the ground-layer turbulence, the masts have to be at least 10 m high. In most cases, heights of 12 to 15 m are recommended, the higher limit being defined by erection and operation complexity, not least vulnerability to high wind forces. At summits highly favourable as observatory sites, such a range in height above ground also covers all, or at least the dominating part, of the ground layer, while at sites less favourable, the situation might be more complex.

From close to ground level up to the top, the masts are provided with horizontal arms, two to three metres in extension. At the extremes of these arms, sensors for microthermal recording are attached. On every mast, a total of seven arms are, as an example, installed at heights above ground of from three to fifteen metres.

The basic idea of a simple microthermal sensor is to provide data on thermal variations in the atmosphere. To be adequate for our purpose, the sensors must be able to produce reliable data of high resolution in temperature as well as in time. Recommendable targets are temperature resolutions of down to 0.01 degree C and time resolutions down to 1-2 milliseconds, the latter target being dependent on the local wind-speed regime as well as on the strategy adopted concerning observing at higher wind speeds.

A simple yet rather reliable type of microthermal sensor can be constructed with thin metal wire. The conductivity of this wire will vary rather clearly with its temperature. The conductivity, in turn, can, with high precision, be measured with a simple electronic arrangement. These measures, then, are a measure of the corresponding, rapidly varying, temperature of the wire, or of the atmosphere passing over it.

It is of importance to use an arrangement that provides low thermal inertia. In practice, this is secured through selection of wire material and dimension as well as of its mounting. A choice recommended is platinum wire with a thickness of around 25 micrometres, providing, at the same time, rather favourable conditions for microthermal measurements and reasonable ease of handling. Conveniently, the platinum wire can be wound on spools of plastic material. An alternative choice might be thermocouples with very fast response (Jorgensen et al., 2009).

The sensor arrangement proposed provides measurement units that are relatively easy to handle. Also, they are favourably insensitive to effects of wind gusts. At the same time, experience has shown that they can be vulnerable to precipitation and to birds. Thus, it might be wise to protect the sensor units in cages. If this is decided, the cages have to be constructed for minimum influence on the microthermal data to be extracted. This influence can be conveniently estimated with the help of computational fluid dynamics.

From the microthermal recordings, high-speed data are obtained on microthermal variations. Together with data on wind speed and direction, they serve as a basis for characterisation of the atmospheric temperature structure. Thus, care has to be taken concerning the compatibility of microthermal measurement time resolution and wind speed, with special regard to the highest wind speeds judged acceptable or somewhat more than acceptable for observing purposes.

The microthermal data, together with corresponding data on wind speed and wind direction, provide a basis for analysis of the microthermal flow over the summit, useful for the purposes discussed above. In particular, and in a rather direct manner, the flow data serve as invaluable information regarding the choice of place and height above ground of the final telescope installation. The higher above ground we install the telescope, the smaller will be the influence of seeing deterioration due to ground-layer turbulence, an influence that can easily be rather disturbing, if not, at least at occasions, dominating.

While potentially highly disturbing, the ground-layer flow has, normally, a pattern that is conceptually readily predictable. Regularly if not nearly always, the microthermal noise will be a decreasing function of height above ground. This behaviour sets the scene for optimum telescope installation with the primary mirror rather high above ground. Fig. 77 illustrates the variation of microthermal activity with height above ground.

However, increasing the height above ground of the telescope and its primary mirror implies not only a decreasing influence of ground-layer turbulence, in itself highly valuable. Unfortunately, it also means increased installation and operation complexity as well as increased costs that are often considerable. Thus, a compromise has to be found, providing optimum freedom from ground-layer-turbulence complications at an acceptable cost in complexity and money. For an adequate discussion and decision concerning this compromise, solid information on the behaviour of the ground-layer flow and micro-thermal activity is of major importance.

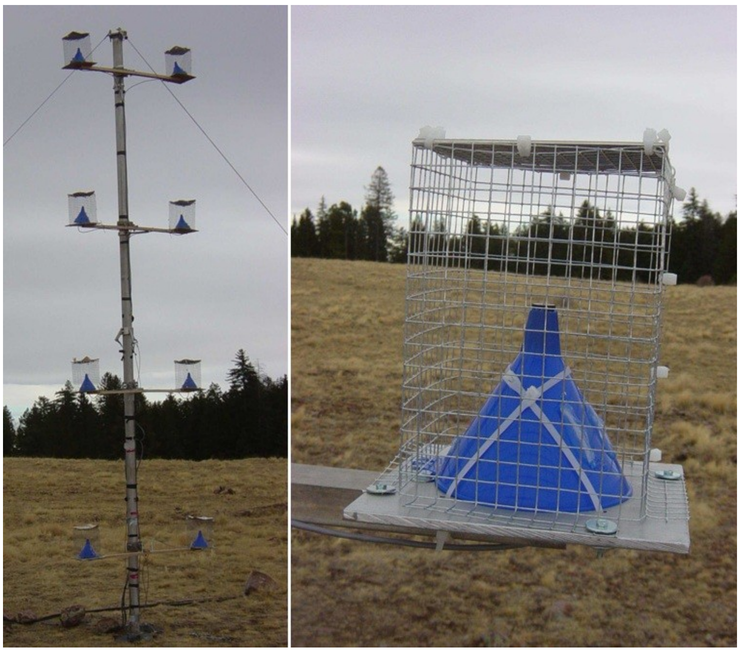


Figure 76. A microthermal sensor mast and its protector cages (Jorgensen et al. 2009).

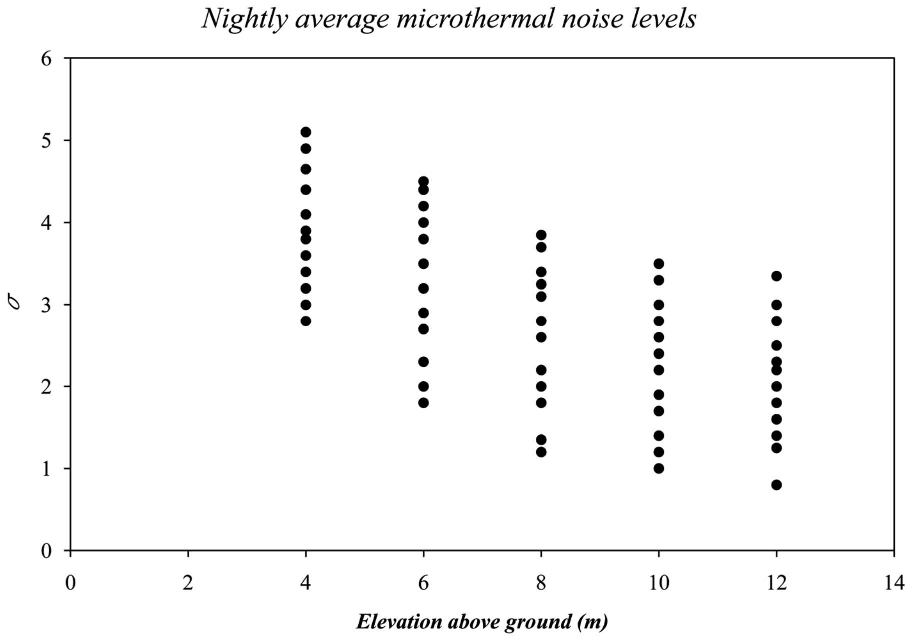


Figure 77. Ground-layer micro-thermal noise as a function of height above local ground (Ardeberg, 2010).

Height above prevailing inversion layer

The local inversion layer is normally a space characterised by strong effects of atmospheric turbulence. Up to elevations well above this layer, turbulent air is often carried up and spread into air sheets intrinsically void of stronger effects of turbulence. Thus, an observatory site well selected should be located at an elevation prudently higher than that of the prevailing local inversion layer. It follows that determination of the prevailing local inversion layer and its variations in elevation is an important part of site selection and evaluation.

Amount of precipitable water vapour

If the science case considered calls, or at least might call, for observations at longer wavelengths, the influence of atmospheric water vapour has to be taken into account. Bands of water vapour exert a major and unfortunate influence already at wavelengths shorter than 1000 nm. At higher wavelengths, their strength and influence is even larger or much larger. At the same time, it should be noted that the influence of lines of water vapour can be a seriously disturbing factor at even much shorter wavelengths (Ardeberg et al., 1986; Lundström et al., 1991).

Normally, for practical comparisons, the amount of atmospheric water vapour is measured in terms of precipitable water vapour. The corresponding quantity given is the height in millimetres of the amount of water resulting. While high and dry sites can have prevailing amounts of perceptible water vapour of less than half a millimetre, corresponding amounts less than two millimetres are normally seen as favourable for most purposes, especially if reasonably stable. Unfortunately, the prevailing amount of precipitable water vapour is, at many observatory sites, much higher than that, reaching levels to be expressed in centimetres rather than in millimetres.

The variability of the amount of atmospheric water vapour is very high. Not least is this variability, often, dependent on the season and the diurnal cycle. In all cases, it is important to note that the impact of lines and bands of water vapour can, and often does, vary both rather rapidly, even over minutes, and with a high degree of unpredictability. This makes atmospheric water vapour a site parameter of considerable importance.

Measurements of the amount of atmospheric water vapour can be made in several manners. A rather convenient and reliable method is to use sky-radiance monitors (Morse and Gillett, 1982; Merrill, 1985; Ardeberg et al., 1986). Working at near-infrared to thermal-infrared wavelengths, these monitors can be operated over the complete diurnal cycle. For low amounts of atmospheric water vapour, the precision of the data resulting depends to a large extent on calibration procedures, while, at higher amounts of atmospheric water vapour, saturation can be a serious problem. Figs. 78 and 79 show, respectively, examples of atmospheres with rather low and rather high amounts of water vapour.

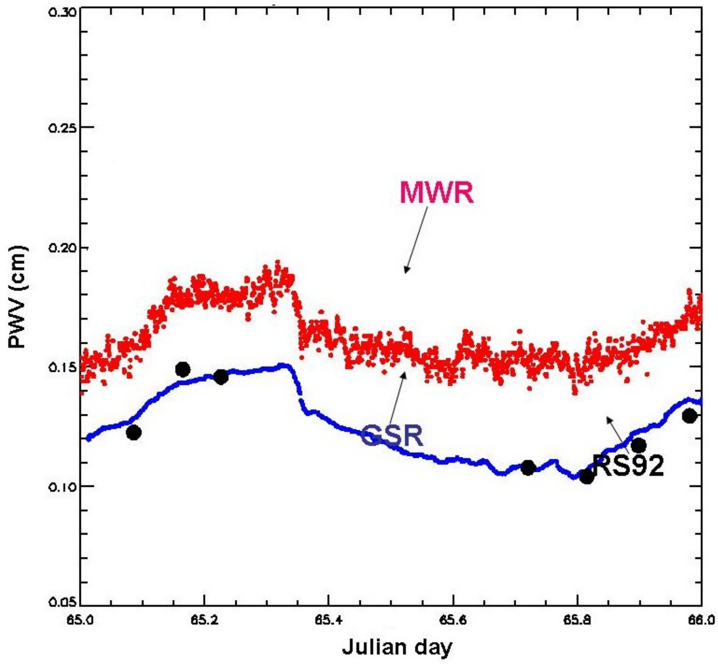


Figure 78. PWV recordings in Alaska at temperatures below – 30° C (Westwater et al., 2008).

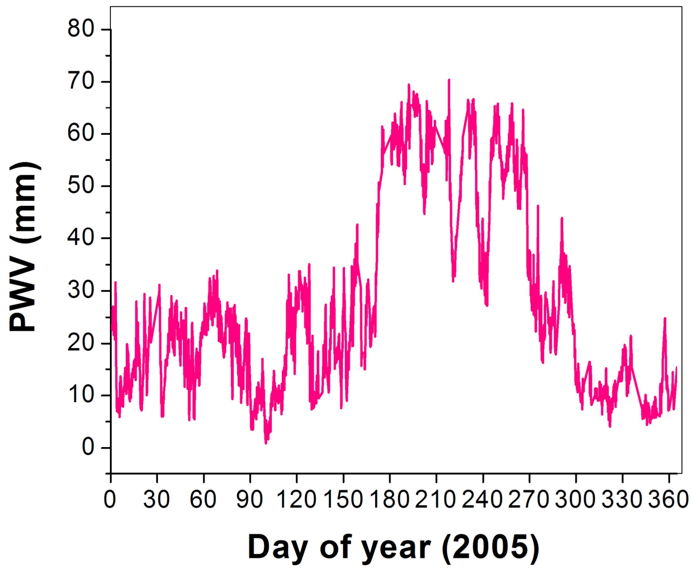


Figure 79. PWV recordings in Kanpur, close to the Himalayas (Ramesh, Indian Institute of Technology).

Sky brightness level

A naturally dark sky is an important asset for an observatory site. The level of sky brightness will have a considerable impact on a wide range of observations and their limits in luminosity. The brightness of the sky varies with wavelength and time. In wavelength, the evaluation data should include the range intended for observations. The time variability has to be measured over the diurnal cycle as well as over the seasons.

In absolute terms, the prevailing brightness of the sky varies rather much between observatory sites. In many cases, the sky brightness is a major site weakness, when other site parameters are favourable. For this reason, the brightness level of the sky should be measured at an early state in a site evaluation programme.

Reliable data can, in the wavelength range 300 – 900 nanometres, be obtained with relatively simple photometers, standard sets of filters and data for well-calibrated photometric standard stars. At longer wavelengths, such measurements get increasingly difficult and error-prone. More reliable data can, in these cases, often be obtained from spectroscopy, although such data can prove hard to obtain at sites with no or only basic infrastructure.

Atmospheric transparency

For all sorts of observations, a high and stable atmospheric transparency is of large importance. For photometry of high quality, it is an absolute necessity. The, normally, strong role of photometry in observational activity makes atmospheric transparency one of the prominent parameters in site-evaluation activities. A favourable observatory site must have an atmosphere with a transparency that is both high and predictable at higher as well as at larger zenith distances, in the latter case in practice down to distances around at least 60 degrees.

The favourably high and stable atmospheric transparency also has to be available over a reasonably high interval in wavelength. In practice, this interval should, for an observatory intended for light at visible and adjacent wavelengths, cover from around 300 to at least 2 000 nanometres. It is of important advantage if the high and stable transparency of the atmosphere is independent of season or, at least, varying with season in a reasonably limited and predictable manner.

The extinction of the atmosphere is a function of its composition. An immediate consequence of this is that the stability of this extinction depends on the degree of homogeneity of the atmosphere and on its movements. Thus, the prevailing atmospheric transparency and its stability depend on the type of air mass, its purity as well as on the speed and direction of the wind. These factors, in turn, depend on the location of the site and on its surroundings.

Serious site testing and evaluation always has to include thorough assessment of atmospheric transparency and stability. Series of photometry have to be made of well-calibrated standard stars over zenith distances from close to zero and up to more than 60 degrees. In addition, several wave bands should be included, taken into account the wavelength range foreseen for future observations.

With a favourable atmosphere, evaluation of the assessment photometry is rather straightforward. The atmospheric extinction being a direct function of the amount of atmosphere involved, the extinction derived should be a linear function of the air mass or of the secant of the zenith angle. Extrapolation to zero air mass yields the quantities unaffected by atmospheric extinction. For any given standard star, these quantities, at the wavelengths measured, should be stable with time. A strong dependence of the atmospheric transparency on wavelength is, in all cases, unavoidable. Fig. 80 illustrates the nature of atmospheric extinction, showing the differential depth in the atmosphere to which light of different wavelengths can penetrate.

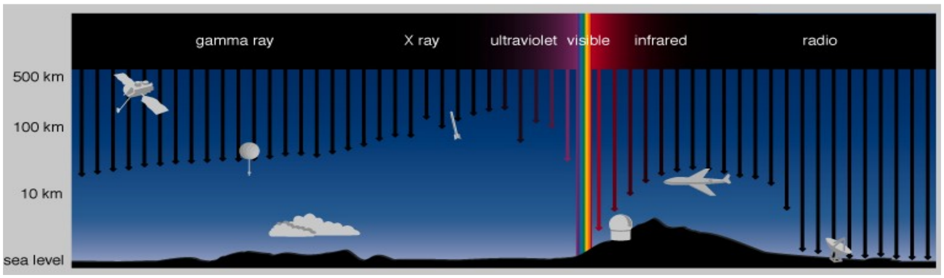


Figure 80. Atmospheric extinction in different parts of the electromagnetic spectrum.

Dust in the atmosphere

Many mountain summits otherwise favourable as observatory sites are adversely affected by dust. If more or less constantly mixing into the atmosphere, the dust will, unavoidably, cause a number of problems. The dust will severely deteriorate the quality of atmospheric transparency, making the extinction higher and less constant. Also, it will endanger the function and quality of gears and other mechanical telescope units. Further, atmospheric dust will spread over primary-mirror surfaces decreasing their reflectivity.

Atmospheric dust is a problem primarily in regions of sandy nature such as sand deserts. In general, it is a problem hard to avoid completely at observatory sites, as they are often situated in regions with a dry climate. It should be noted that dust, not least of finer dimensions, can often be carried over large distances, up to several hundred kilometres. Sand storms are events of sometimes quite frequent occurrence. When they prevail, observatory operation should be shut down and premises closed and, if possible, sealed.

Site-evaluation campaigns should include surveys of atmospheric dust. Dust meters should be erected and the amount of dust be measured as should be the size distribution of its content. It is further important to determine the directions from which the dust is carried in.

Wind regime

Characterising wind patterns, wind speeds and wind directions is an essential part of site assessment procedures. Few site parameters influence observing quality in such a diversified manner as the wind regime. Due to effects of wind, the quality of the data obtained can be decreased. Also, and not infrequently, the complete observing activity may have to be interrupted. Not least in terms of observing efficiency, wind patterns have a large impact.

There can be little doubt regarding the negative effects of high wind speeds. They can, and often do, cause an increase in atmospheric turbulence and, thus, a decrease in image quality, an increase in the amount of air-born dust as well as shaking of telescopes and other observing installations. The combination of wind direction and wind speed with patterns of local topography can impose drastic variations of the prevailing image quality with wind direction and speed. In many cases, excellent image-quality patterns for certain directions of the wind can be combined with image qualities of rather mediocre quality when the wind comes from other directions characterised by other local topographic patterns.

Strong winds impose closing of observing operations. Observing in directions close to that of arriving winds normally should be halted at wind speeds surpassing around 15 metres per second, while observing should be completely halted when wind speeds are higher than around 20 metres per second. The wind-speed limits quoted can be modified with the use of proper wind screens, fully blocking the wind or partly transparent to it.

Both the speed and direction of the wind show frequent changes. This is also the case for the amount of gusts making the influence of the wind rather hard to eliminate. The wind-regime changes have many regular and irregular cycles, to some extent depending on the location of the site. Regular or semi-regular cycles nearly always present are diurnal and seasonal.

A rather convenient way to characterise the prevailing wind pattern of a site is to arrange long-term observations of wind speed and wind direction combined into a so called wind rose. In a polar diagram combining wind direction and wind speed, data are recorded in a cumulative fashion. The wind-rose diagram will show the frequency of wind directions as well as the corresponding prevailing speed pattern. The wind rose provides data of major importance for assessment of site quality as well as for planning of observatory installations and of possible measures of summit re-modelling.

Notably, a wind rose showing long-term stability has important general advantages. It sets the scene for relatively easy planning of observatory installations as well as of following observation routines. Most clearly, the same is due for a wind rose with relatively narrow dominating components, making a range of planning details easier than those due for a wind rose with large spread in both variables. Fig. 81 shows two wind-rose diagrams, one for a site with generally good wind conditions, the other with excellent wind conditions. In Fig. 82, the wind rose is given for best seeing conditions at Paranal.

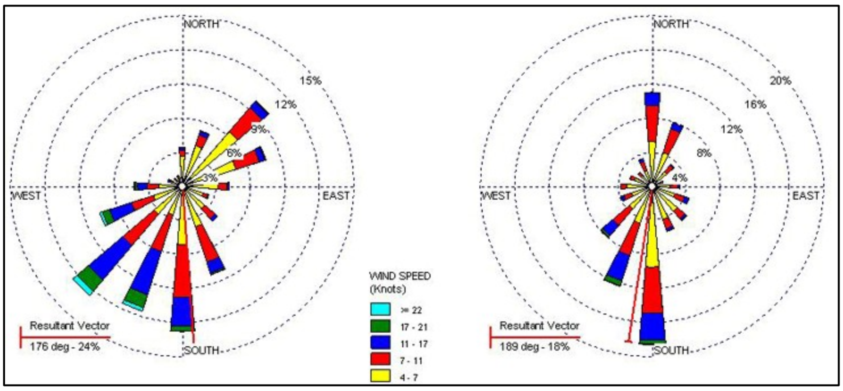


Figure 81. Wind-rose diagrams for two different sites. The left-hand diagram is characteristic for a site with generally good wind conditions, while the right-hand diagram characterises a site with a wind regime excellent for observing.

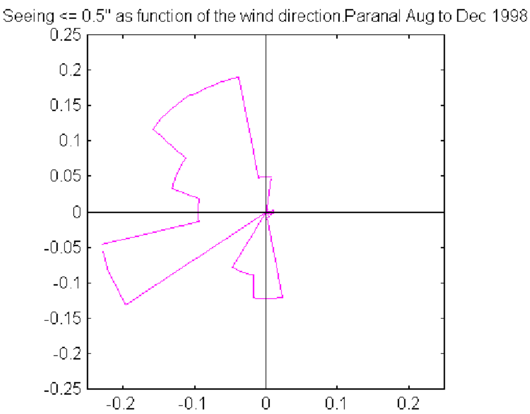


Figure 82. Paranal wind rose for best seeing, with FWHM ≤ 0.5 arcsec, only. (Long Term Follow-up of the Astroclimate at Paranal report, ESO)

Site temperature

To maintain favourable observing conditions, a stable temperature regime is of high importance. Large diurnal temperature variations create a number of problems as do large temperature variations during observing nights. Thus, the range of temperatures characteristic for a site is a parameter essential for its assessment for observatory purposes.

Large differences between day and night temperatures are unfavourable for maintenance of stability of optical components and mechanical structures of telescopes and instruments. General temperature-variation induced deformations and relaxations are detrimental to all types of observations, not least to control of high image quality. Even if such effects to a certain degree can be compensated, larger effects of temperature variations are notoriously hard to accommodate.

Even more difficult to control than day-to-night temperature variations are variations of temperature during observing nights. While temperature-control units and routines can, with good effects, be applied to the idle telescope in the enclosure during day-time, corresponding measures during observations are more complicated and prone to have side effects not wanted. While active control of primary mirrors and of secondary-mirror mountings can compensate such effects to some degree, residual influences are hard to eliminate.

Absolute temperature levels as well as both day-to-night temperature differences and corresponding nightly variations are practically always season-dependent. Thus, temperature monitoring of sites for evaluation purposes have to include not only the full diurnal cycle but also all seasons. To take longer-time climatic variations and their influence on the temperature regime into account, monitoring should be extended over a number of years.

Artificial light pollution

To secure favourable observing conditions also for fainter celestial objects, dark night skies form a mandatory characteristic. At the same time, global evolution of societies implies a highly notable and fast decrease of the over-all darkness of night skies. This is illustrated in figs. 83 and 84.

Figure 83. Illustration of the impact of human-made light pollution on sky visibility. The upper image box shows the Milky Way above the Alborz mountain range in northern Iran, the lower the washed-out sky of metropolitan Tehran, 65 km from the location of the place from where the upper image was exposed. Photo courtesy Babak Amin Tafreshi.

Part of artificial light pollution is air traffic, also contributing to general air pollution. Site evaluation should include assessments of the influence of air traffic. As far as possible, this should take into account future developments of air routes and traffic intensity.

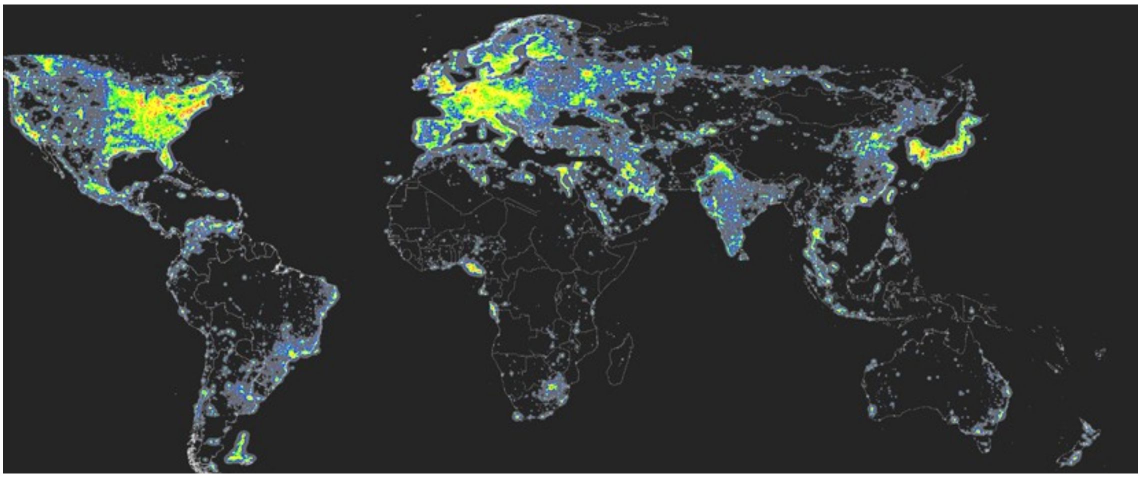


Figure 84. The World Atlas of the Artificial Night Sky Brightness. Photo courtesy Light Pollution Science and Technology Institute.

Background Radiation

However well chosen an observatory site might be, also concerning dark night skies, effects of background radiation are always present. While some of the sources of this radiation are constant and unavoidable, some other background-radiation parameters may be somewhat dependent on the site. Largely though, most observatories, independent of their locations, suffer from the effects of background radiation.

The influence of the background radiation is relatively pronounced in the wavelength interval long wards of around 1000 nanometres. Moreover, here it coincides with a sky emission rapidly increasing with wavelength. Further, from around 2 500 nanometres, effects of radiation from telescopes and adhering installations add to the problems of observing contrast. These problems have an rather significant influence on the limiting magnitude attainable at longer wavelengths.

Local relative humidity

Higher levels of local relative humidity influence observing conditions in a number of negative manners. It affects optical elements of telescopes and instruments as well as corresponding mechanical parts. In combination with falling temperatures it can cause condensation and even icing of elements. Site testing and evaluation should, thus, include monitoring of the local relative humidity. Special attention should be given to its variations over the diurnal and seasonal cycles.

Seismic activity

Significant seismic activity is a clearly negative observatory parameter. If it more or less frequently includes pronounced earth-quake events, great care has to be taken in terms of site selection as well as concerning installation strategy. Many observatories are installed on mountains and in areas with significant seismic activity. Thus, it is well proven that, to some non-negligible degree, seismic activity can be accommodated with adequate design of site installations.

At any rate, seismic activity is a parameter requiring careful study for all site candidates. This care is especially important if interferometry is a topic on the scientific agenda. In the latter case, also effects of micro-seismic activity should be measured and included in the site-quality assessment.

Convenience parameters

In addition to the site parameters discussed, there are a number of additional site factors with a character of convenience parameters. While not necessarily the first qualities to be taken into account for site evaluation, they may well be of importance in the final site selection procedure. These parameters can have a rather significant impact on a wide range of site-related issues. Examples are parts of the sky available, long-range climatic stability, weight of future observatory contributions to world-wide collaborative programmes, amount of work and money necessary for an acceptable infrastructure including roads, buildings, water and food supplies and availability of connections to large-scale communication net works as well as foreseeable efforts in terms of travel.

An observatory close to the equator will have the advantage of access to both hemispheres, in itself an important asset. On the other hand, closeness to the equator is not compatible with best observing conditions. An observatory far from the equator, say more than 40 degrees, will, normally, have the combined problems of limited sky access and non-optimum climate conditions. Sites with locations both close to and far from the equator should be critically reviewed for climate stability.

Also the longitude of the site may have important effects, not only in terms of climatic quality and stability. A longitude placing an observatory in an interval largely void of major similar telescope installations will imply high strategic advantages concerning world-wide collaborative programmes including target monitoring as well as a range of target-of-opportunity programmes. The benefits of partnership in such programmes are considerable in a wide context.

Most places attractive as future observatory sites are, naturally, located in remote areas with limited access to urban installations. While in itself part of the quality of the site, the remoteness has a number of implications on the amount and cost of the work necessary to convert the site from an attractive candidate for observatory installations to a well-functioning modern observatory. The accessibility in a wide sense has many consequences.

At an early phase of the site evaluation programme, questions of accessibility and infrastructure have to be seriously studied. Access roads and their connection to the national system of roads as well as a range of support buildings must be tentatively planned and cost evaluated. Provisions of water, food and accommodation have to be studied and corresponding efforts and costs estimated. Connections to national road and air communication networks must be investigated, and schemes for travel studied. In addition, a strategy for and implications of site safety measures and preparation for emergency situations have to be given solid attention.

The work schedule of operation staff has to be given special attention. This includes the length of site-work periods and the time and ease of transfer between work and home stations. The importance of attracting highly qualified staff implies a necessity to study access to health care, school service and the general offer of urban facilities including the cultural domain. Lack of adequately solid preparations in these terms has been an all too frequent mistake of many site-selection programmes.

Telescope enclosure

General

A modern, powerful telescope for visual and adjacent wavelengths with high ambitions in the field of image quality is a rather sophisticated instrument. Like its predecessors, it needs an enclosure. However, unlike its traditional counterparts, the modern telescope requires much more from its enclosure than protection and support of its infrastructure. While these requirements are still highly valid and important, they are just examples, and by far not the most demanding ones, of contributions asked from the enclosure.

Rather than visualizing a telescope protected and supported by an enclosure, we should promote the concept of a telescope installation consisting of both a telescope and an enclosure. The end result, in terms of scientific output, will benefit very much from such an approach. Seen in this context, we should attempt an enclosure as much as possible working as a partner of the telescope, sharing its challenges. In general, the challenge of highest weight in this context concerns image quality, a parameter with special scientific impact but also a factor of highest vulnerability. While, in terms of maintenance of high image quality, the telescope is highly dependent on assistance from the enclosure, the reality is often the opposite (Vernin and Muñoz, 1992). That the enclosure has a significant adverse influence on resulting image quality is not an unfortunate exception; rather, it is a deplorable fact regarding all too many installations of telescopes.

Confronting concept and real life, which are the main achievements to be expected from a modern, sophisticated telescope enclosure? To some advantage, they can be divided into a number of areas. First, the enclosure must protect the telescope and its instrumentation against adverse weather conditions in general. Second, it has to provide day-time protection from a range of sun-light-connected influence problems. Third, the enclosure should maintain the temperature around the telescope at a level as stable and ideal as possible. Fourth, it should not only allow but rather promote free wind-carried air flushing of the telescope and the observing -floor installations. Fifth, the enclosure should not provoke any temperature gradients around the telescope. Sixth, it should support the maintenance of laminar air flow around the telescope. Seventh, it should support reasonable observing activities also during nights with wind speeds approaching close-down speed. Eighth, the enclosure should support and adjust to handling activities concerning telescope and instrumentation. Ninth, it should have a size large enough not to introduce any operation and handling problems, yet small enough not to include any air volume unnecessary and leading to additional local turbulence. Tenth, it should fit into local site topography, not implying any additional local turbulence. Eleventh, the enclosure should promote safety of staff and visitors, also in cases of possible emergency.

Weather protection

A traditional yet highly important function of the enclosure is to protect the telescope and its instrumentation from detrimental effects of adverse weather conditions. A prime example of such conditions is that of high wind speeds. Often, they are accompanied by pronounced influence of wind gusting, making conditions even more critical. The enclosure has to be constructed to withstand even the worst predictable local wind conditions. It might be quite prudent to consider clamping possibilities in places with strong winds foreseeable.

Protection should also be efficient regarding rain, snow and hail. While these effects of precipitation are, normally, relatively easy to handle, conditions get much more critical when they combine with strong winds. For this reason, good sealing properties of the enclosure are very essential. In addition to adequate construction, this requires solid maintenance.

There are two weather effects demanding special attention. They are connected to dust and icing. If the atmosphere around the observing facilities has a significant load of dust, no observations should be allowed. In addition, such conditions require high-quality sealing arrangements. This is especially the case if the dustiness combines with high wind speeds.

A weather problem of very special nature is icing. It results from a combination of under-cooled rain and strong wind. At higher altitudes this combination is not entirely rare. The moisture is carried nearly horizontally with the wind. When the wind hits fixed installations, the under-cooled rain converts into ice attached to the structure hit. An increasingly thick ice-layer builds up. The build-up of the ice layer is often rather quick. Thus, the side of the structure hit by the wind gets an increasingly more thick and, importantly, more heavy layer of solid ice, covering, say, only around a fourth of its circumference. On larger installations, the weight of the one-side ice layer can reach impressive amounts. In serious, but not completely rare, cases, structures can break down from the effect of asymmetric ice load.

Against effects of heavy icing, there are two remedies. The conceptually easier one is to let the enclosure rotate. Then, the ice layer building up will be symmetric, and thus less harmful to the stability of the construction. This type of remedy requires timely action when conditions of icing set in. A less vulnerable but not trivial remedy is to give the enclosure a low centre of mass and generous clamping facilities.

Sun-light protection

One of the conditions characterizing an observatory site as adequate or better is that of a reduced amount of night-time clouds. In practice, normally this means frequently clear skies also in day-time. As sites selected for modern observatories operating at visual and adjacent wavelengths are more or less without exception at higher altitudes, considerable effects of sun-light heating has to be expected. This has a number of consequences demanding attention and actions.

If, under the circumstances discussed, the telescope and its instrumentation are directly hit by sun-light, severe problems are ahead. The resulting heating of optical and mechanical elements and structures will, first, imply a range of deformations. When the exposure to sun-light is over, the temperature of the components will decrease, provoking new deformations. Importantly, there is no way to avoid not only effects of heating as such, but, worse, these effects will be rather asymmetric depending on the degree of exposure to the sun-light. Gradual deformations will mix with those caused by mechanical relaxations.

Added to the effects of deformation, we have to expect thermal disturbances as such. When night-time observations are initiated, the telescope will have a temperature exceeding that of its ambience. Thus, the air around the telescope will be fed with locally forced turbulence. As many of the optical and mechanical parts of the telescope unavoidably have significant thermal inertia, the telescope-fed air turbulence will endure for large parts of the night if not all of it.

In addition, sun-light will affect the observing floor and installations thereon. Again, the air surrounding the telescope will, during observing time, be subjected to injections of effects of local turbulence. The turbulent air so produced will stream up and along the telescope.

Even when a closed enclosure protects the telescope against direct sun-light, effects of solar heating are still present and disturbing. Also enclosures perfectly suited to protect their respective telescopes will transmit disturbances. First, the outer shell, or cladding, of the enclosure will increase its temperature, with emphasis on its parts directly hit by solar radiation. As a result, the air volume in the enclosure will be heated.

Heating of the air in the enclosure will not only, as a direct consequence, result in turbulence around the telescope. It will also imply a temperature stratification of this air volume. As a result, the upper parts of the telescope will get a temperature higher than that of its lower parts. Deformation is introduced as is stratified thermal interaction with the surrounding air volume.

While complete elimination of sun-light heating is hard, if not impossible, to achieve, the adverse effects of solar heating can be significantly reduced if adequate measures are taken. For any telescope installation including ambitions regarding image quality, such measures are natural parts of the construction strategy. Below, some of them are discussed.

Temperature stability

An image quality of higher class requires maintenance of a controlled temperature regime in the enclosure. Importantly, temperature differences have, as much as possible to be avoided. To the extent possible, all parts of the telescope, its instrumentation and the observing floor as well as the air volume in the enclosure should have mutual temperature differences that are either insignificant or, at least, minimized. The corresponding ideal common temperature is, at any moment during observations, that of the ambient free air during observations. To the extent possible, also in day time, the temperature of the enclosure, the telescope and all other items in the enclosure should be maintained at a temperature as close as possible to that of the ambient free air of the observing night approaching. In addition to the temperature-stability challenges involved, the latter ambitions involve an approach to prediction of outside night-time temperature, an additional non-trivial problem.

Special attention has to be given to elements with large thermal inertia. This concerns not least a number of entities that are of compact nature and of higher mass. Examples are primary mirrors and their cell structures, centre sections and telescope mountings but also back-end devices and instruments and, in addition, the enclosure itself and not least the observing floor.

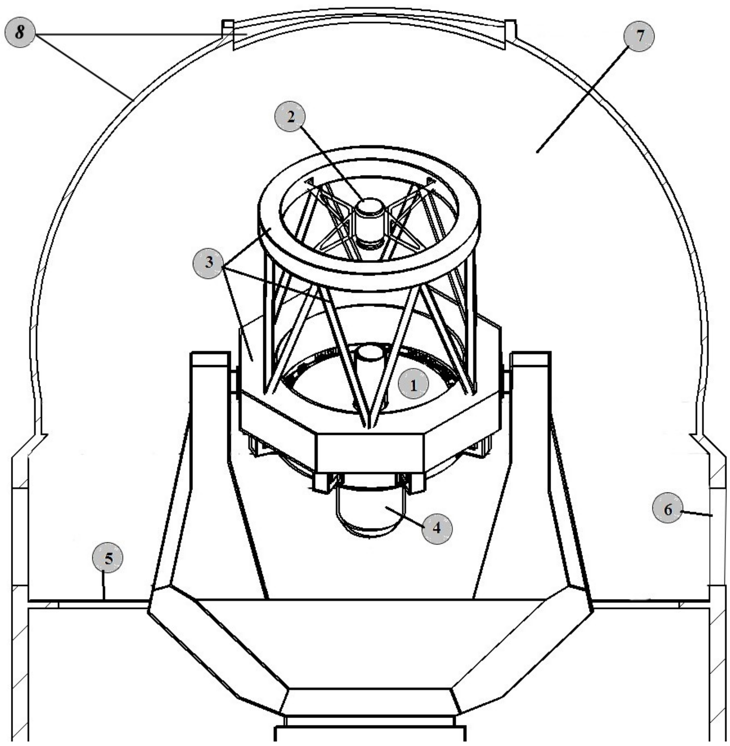


Figure 85. Some of the more prominent enclosure-related conceptual sources of disturbances of temperature homogeneity. The entities noted are the primary mirror (1), the secondary mirror unit (2), the mechanical structure of the telescope (3), the instrumentation (4), the observing floor (5), the enclosure walls (6), the enclosed air volume (7) and the enclosure and its opening (8).

The situation is illustrated in Fig. 85. While favourable choice of material can be very helpful, maintenance of temperature balance is a prime requisite for high image quality.

Without a series of precautions and active functions, regularly, the temperature of the air volume, the telescope and everything else inside the enclosure will have a temperature at the beginning of the observing night that is higher than that of the surrounding free air. In addition, the temperature range of enclosed air and devices is significant. Not astonishing, detrimental effects are abundant. Air streaming and turbulence affect the enclosure volume of air. Further, the excess heat will leave the opened enclosure and produce turbulence in the local air in front of the telescope. The image quality is bound to suffer.

While not easy to achieve, maintenance of a temperature equilibrium inside the enclosure at a level close to that of the local atmosphere of the approaching observing night is an important prerequisite for best possible image quality. In practice, the only approach realistic is to apply a combination of measures. These include active cooling and airing coupled to temperature probing and feedback arrangements. Reference is made to Racine (1991) and to Fig. 86.

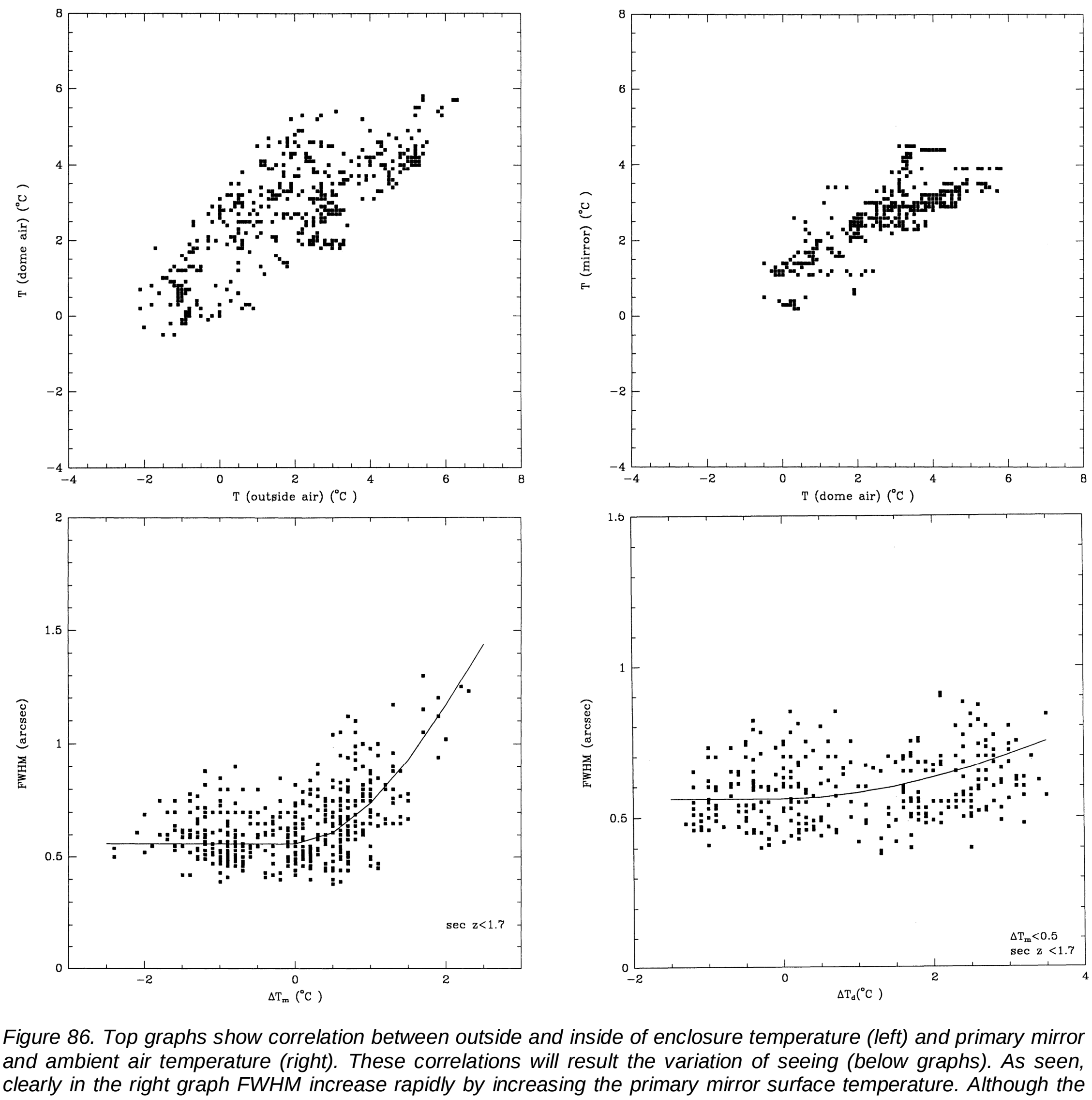


Figure 86. Top graphs show correlation between outside and inside of enclosure temperature (left) and primary mirror and ambient air temperature (right). These correlations will result the variation of seeing (below graphs). As seen, clearly in the right graph FWHM increase rapidly by increasing the primary mirror surface temperature. Although the FWHM of enclosure (dome seeing) changes by variation of inside temperature too, but slightly. (R. Racine et.al., 1991)

Free air flushing

As demonstrated, the contributions from the telescope enclosure to mechanical instabilities and air turbulence detrimental to image quality are many and rather significant, often even dominant. As a result, considerable efforts have gone into the possibility of the operation of telescopes without any enclosure protection during observations. Examples tested and analyzed are retractable and inflatable enclosure constructions. Figs. 87 and 88 shows two examples of such constructions contemplated but not realized.

A prime reason to abandon the concept of an inflatable enclosure was that of operation security in case of strong wind but also in general. The concept was extensively tested by ESO. In real observatory conditions, a half-scale inflatable dome for the VLT was erected, tested and assessed. While basically functioning, the operation smoothness and reliability did not meet expectations. In particular, structural deformations in conditions of wind speeds above 15 m/s made handling, not least closing and sealing, a matter of considerable uncertainty.

As the OWL telescope was never realized, its concept of a retractable dome was never given any real testing and, thus, no final thorough assessment. Still, its considerable operation complexity was obvious. While, in the particular case of OWL, a substantial part of the difficulties anticipated were related to the size of the construction, it appears beyond doubt, that also for telescopes of more modest size than OWL, retractable enclosures may well introduce more problems than they eliminate. In total, concepts of telescopes operated without enclosure protection have been tested and evaluated, and the result is that, in general, the advantages of in-

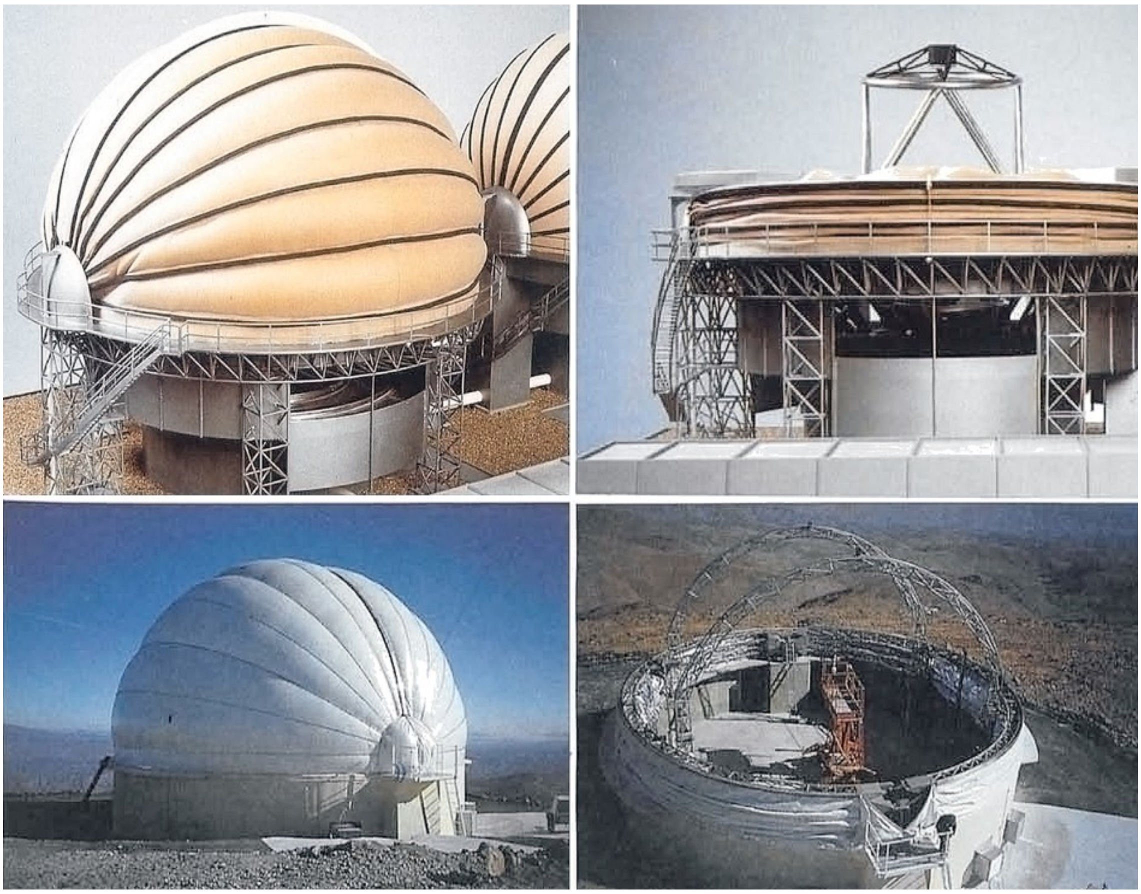


Figure 87. Large-scale testing of inflatable dome for ESO VLT, pictured here inflated and deflated, respectively (Zago, 1988).

enclosure operation have been judged larger than the corresponding disadvantages. Thus, in practice, we have to maximize the favourable aspects of telescope enclosures while minimizing the corresponding negative effects. It should be realized that the latter task is a considerable challenge.

The logical manner to combine the advantages of in-enclosure telescope operation with optimum free air flushing is to make the enclosure optimally wind transparent. This includes an enclosure design not only permitting wind-driven air as free a passage as possible but also maintaining the laminar flow of this air. Accordingly, we have to design an enclosure with both optimum protective qualities and arrangements for free air flushing of its interior, the telescope and its instrumentation. At the same time, we have to keep the enclosure as small and cost-effective as possible.

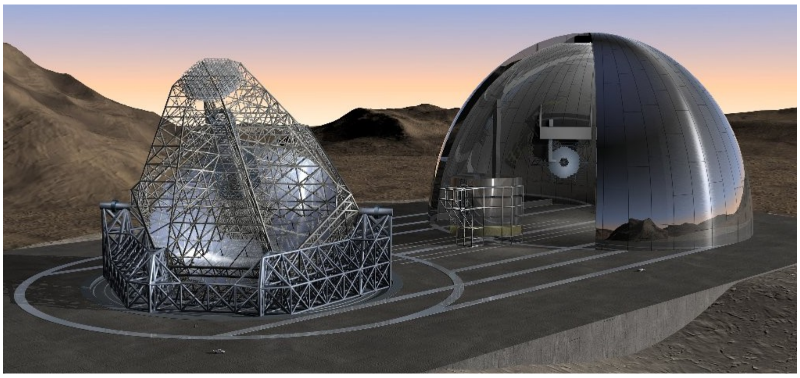


Figure 88. Concept of retractable dome for ESOs version of an overwhelmingly large telescope (OWL) (The ESO 100-m telescope concept, 2005).

A strategy tested and found highly attractive is to give priority to free air flushing of the primary mirror. The reasons for this approach are several. The primary mirror is the heart of the imaging device. It has, even when relatively thin, a considerable thermal inertia. When affecting local turbulence, it does so concerning both incoming parallel and exiting reflected light. Its surface is a most critical element for small-scale turbulence. Finally, the primary mirror affects not only its immediately surrounding mirror cell but also the rest of the telescope, in particular the centre section, the top ring and the secondary-mirror mounting.

To promote a free air flushing of the telescope, its instrumentation and surroundings, the design of the enclosure must include the option of generously large ports around the observing floor. Enabling adjustment and optimization of wind protection versus the benefits of free air passage, these ports must be constructed for flexible and easy operation. Further, given the special importance of the primary mirror, the design of the enclosure discussed has to be combined with a primary-mirror mounting leaving the mirror as exposed to the passing free air as possible. Such an arrangement necessarily requires a certain compromise in terms of mirror protection. However, with prudent operation of the telescope, the exposure of the primary mirror should not constitute any unacceptable risk factor.

In practice, a well-proven manner to approach the challenge discussed is to provide the enclosure with ports surrounding the observing floor. These ports should have generous dimensions. For a 3 m class telescope in a minimized enclosure, they should be around two meters high or higher, depending on enclosure design. To promote free air flow, the ports should be operated in an overlapping and/or collapsible manner. An alternative is to have the ports moving vertically. The latter option is, for most types of enclosures, more complicated in practical situations than often understood.

For larger telescopes and enclosures, hatches further up the sides of the enclosure may be helpful and even necessary, at least if ambitions are high concerning image quality. The corre-

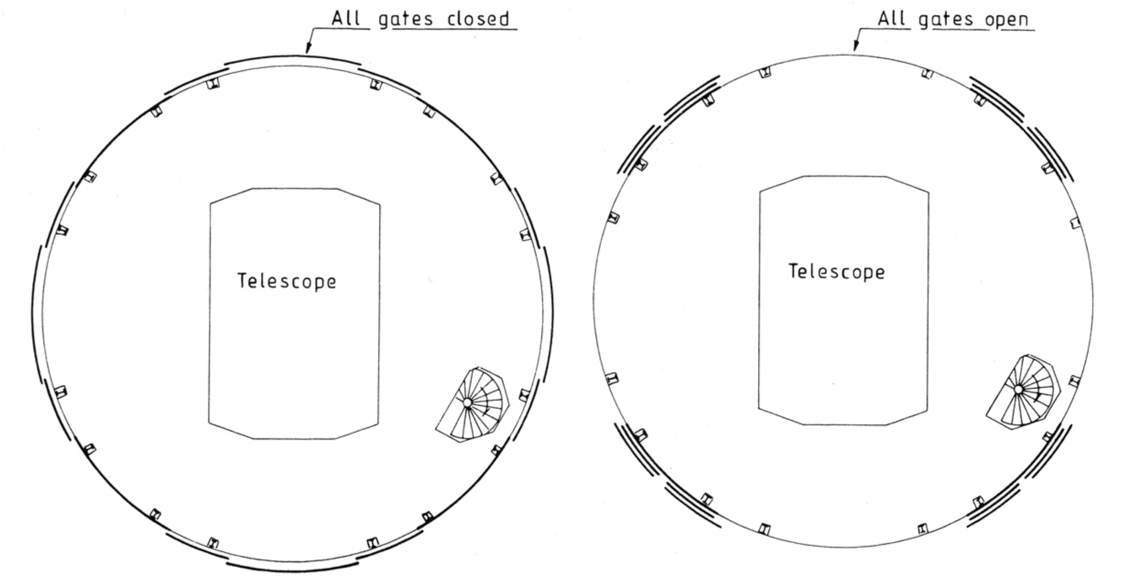


Figure 89. The approach to fully free air flushing of telescope and adhering facilities pioneered at the Nordic Optical Telescope. The maximum free opening around the observing floor is 240° and the mounting of the 2.6 m primary mirror is open (Ardeberg and Andersen, 1982).

Figure 90. An early concept of the enclosure of the Gran Telescopio Canareas with a 10 m primary mirror (Rutten, 1999).

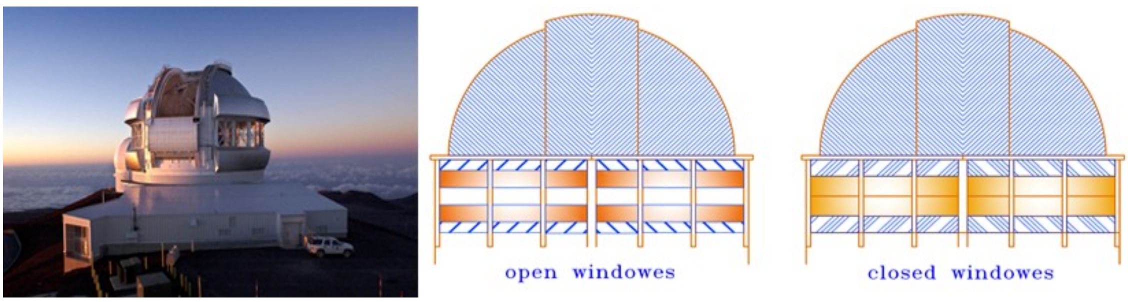


Figure 91. Vertically-sliding wind hatches on Gemini telescope enclosure .

sponding pre-construction assessment necessary should, preferably, make use of CFD modeling and simulations as well as wind-tunnel techniques and evaluation. Fig. 89 demonstrates an approach well tested and favorably assessed for a 2.6 m telescope. A concept for an enclosure of a 10 m telescope is shown in Fig. 90.

Temperature-gradient minimization

With regard to measures promoting high image quality, few precautions required are as important as decisive fighting of the sources of temperature gradients. These sources are both plentiful and hard to eliminate. Often, they have their origins in devices that are difficult or, often, impossible to exclude or exchange. Thus, before embarking on a project to minimize the accumulated influence of temperature gradients on image quality, the scope of the work approached should be fully realized. It will include special efforts not only in terms of design and construction but also concerning choice of components and, not to forget, restrictions regarding operation.

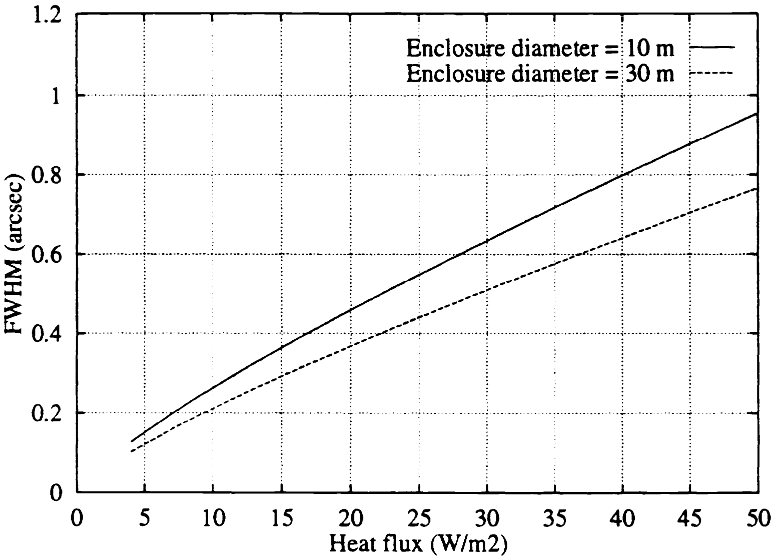


Figure 92. Relation between observing-floor heat flux and recorded image quality in terms of FWHM (L. Zago, 1997).

To minimize problems caused by temperature gradients, the basic rule is to follow a strategy aiming at maintaining, at all times, including day-time, the complete telescope and its instrumentation, the totality of the enclosure and all additional equipment therein at a temperature as close as possible to that of the approaching or running observing night. Concerning the enclosure, an important measure is to provide an outer shell, or cladding that reflects, in a maximized manner, day-time solar radiation. At the same time, it must not cause night-time observing-floor under-cooling. There are a number of materials and paintings more or less suitable for the purpose. At the same time, it is worth noting that aluminum is in general a rather acceptable and easily-managed choice.

While an efficient cladding is a necessary ingredient in temperature-gradient reduction, it is far from sufficient. It has to be accompanied by efficient enclosure-wall insulation. Heavy insulation is a relatively uncomplicated approach. More efficient is to mount the cladding at some distance from the supporting enclosure wall, thus creating an insulating air shell. Even more efficient is to circulate the air in this shell under thermal control.

A fundamental approach is to avoid, to the extent possible, all heat sources not absolutely required and to choose those necessary carefully for minimum heat production. In addition, unavoidable heat sources should, again to the extent possible, be thermally sealed and provided with thermal control. Excess heat should be ducted away, normally with some liquid agent. A closed heat-control system should transport excess heat to a heat exchanger. Release of the heat must be made in the prevailing off-wind direction and at a prudent distance from the telescope installation.

Even with solid thermal arrangements as described, the air in the telescope enclosure will, during day-time, rather regularly, heat up. Also in case of modest heating, the enclosed air volume will attain a slowly varying temperature structure with the temperature rising with height above the observing floor. This temperature stratification will impose itself also on the telescope resulting in a temperature gradient along its structure. In a similar manner, the enclosure will be affected.

A conceptually simple yet rather efficient measure to minimize day-time enclosure-air temperature stratification is to provide the inside volume of the enclosure with fans. These should be operated in a manner providing efficient air circulation inside the enclosure. The power and distribution of the fans should be decided following CFD modeling and simulation, at the same time as some over-sizing of the fanning system is recommendable. While the fans will improve temperature homogeneity, they will not be able to maintain the enclosure air at the observing-night free-air level. For this purpose, active air-temperature control must be applied, including ducting the excess heat away.

Many telescope installations have control and other facility space connected to the observing floor. The reasons are many, all of practical and economic nature. These facilities may be located either beside and/or below the observing floor. Whatever the case, adverse observing-floor temperature gradients are introduced, not least during night-time. With respect to thermal -gradient propagation, installations of control rooms or other higher-temperature facilities are especially disturbing if they are located below the observing floor. Thus, this scenario will be used to demonstrate an approach aiming at neutralization of the thermal gradients introduced.

In the absence of protective measures, a tempered facility below the observing floor will result in a heating of this floor. This, in turn, will provoke temperature gradients along and around the telescope. An efficient though not fully trivial counter-measure is to introduce a combination of a cooling-jacket around the tempered facility and a temperature-controlled false floor above it.

A pioneering installation of a combination of a cooling-jacket and a false floor as discussed was designed and constructed for the Nordic Optical Telescope (NOT) (Vernin, 2008). For this telescope, the control, electronics and machine rooms are placed below the observing floor in an enclosure building co-rotating with the telescope. These facilities are covered in a cooling jacket. The exterior, inside the cladding, is provided with generous insulation. Inside the insulation, the cooling jacket proper has forced circulation of temperature-stabilized air.

Below the observing floor, above the control, electronics and machine rooms, a false floor is installed. It is, like the cooling jacket proper, provided with air-temperature control and heavy air fanning. The observing floor is kept at a temperature slightly below that of ambient air. Included in the cooling-jacket installation is temperature control of the oil of the hydrostatic bearing of the telescope. Reference is made to Fig. 93.

The image-quality performance possible with the arrangements discussed is amply proven from the results provided with NOT. In passive mode, the regular image-quality distribution, expressed in terms of FWHM, showed a most frequent value of 0.60 arcsec and a limiting value of 0.30 arcsec. With active optics, the corresponding data are significantly better. Reference is made to Andersen et al. (1992), Ardeberg (1992) and Ardeberg and Andersen (1994). As later independent evaluation and assessments have shown (Vernin, 2008), a major reason for the high image quality is that the image degradation contributed through the enclosure is negligible.

In practice, experience seems to show that, with respect to the temperature of ambient air during observations, slight under-cooling of structural telescope and enclosure units is more favorable for image quality than slight over-heating. In any case, experimentally it seems demonstrated that, for optimum image quality, all temperature differences have to be kept below half a degree (Racine et al., 1991).

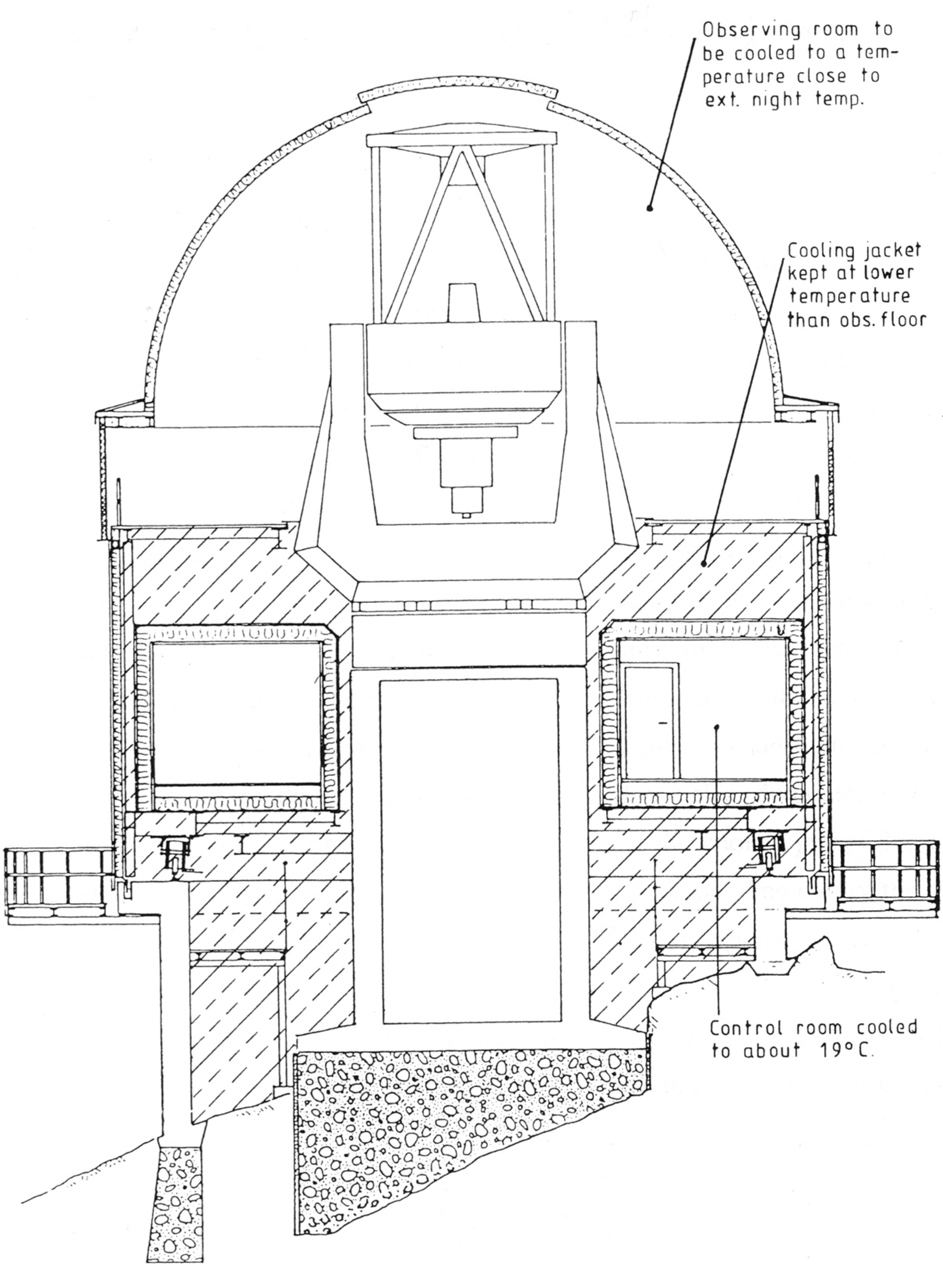


Figure 93. Cooling jacket and false floor below observing floor for NOT (Ardeberg and Andersen, 1982).

An observing floor of (thin) steel has many advantages. It is easy to handle, it is space saving and it has low thermal inertia. An essential part of the temperature-control arrangement is a distributed system of temperature sensors. Constant temperature monitoring is highly important as is real-time continuous corrective measures in a feed-back manner.

Excess heat and ducting

Normally, during observations, the cooling-jacket system will produce large amount of excess heat. The corresponding hot air has to be ducted away. A well-insulated air duct directs this air to a place at a safe distance, preferably of the order of 100 metres, from the telescope installation and in the prevailing down-wind direction. Here, the excess warm air should, preferably, be treated to a heat exchanger.

In the heat exchanger, the warm air is removed and replaced with cool, fresh air. Letting the warm air escape directly is simple but not a good idea. First, it might, in case of unfavourable wind conditions, find its way back to the telescope, causing added air turbulence. From all points of view, a positive use of the warm air is a bonus. A good use of the excess heat is to blow it into a support building, otherwise heated by other means.

Laminar air flow

One of the primary qualities of a site favourable for observations with high image quality at visible and adjacent wavelengths is a high degree of undisturbed laminar air flow, preferably also at higher wind speeds. While a solid site evaluation should take care of a correct site choice, it is of fundamental importance that the natural laminar air flow is not corrupted by an inadequately designed enclosure. To safeguard an enclosure design with these considerations in mind, a number of criteria have to be included.

The intrinsic air flow must, as far as possible, be able to pass unhindered through the building. This requirement is, in itself, highly coupled to the demand on free air flushing. However, the incoming air should not only be allowed to stream over the telescope and other installations in the enclosure in a manner as efficient as possible. It should, on its way in the enclosure, meet as few and reduced obstacles as possible. Confronting constructions will, to higher or lower extent, produce mechanical and thermal effects harmful to corresponding essential homogeneities.

While the telescope and its instrumentation are unavoidable flow obstructions, they should be designed and mounted to be as flow transparent as possible. All other installations in the enclosure should be kept to an absolute minimum. They should not only be few in number, they should also be as temperature neutral as possible.

All sorts of compressions of the air flow are detrimental to the image quality. Thus, it is essential to maintain exit openings of a size corresponding to those of entrance openings. This balance should be independent of observing direction, a requirement most naturally, even if not only, supported by a symmetric opening architecture. Worst of all in this context are effects of air trapping and capturing. In all respects discussed, CFD modeling and simulations as well as wind-tunnel testing are highly helpful supports towards an adequate enclosure design.

Observing at non-optimum wind speed

The wind speed during observations is a parameter of large importance for the results of the work undertaken. Potentially and often very much in practice, it influences the observations in terms of efficiency, flexibility and quality. While a modest wind speed is an ideal and the lowest wind-speed regime is largely unproblematic, for the sake of optimum output of the telescope facility, arrangements must be made to allow successful observing work also at wind speeds exceeding the ideal ones. Clearly, the aim must be not only observations as such but observations as independent from wind-speed conditions as possible.

An easy way to avoid adverse wind effects in case of strong wind but still pursue observing is to avoid observations into the wind direction. As this is not always the best of solutions, arrangements should be made to allow observations also in or close to the direction of the wind, at the same time as excessive wind speeds must lead to closing of the enclosure. While arrangements for observations into hard winds should be used only when needed, they should always be available.

For a 3 m class telescope, it should, without significantly negative effects, be possible to observe into the wind direction with wind strengths up to around 15 m/s. Off-wind observing should be possible in wind speeds up to approximately 20 m/s. When the wind speed exceeds 20 m/s, normally, all observing activities, even down-wind, should be halted. Corresponding real-world limiting wind speed should be based on CFD and wind-tunnel trials and may well differ notably from those here quoted.

A straightforward manner to decrease the adverse impact of high wind speeds is to equip the enclosure with not only an observing slit or a similar opening but also with wind screens or hatches, the function of which is to decrease the size of the total observing window, These screens can be either fully covering or be semi-transparent to the wind.

A wind-screen arrangement against adverse effects of strong winds should, normally, define an observing opening as small as possible to provide optimum protection against wind, yet be large enough not to interfere with the observations, photometric observations being especially vulnerable to such interference. In itself, a fully covering wind screen might be regarded as an ideal wind breaker. However, with such a wind screen, it is hard, if at all possible, to avoid edge effects and air compression resulting in additional air turbulence.

A more adequate solution is often a wind screen that is semi-transparent to the wind flow (Fig.94). The wind will be filtered, its force will be diminished and its action as a

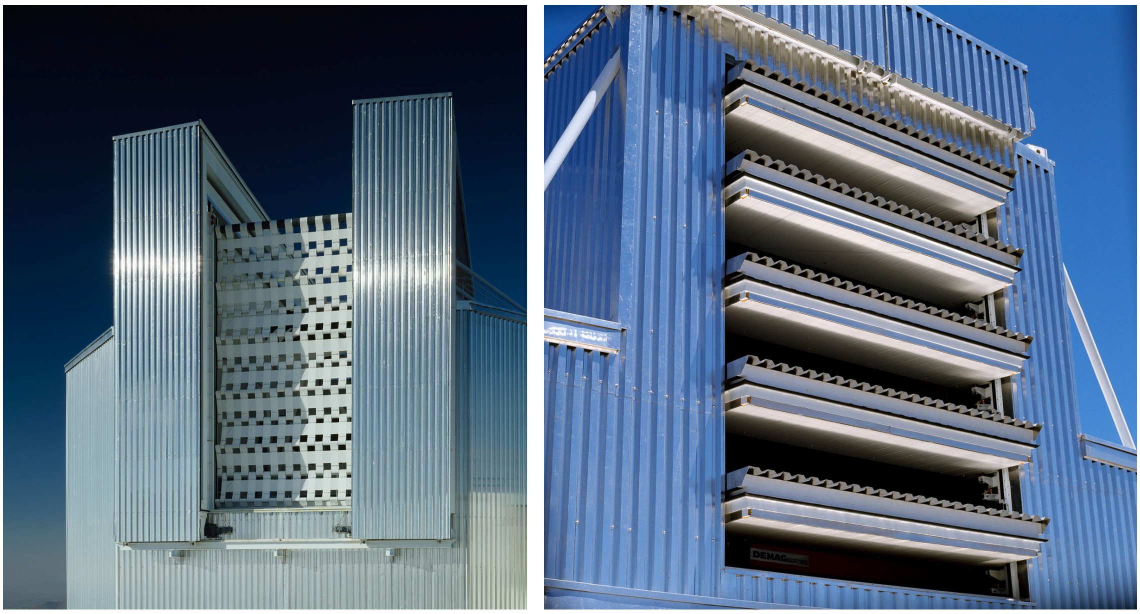


Figure 94. one of a full wind screen, another of a wind-transparent wind screen (photo courtesy ESO NTT).

source of additional air turbulence will be diminished. In favorable circumstances, a semi-transparent wind screen, structured in the form of a venetian blind, can rather successfully maintain a stable, laminar air flow.

Support for telescope and instrumentation handling activities

An important part of the function of the enclosure is to provide support facilities for the handling of the telescope, its parts and its instrumentation. It should do so in off-observing mode but also during observations. For this reason, the enclosure should be equipped with a number of facilities facilitating a range of telescope and instrumentation handling activities. At the same time, it is essential to limit the amount of devices installed in the enclosure in order to preserve best observing conditions. In general, this concerns thermal inertia and local air turbulence. However, care must also be taken not to create too much equipment contributing to background emission in the near infrared, if and when observations in this wavelength range are contemplated.

A fundamental requirement regarding the enclosure is that it does not cause unnecessary delays in terms of telescope movements, tracking and, not least, slewing. While enclosure problems concerning object tracking in practice should be, and are, few, those affecting rapid change of observing direction are, often, rather pronounced. Whatever the targets for the telescope in terms of its acceleration, slewing and deceleration abilities, the enclosure must, not to cause unnecessary inefficiency, be able to follow the telescope in its movements. If it doesn't, its design and construction are simply not fully compatible with those of the telescope.

Most enclosures of conventional telescopes have adjustable, moveable observing floors. Often, these floors are divided in two parts, individually moveable in height. In a number of ways, this is a very practical and helpful arrangement. It provides a convenient support for observing-night activities around the telescope. It offers practical assistance for exchange of auxiliary instrumentation, and it gives improved access to telescope parts and instrumentation during maintenance work.

At the same time, an observing floor with individually moveable parts involves a range of serious problems. It can, if not cautiously handled, lead to collisions with the telescope and its instrumentation, collisions that can be very serious. Moreover, a divided observing floor, the parts of which are moved individually, is a safety hazard for staff, not least during night-time. Thus, while such an observing floor undeniably provides a number of advantages, these advantages should be seriously compared to the risks involved.

Nearly all conventional as well as many modern telescope enclosures are equipped with one or more cranes. These are intended for handling of both telescope parts and instrumentation. Essential examples of such handling concerns the primary mirror, for example in connection with realuminisation, and the secondary mirror but also other parts of the opto-mechanical telescope structure. In addition, enclosure cranes are practical devices when instrumentation is exchanged or modified.

Negative aspects of cranes regard their installation and need for extra space, thus causing increased telescope enclosures, additional local turbulent air and increased enclosure costs. Further, for observations in the infrared part of the spectrum, cranes create additional background radiation and noise.

A viable alternative, replacing enclosure-installed cranes, is adoption of moveable lifting devices, motorized or fully manually handled. Such devices can be tailor-made to provide optimum support of telescope and instrumentation exchange and operation.

Optimum size of the telescope enclosure

It is easy to mention an optimum size of a telescope enclosure. It is much harder to provide corresponding measures, and especially so in a more general sense. For many practical purposes, for instance removing and replacing the primary mirror, changing auxiliary instrumentation, servicing the telescope and changing focal station, an enclosure with generous space is highly positive. On the other hand, the same, generously large, enclosure will imply a number of less advantageous characteristics. In particular, an enclosure with large size is, generally, more prone to generate internal air turbulence, or enclosure seeing. In addition, a large-sized telescope enclosure means a heavy and expensive building.

Clearly, a telescope enclosure with a size minimization causing every-day problems due to an excessively squeezed volume and corresponding handling difficulties should be avoided. On the other hand, there is little reason paying for an over-sized enclosure prone to destroy image quality. From all points of view, it is an excellent investment of time and effort to make an exhaustive inventory of all needs, immediate and foreseen, for space inside the telescope enclosure and, based on this inventory, design an enclosure spacious enough but not more (Fig. 95). The only trouble remaining is that this is a one-time choice with highly limited possibilities for practically realized second thoughts.

Sizing the telescope enclosure, it is essential to take future developments into account. Such developments may include additional and modified focal-station platforms. They may also be concerned with new, space-requiring instrumentation. At any rate, design and construction should be made in a manner allowing future experimental use of the telescope facility.

Figure 95. The CFHT telescope enclosure (right) comparing to the ESO NTT telescope enclosure (left). Both telescopes have a 3.6 meter primary mirror but there is a special concern in NTT design for minimizing enclosure inside air volume and at the same time providing enough space for service and maintenance.

Compatibility with local topography

Arguments have, above, been forwarded for proper, well-founded selections of telescope site and sub-site as well as the design of the telescope enclosure. Site, sub-site and enclosure being chosen and designed with due care, it seems a most natural precaution to take a further step in the direction of optimum compatibility between the (sub-)site of the telescope and its enclosure. This is a rather rewarding path towards full benefits of both a (sub-)site well selected and an enclosure well designed and constructed.

In general terms, the telescope enclosure should, as well as possible, fit into the local positioning of the telescope is an essential matter, some remodeling of the local observatory ground may provide considerable additional benefits. The enclosure should effect the passing air as little as possible, not least with regard to the ground-layer air flow and the corresponding pattern of ground-near air turbulence. While these intentions might be difficult to convert into reality in all circumstances, they should at least be seriously attempted regarding prevailing wind conditions. All the time, it should be endeavored to take optimum advantage of the best local natural laminar air flow in the direction of prevailing winds. A good example should be the NOT site (Fig. 96).

Efforts should be taken to achieve minimum effects of upwards air flow caused by the telescope enclosure. The wind flow should stream around the enclosure rather than climb it and, eventually reach into it and the observing floor. This may be relatively easy to achieve in case of weak or modest ground-layer turbulence, but be highly challenging when ground-layer turbulence is strong.

Figure 96. The NOT enclosure on Roque de los Muchachos (photo A. Ardeberg) .

While it is rather natural to attach highest priority to the turbulence regime affecting the telescope under development, other telescope installations, existing, under construction, designed, planned or contemplated, other telescope facilities should not be mentioned. Not least should lee-way effects be taken into account and minimized as long as possible.

In all planning of optimum compatibility between local site topography and the telescope enclosure, the prevailing wind-rose pattern should be taken into account. In addition, it is more than wise to use CFD modeling and simulation for the purposes discussed. Also, it may be helpful to make a comparative study with the help of wind-tunnel testing. In the latter cases, modeling and simulation should include both the telescope enclosure and a generously large part of the surrounding site, not least in the direction of the prevailing wind.

Promotion of safety

Naturally, installation of a telescope facility must be guided by efforts to secure observations of a quality as high as possible. Still, safety, of staff and visitors alike, must be an absolute concern. Thus, all design and construction work must be carefully screened for safety risks and hazards. Among the measures to be taken to promote optimum safety is a concept allowing safe and speedy exit from all parts of the enclosure in all foreseeable cases of emergency. In addition, if a fully co-rotating enclosure is chosen, safe entry and exit must, in all positions of the enclosure building, be guaranteed.

All risks of packed snow and ice falling from the enclosure onto staff and visitors must, to the extent possible, be avoided. As a whole, a thorough strategy concerning how to handle loads of ice and snow on the telescope building must be developed. In addition to promoting safety, such a strategy might also minimize the number of observing nights lost due to loads of snow and ice on the enclosure. The all candidate sites for INO340 telescope have a long winter with a lot of snow that can introduce dangers and difficulties for observers (Fig. 97).

Figure 97. picture shows remain snows on Bordu tops (one of candidate sites for INO340 Telescope) at the late of spring (photo A. Daroudi).

Mode and speed of rotation of telescope enclosure

In a traditional telescope enclosure, the observing floor and the corresponding walls are fixed, while the upper part, the dome, revolves with the telescope, either individually or in a slaved version. This type of arrangement has several advantages. As the moving part of the enclosure is relatively light, at least compared with the complete enclosure building, bearings and motors can be more modest than in the case the enclosure rotates in its entirety with the telescope. A fixed main part of the enclosure building means fixed entrances, implying safety precautions easier to handle, and simpler access-road arrangements. Also, a non-moveable main enclosure structure makes the over-all building design and construction easier and more economic.

In a co-rotating telescope enclosure, everything co-rotates with the telescope, including observing floor and, often motor electronics and control rooms below the observing floor. This implies a number of advantages relative to the case of a traditional enclosure with rotation of the upper dome only. A prime advantage is connected to free air flushing of the primary mirror.

If the entire enclosure rotates with the telescope, the orientation of all ports, hatches and other arrangements for free air flow at all times maintains its orientation with the telescope. If the openings constitute a major part of the walls, this is a convenient arrangement. When the enclosure openings are more reduced in size, a fixed enclosure may, on the other hand, provide easier means for adjustment of the opening strategy to that of the prevailing wind direction.

The rotation speed reachable with the telescope enclosure has a number of implications. The higher the maximum speed of the enclosure, the smaller are the losses of observing time resulting from lag time in the process of co-ordination of the position of the enclosure with that of the telescope. In this respect, it is essential to consider the effect of acceleration and deceleration, which, for obvious reasons, normally will tend to differ between the telescope and the enclosure. In addition, corresponding speed requirements are due for the movements of enclosure ports and hatches.

For most type of observing programs, requirements of rotation speed of the enclosure, as well as of the telescope, are, in a general sense, reasonably easy to meet. However, there are some modes of observing that call for high-speed pointing and, thus, special arrangements in terms of rotations speed. An example is target-of-opportunity observations of objects with γ-ray bursts. With this and some similar programs, a key requirement is, upon alert, an immediate break of observations in process, followed by pointing of the target-of-opportunity object as quickly as possible. It is, again, emphasized that, in practice, for successful target-of-opportunity observations, requirements on rotation speed as well as on acceleration and deceleration are very large and may well be in conflict with general design priorities defined by more regular observing programs.

Enclosure concepts

Telescope enclosures, not least modern ones, tend to have rather diversified designs. In general, they may be divided into four main categories. These types can be labeled classical, co-rotating, collapsible and retractable. Each of the different enclosure types has advantages as well as disadvantages of its own. The degree of these largely depend on the telescope enclosed and the priorities attached to its use.

Classical telescope enclosures

A classical telescope enclosure has a cylindrical lower part and a dome-shaped upper part. The lower part, with observing floor and walls, is fixed. The upper part, the dome, is rotatable and provided with an observing slit covered by shutters moving in the azimuth direction. Often, the slit is equipped with one or two hatches, moving perpendicular to it. In case hatches are available, they are normally parked, fully down or up, when wind conditions are benign, while they are used to decrease the wind interface area when wind speeds are high, and especially so when observations are made in or close to the up-wind direction. Some semi-classical enclosures feature observing slits covered by one or two hatch(es) only.

Classical telescope enclosures provide some clear advantages compared to other types of enclosures. The former are normally of generous dimensions. This is partly due to the fact that they enclose telescopes the primary-mirror focal ratio of which is in the order of f/5. However, the large size also reflects a wish for practical possibilities for handling of telescope parts and the instrumentation. The telescope can, often with rather large margin, be rotated inside its enclosure, and maintenance is not space limited. Cranes and lifting devices are given ample space.

The price to be paid for the generous space and favourable work conditions inside classical telescope enclosures is twofold. First, a large enclosure means a heavy enclosure and, thus, an expensive enclosure. Second, a large enclosure encloses a large air volume. Consequently, maintaining the day-time temperature of all the enclosed air around the telescope at the same temperature, and reasonable close to the temperature of the night following, is a demanding challenge. In addition, maintaining a laminar air flow and free air flushing around and of the telescope during observations are tasks made complicated because of the large air volume to be handled and controlled. Further, cabling is an obvious problem, although a problem with a diversity of solutions designed for necessity, often with remarkable success. Fig. 98 shows a classical telescope enclosure with a large and heavy foundation.

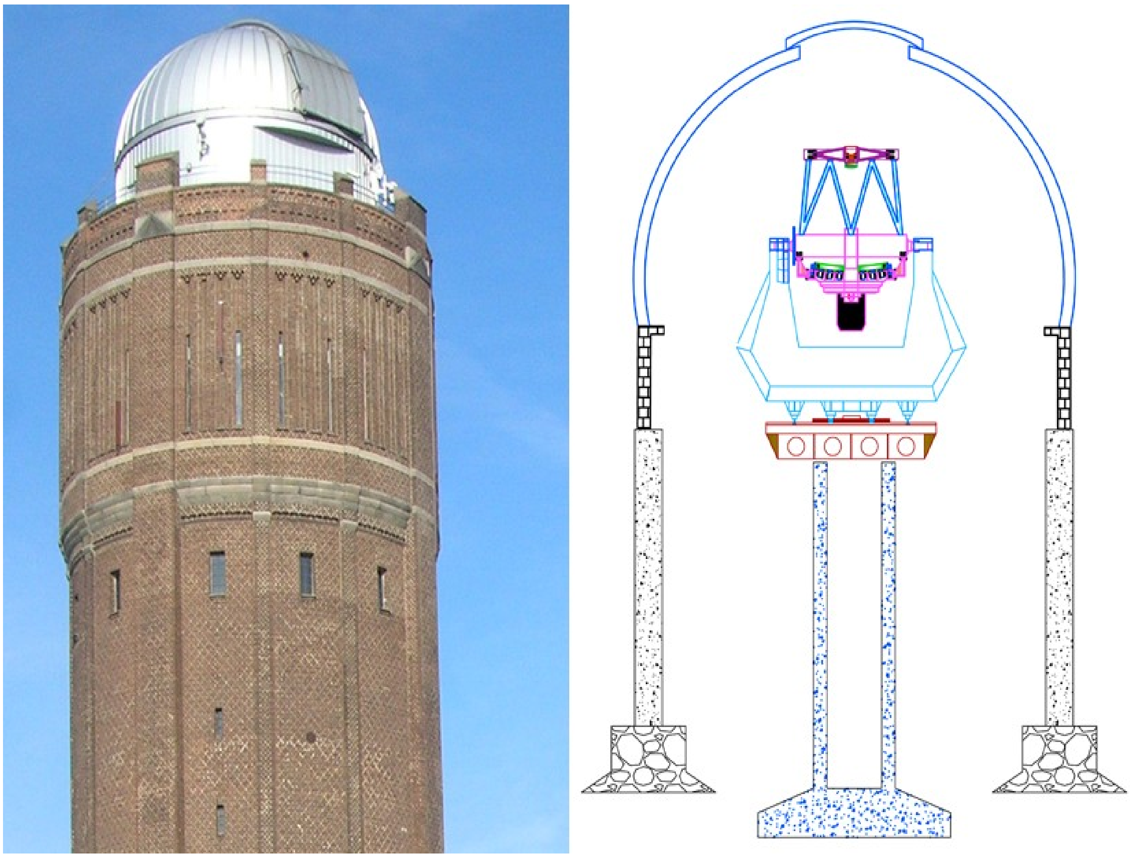


Figure 98. Lund Observatory 1.5 m telescope in a classical enclosure atop a tower.

Telescope enclosures co-rotating with the telescopes enclosed

A variation of the classical telescope enclosure features co-rotation with the telescope. The entire enclosure, from observing floor to its upper parts are rotated with the telescope. Sometimes, although not always, also control, motor and electronics rooms below the observing floor share this rotation.

In principle, a co-rotating enclosure could also be an enclosure of large dimensions. In practice, this is, however, not exactly attractive, as a heavy, rotating enclosure, in addition to a large volume of enclosed air, implies demanding investment as well as large demands on functionality. Thus, co-rotating enclosures are normally relatively compactly designed and light-weighted constructions.

At the price of a necessity for squeezed-space operation and maintenance, co-rotation of the enclosure has some advantages. An obvious benefit is the simplicity of cabling. Not least, does this simplify tentative experimental configurations of auxiliary instrumentation. Also, it is much easier to minimize the size of a co-rotating building than that of a fixed structure, as there is no, or at least more limited, need for consideration of free telescope movement in the enclosure. The freedom for installations of instrumentation and other devices is considerably increased. In case the co-rotating building includes control, motor and electronics rooms, these advantages are further enhanced.

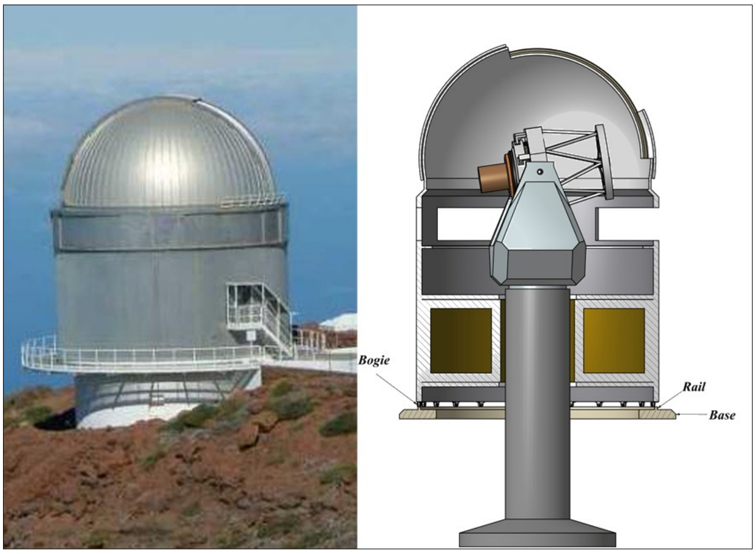


Figure 99. Left, NOT has a co-rotating enclosure. Right image, A simple cross-section view from a typical symmetric co-rotating enclosure, NOT type, illustrated.

At the same time as internal cabling is favored in an enclosure co-rotating with the telescope, corresponding external connections are made more complicated. A co-rotation including control, motor and electronics rooms solves some of the problems resulting, while electricity connections and air ducting demand special solutions.

While classical fixed enclosures have to be symmetric or at least close to symmetric, this is not the case for co-rotating enclosures. These enclosures may be circular, elliptical or box-shaped with a large freedom of design options. This allows constructions minimizing costs of investment as well as of the amount of air enclosed. Fig. 100 shows an example.

Figure 100. Telescopio Nazionale Galileo, right and NTT , left (showing asymmetric enclosure and space minimization).

Collapsible telescope enclosures

As discussed above, a telescope aimed for highest possible image quality should be optimum treated to temperature equilibrium and free air flushing. Both these requirements are to a high degree satisfied if the telescope is freely exposed to ambient air and to wind action. Such an exposure of the telescope can be achieved if it is placed in an enclosure that is collapsible.

Well before a night of observations start, the collapsible enclosure is unfolded, leaving the telescope without protection. During day-time and in general when the telescope is not in use, the collapsible enclosure, now in its closed version, should assume the same functions as a traditional enclosure. A version of a collapsible enclosure is illustrated in Fig. 99.

Obviously, the collapsible enclosure has a number of attractive features with respect to thermal equilibrium, removal of surface turbulence and resulting image quality. At the same time, a telescope working unprotected implies an increased risk factor with regard to wind shaking and dust impact as well as to influence of unwanted light sources, celestial and artificial alike. Further, arrangements around the telescope, for auxiliary instrumentation and other pieces of equipment, requires somewhat special planning if housed in a collapsible telescope enclosure.

Achieving a high degree of functional safety for a collapsible enclosure is, normally, not a trivial undertaking. In a collapsed position, difficulties can be seen as manageable. When the enclosure is in its closed version, however, high stability in case of harsh weather conditions has its price. Technically viable, corresponding arrangements easily result expensive.

Of special concern are measures guaranteeing that the enclosure rapidly and safely can be converted from collapsed to closed in case of rapid deterioration of weather conditions, not least in the case of hard wind. The degree of complexity in this context depends, to a large degree, on the size of the telescope to be enclosed. In this respect, wind forces are prime causes of concern.

Figure 101. Faulkes telescope uses Collapsible enclosure.

Retractable telescope enclosures

In many respects, a retractable telescope enclosure offers advantages similar, if not equal, to a collapsible enclosure. The scene is set for free air flushing of the telescope as well as thermal equilibrium around it. At the same time, operation of a large retractable enclosure implies a number of difficulties. As for collapsible enclosures, timely positioning and closing of a retractable telescope enclosure is a challenge, and especially so in case of large sizes. Example of retractable enclosures is shown in Fig. 102.

Figure 102. The SDSS telescope and its retractable enclosure. Left photo shows the telescope on day time and right during the observation (photo Princeton University).

Architecture of telescope enclosures

From the beginning of the twentieth century, all enclosures of major telescopes had a rather similar over-all architecture. Centered around the telescope, they had a lower, fixed, cylindrical bas, and a hemispherical rotatable upper part, the dome. The dome had a large slit for observations, equipped with side-moving doors. Fig. 103 shows two well-known enclosures of this époque.

Figure 103. The enclosures of the Hale 5-m telescope (left) and the Special Astrophysical Observatory 6-m telescope (right).

Later, and especially towards the end of the twentieth century, the architecture of telescope enclosures gradually got rather diversified. While matters related to internal air turbulence were important, considerations of cost were prime drivers. Many enclosures are, thus, both minimized and remarkably asymmetric. This can be seen in Fig. 104.

Minimizing an enclosure often means making it asymmetric. This is, in itself, positive. On the other hand, asymmetric telescope enclosures have, compared to symmetrical classical enclosures, a number of more or less pronounced weaknesses. They complicate maintenance of over-all site laminar air flow, producing strong and, especially in the case of large buildings, far-reaching down-wind turbulence vortices. They tend to drive approaching air more upwards then symmetric enclosures do. Compared to their symmetrical counterparts, asymmetric telescope enclosures often cause larger wind-pressure and snow-load problems.

Figure 104. Some telescopes with asymmetric enclosures. LBT at left, DCT at middle, and Subaru telescope at right.

On shutters and hatches

Shutters in the sense of doors or covers facilitating sealing and opening the observing slit of the telescope enclosure are entities with impact on observational safety and flexibility as well as on total installation budget. In addition, they are units not fully simple neither to design and construct nor to maintain and serve in an optimum manner. Thus, the concept, design and construction of shutters have to be given thorough consideration.

Whatever the concept chosen, normally, the observing slit available has to cover an interval in height above the horizon stretching from typically 15 or 20 degrees to at least 100 degrees, preferably more, the latter limit depending on the rotation speed of the enclosure with respect to that of the telescope. The width of the full opening should, for an enclosure not co-rotating with the telescope, in all observing positions, allow at least twenty to thirty minutes of telescope tracking without change of the enclosure position. For an enclosure co-rotating with the telescope, the slit could be less wide while still permitting at least fifteen minutes of telescope tracking without modification of the position of the enclosure.

The more traditional approach is to design the enclosure shutters as two horizontally-moving sliding doors with a contour close to equal to that of the enclosure, whether dome- or box-shaped. Their design and construction can benefit from a large body of experience from many projects. However, inherently, they include some operational disadvantages. They tend to be heavy and in need of rather solid sliding arrangements, all of which is cost driving. They have considerable wind-catching problems making their design even more cost driving. They are not trivial to seal. The latter problem concerns both rain and snow loading, and not least extra problems with low temperatures, as well as dust storms. Finally, the interface between the shutters and the enclosure body may well drive air turbulence.

A more modern, although not exclusively so, approach for dome-like buildings is to design the enclosure-slit shutters, or hatches, as structures moving along the slit. Such a shutter may either be designed as a single unit covering the total slit, or around at least 80 to 85 degrees along its path, or be composed of two, or even three, subunits. When moved to open the observing slit, the hatches may move either fully backwards or partly so and partly forwards. In both cases, care has to be taken, not least concerning the hatches moving down from the dome-like upper enclosure structure to its lower part.

A dominating sliding shutter part may also be combined with a lower part opening around a horizontal hinge. The latter option may seem attractive for installations driven by wishes to observe also close to the horizon. At the same time, such a solution may well be non-ideal in case of stronger wind. One solution of this dilemma is to give high attention to the part of the hatch hinged. Another solution is to maintain the possibility of observations close to the horizon but for benign wind conditions only.

For many reasons, it may be attractive to combine horizontally moving shutters, or doors, with vertically moving hatches. The main advantage of such a solution is the possibility to decrease the area of the observing slit. This may be especially attractive in case of high wind speed. More comments on the advantages and disadvantages incurred are offered above under the heading “Observing at non-optimum wind speed”. Some shutter and hatch arrangements as discussed are illustrated in figs. 104, 105, and 106.

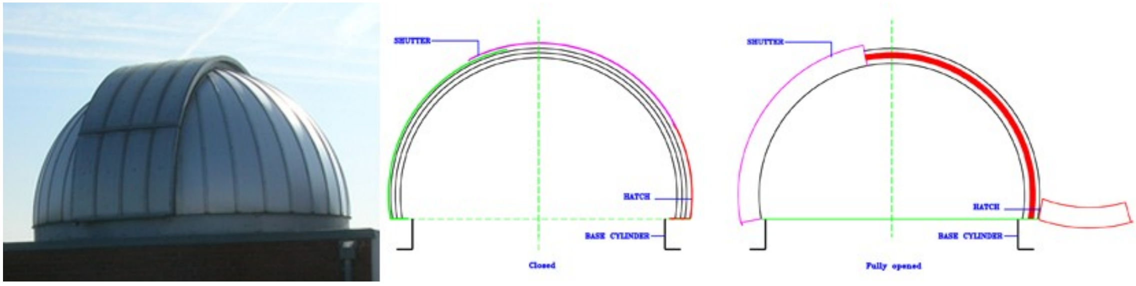


Figure 104. Concepts of enclosure hatches sliding backwards.

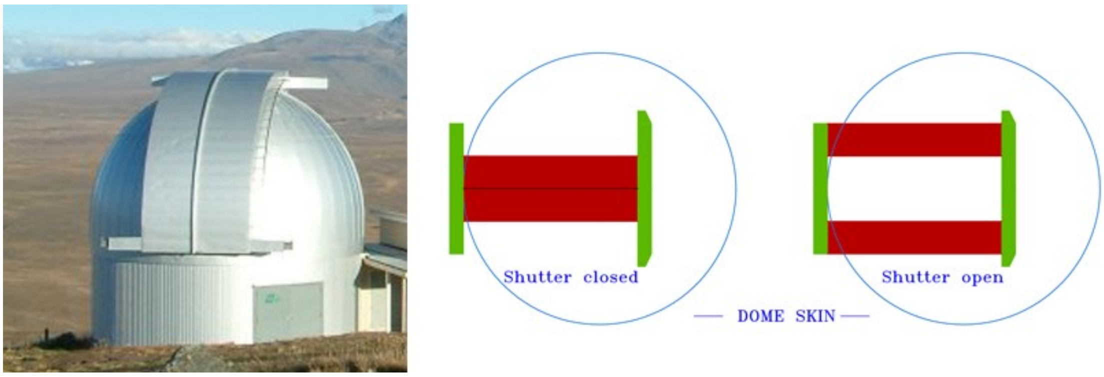


Figure 105. Concepts of enclosure shutters moving horizontally. To the left an image of the Mount John Observatory dome for its 1.8 m telescope, Lake Tekapo, Victoria, New Zealand.

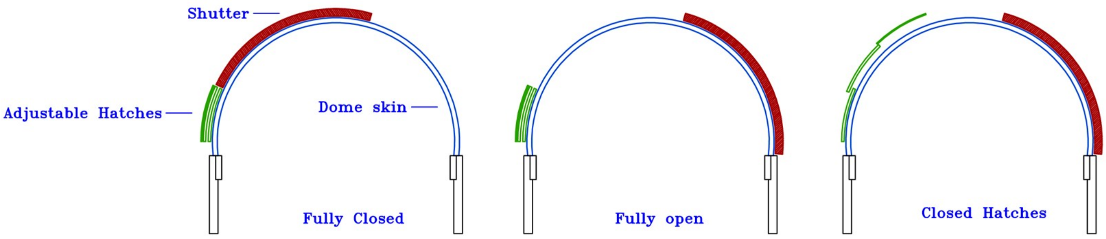


Figure 106. Concept of a multiple-element adjustable enclosure hatch system as used with the Gemini telescope enclosure.

Enclosure foundation

Once the sub-site location of a telescope facility has been chosen, the foundations of both the telescope and the enclosure have to be decided. Except for a natural wish to have both these foundations generally stable and solid and, in earthquake-hit locations, resisting also strong quake activity, we are concerned with at least two important issues regarding the foundation of the telescope enclosure. First, it should be optimally separated from the foundation of the telescope, in order not to influence the stability of the telescope. Second, it should, as far as possible be installed such that the observing floor is situated safely above prevailing ground-layer air turbulence. This will be discussed below, while strategies concerning the foundation of the telescope are addressed elsewhere in this paper.

A recommendable procedure is to, before decisions regarding the foundations of telescope and enclosure, have a thorough geotechnical assessment of the sub-site ground. Normally, this can be achieved through a matrix of drillings to a depth of several meters. The drilling samples, several in number, are then analyzed for strength, stability and damping signatures. Ideally, the foundation of the enclosure can achieve sufficient strength and stability while, at the same time, vibrations caused by enclosure movements are adequately damped before reaching the foundation of the telescope. If that is not the case, actions have to be taken to structure the enclosure foundation in a manner compensating for site short-comings in the site soil quality as discussed.

Concerning vibrations transferred to the telescope, effects of special seriousness can be expected if the influence coincides with a prominent natural frequency of the telescope. Such a coincidence has to be avoided. There are two efficient counter-actions. First, damping between the foundations of the enclosure and the telescope has to be optimized. Second, preparations should be made allowing modification of the frequency spectrum of the telescope foundation. One way to achieve this is to arrange for a possibility to add mass to the foundation. Easy injection of additional concrete is such a possibility.

Regarding the height above ground of the observing floor, solid site-evaluation data are of utmost importance. Of special value are data on microthermal activity as a function of height above local ground level, with special emphasis on data obtained between dusk and dawn. A dedicated site-evaluation procedure followed by thorough assessment of the data is a highly recommendable investment. Corresponding measurements and their assessment are discussed elsewhere in this paper.

Even a minimum height of the observing floor above local ground level still means a certain and larger corresponding height of the prime actor, the primary mirror of the telescope. For the latter height, a minimum is defined by the design and construction of the telescope and its foundation. In the case of a 3 m class telescope, the light-collecting surface of the primary mirror can hardly, when the telescope is in zenith position, be closer to ground level than around, or close to, five meters, as can be concluded from the chapters of this paper dedicated to the telescope design. In practice though, depending on data observed for microthermal activity close to local ground, this may well be too close to the ground as seen from an image-quality point of view.

If, but only if, ground-layer turbulence is clearly shown to be very weak, a minimum height of the observing floor, as discussed above, should be considered. Even in this case, a conservative approach is recommendable, as site-activity developments can well act to raise the microthermal activity of the ground-level, while hardly decreasing it. In the case of a 3 m class telescope, choosing a height of the observing floor smaller than six meters above local ground level is a daring, if not more than that, decision. In practice, the observing-floor height above local ground should be chosen so as to avoid as much as possible the excess air turbulence caused by dusk-to-dawn ground-layer activity. Even in rather excellent sites, this excess nightly turbulence normally reaches several meters above ground. For sub-sites with considerable internal differences in ground level, the corresponding situation may well be more complicated, calling for dedicated ad hoc treatment.

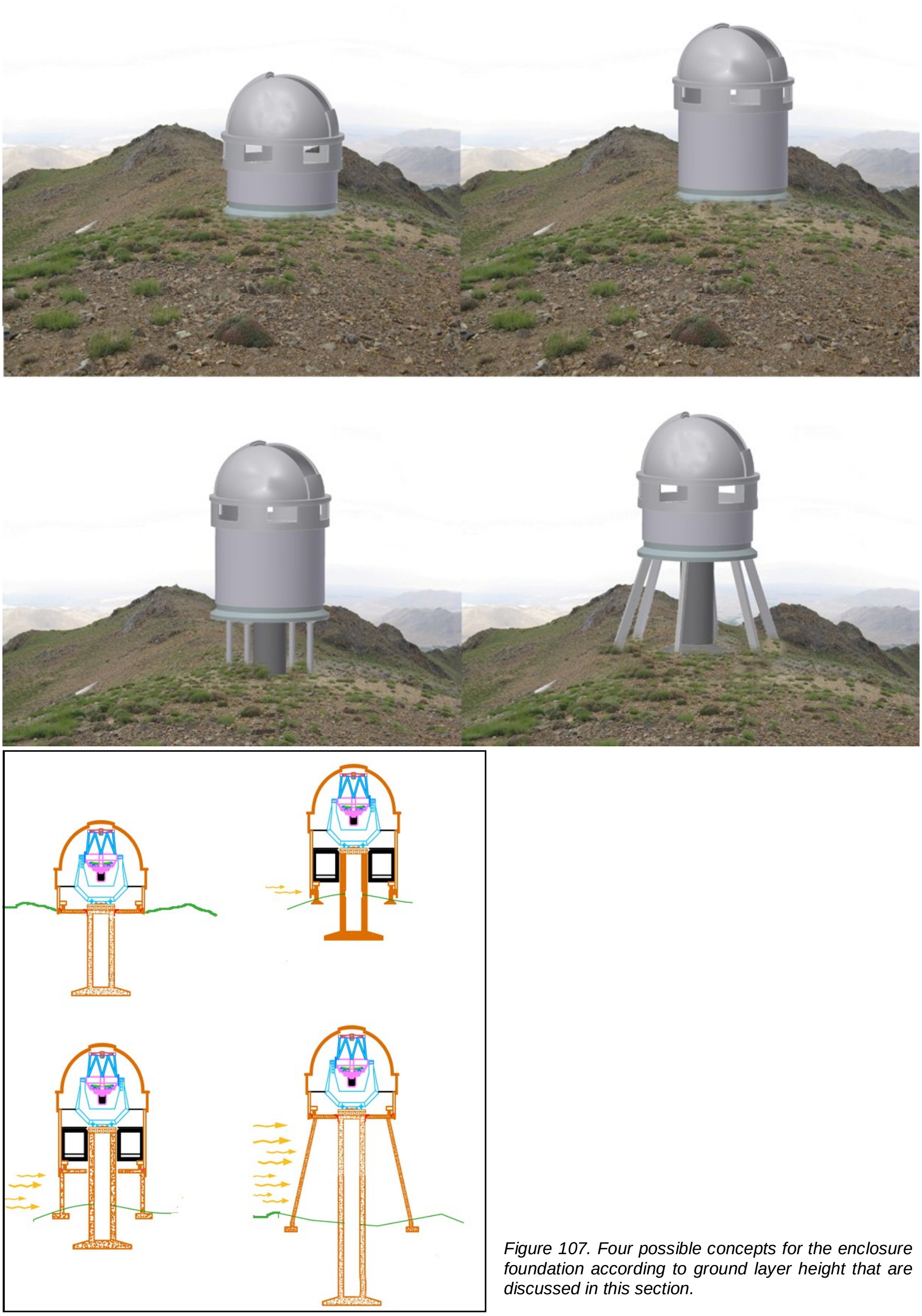


Figure 107. Four possible concepts for the enclosure foundation according to ground layer height that are discussed in this section.

If a small height of the observing floor above local ground level is chosen, location of rooms for observing, electronics and motors below this floor is, in practice, excluded, as it requires part of these facilities to be below ground level. Only if the observing floor is located more than around seven meters above ground can such a concept be regarded as attractive and fully viable. As before, sub-sites with large internal ground level variations have to be treated with special care.

Raising a telescope facility several meters above local ground level is a positive measure in terms of image quality. At the same time, however, it affects the project budget. While a large difference between the heights of the observing floor and local ground is in itself a cost driver, it also implies special arrangements regarding access. Thus, corresponding decisions have to be made on a basis as solid as possible.

Providing prudent measures are taken to ensure efficient minimization of unfavorable temperature gradients, requirements on minimum influence of ground-level turbulence can be combined with demands on budget restrictions through an enclosure concept including location of observing, electronics and motor facilities below the observing floor. Such issues have been discussed above under heading “Temperature-gradient minimization”.

Highly prudent in terms of measures to promote high image quality is to use a base of pillars to raise the observing floor well above ground level. A pillar-based enclosure has three immediate advantages. First, it lifts the observing floor well above ground level. Second, it lets the turbulent ground-layer air stream pass largely unobstructed, implying minimum upwards forcing of the turbulent air. Third, it causes minimum leeward vortex effects, thus causing minimum adverse implications for other telescope installations located in the down-wind direction. Pillars and observing electronics and motor rooms located below the observing floor may also be combined for additional height of the observing floor above ground level. Again, at the same time, such installations are cost driving.

In some locations, the soil is rather soft. This calls for special measures concerning the foundation of the telescope enclosure. A solution can be to use a cushion-type base layer to support the enclosure. A soft soil provides, normally, favorable damping of potential influence of enclosure vibrations on the telescope.

Bearings for rotating enclosure

For an enclosure co-rotating with the telescope, requirements on the bearings are high albeit not as high as for the telescope. An adequate solution is to use bogies on rails. The load is carried by three, possibly four, symmetrically distributed bogies. Each bogie should have (at least) three wheels. Reference is made to figure 108. Two of these wheels carry the main load and provide azimuth rotation of the enclosure, while the third wheel takes up radial forces caused by the enclosure itself but also by influence of winds.

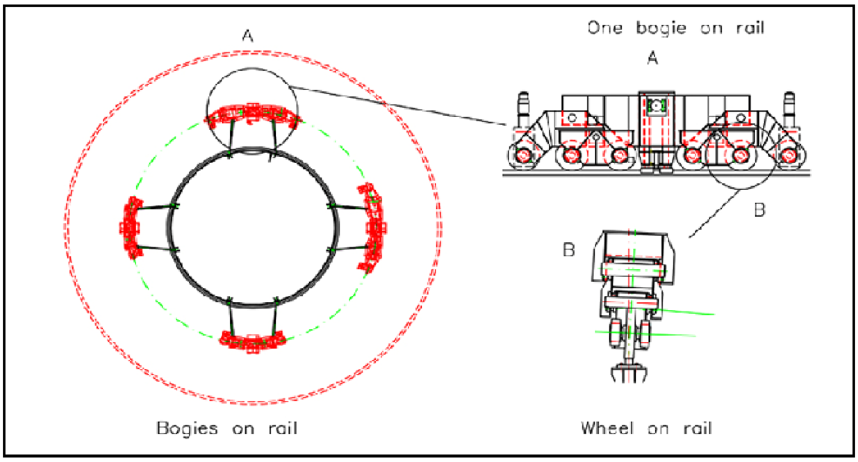


Figure 108. Bogies and rail mechanism for LBT telescope. (LBT Design report).

Both the bogie wheels and the rail have to be of high precision. To avoid contact stress between wheels and rail, the edges of wheels and rail should be rounded. Rather smooth movement of the telescope enclosure is required, or vibrations will occur and, possibly, influence the tracking of the telescope. Further, the wheels have to roll with minimum skidding. Accordingly, the wheel axes must be correctly centered on the rail. To protect the rail, wheels and drivers against incoming dust, a dust trap is introduced and is provided with a liquid dust filter. Details can be seen in Fig. 109.

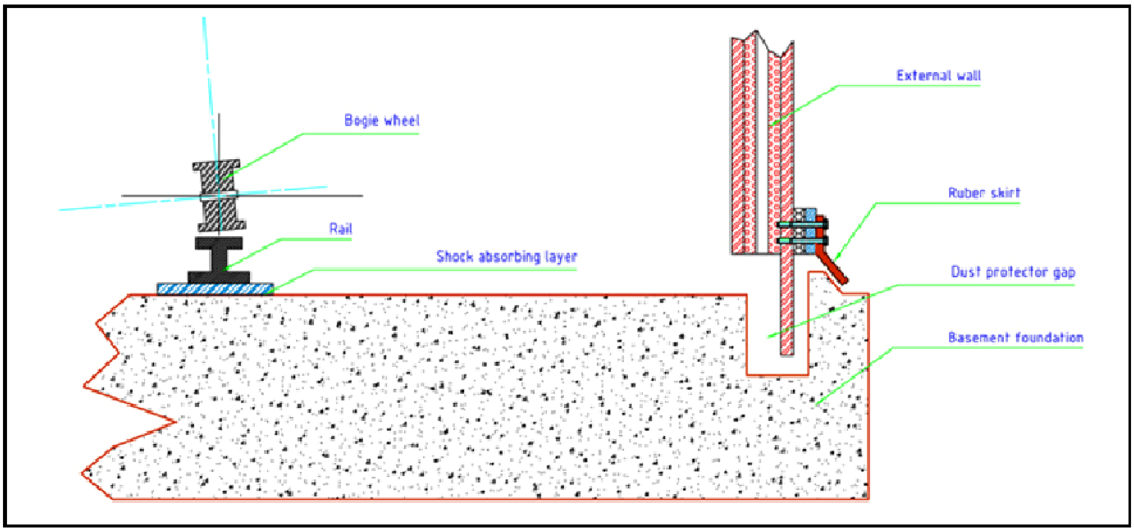


Figure 109. Dust protection mechanism for rotating enclosure.

Optics

An opto-mechanical system

A telescope for optical and adjacent wavelengths is, to a very large extent, a mechanical structure. In telescopes with active and adaptive optics systems, the mechanical parts are emphasized. Modern, advanced optics are in many ways more mechanics than optical elements. Optical structures turn into opto-mechanical structures. In the following, only reflecting telescopes will be discussed, since refractors are not, in practice, competitive for larger apertures.

Still, at the heart of a telescope intended for use in the wavelength region from ultraviolet to infrared, we find optical elements. In addition, while assisted by mechanical structures, the optical elements are of highest importance for the observing quality, not least in terms of image quality and spatial resolution. A telescope for optical and adjacent wavelengths can reach excellence if, and only if, its optical elements are adequately selected and fitted and are of outstanding quality.

Optical aberrations

Optical aberrations are deviations from the behavior of on-axis optical systems. The deviations show up in the way that light rays from points of the object, following passage through the optical system, converge not in corresponding well-defined points but in other constellations. In practice, this shows up as an image with degraded resolution, the amount of degradation depending on the distance from the optical axis. We refer to this as image distortions.

For design and construction of telescopes for optical and adjacent wavelengths, optical aberrations are a prominent concern. As soon as imaging over significant fields of view is on the agenda, optical aberrations have to be taken into account and corrective measures applied. This is of high priority for projects aiming at high-quality imaging over larger fields.

Optical aberrations occur in both reflective and refractive optical elements. In a 3 m class telescope designed for use at optical-visual and adjacent wavelengths, dominant optical elements are mirrors. Thus, in this discussion, reflective systems will be given highest attention. However, most telescopes of the type discussed will, to some extent, include also refractive optical elements. Examples often represented are elements of relay optics and field flatteners. In addition, refractive optical elements are frequent parts of many units of auxiliary instrumentations. Accordingly, some reference will be given also to optical aberrations represented in refractive optical systems.

Monochromatic and chromatic optical aberrations

Some optical aberrations occur whether the light is monochromatic or non-monochromatic. Other aberrations are present only when the light covers a significant range in wavelength. For simplicity, we refer to these aberrations as geometrical and chromatic, respectively. Chromatic aberrations come from effects of wavelength-dependent dispersion. Accordingly, they occur only when refractive optical elements are involved. In contrast, geometrical aberrations occur both for reflective and refractive optical elements.

Spherical aberration

Spherical aberration is a problem for both refractive and reflective optics. It is not dependent on the field angle. Elementary ray tracing easily demonstrates the effects of spherical aberration when optical elements with spherical surfaces are involved. The further from the optical axis the incoming rays meet a concave lens or mirror, the closer to this element do they converge. Thus, the focus is ill defined and the image results unsharp. Effects of spherical aberration are, normally, relatively easy to detect and identify.

Until relatively recently, spherical aberration caused considerable practical problems, not least in connection with telescopes with larger apertures. Spherical mirrors were relatively easy to polish to high precision, while corresponding aspherical shapes were much more of a challenge. On the other hand, it was conceptually much safer to achieve high image quality with aspherical mirror surfaces than with spherical ones. With current rather sophisticated schemes for mirror figuring, the problem has been very much reduced. While still more challenging than spherical mirror surfaces, those of aspheric shape can, with modern computer-controlled polishing routines, be finished to a precision that is, in practice, equal to that of corresponding spherical shapes.

As a result of the advance of figuring techniques, the use of spherical mirrors in telescopes is today rather restricted when at all attempted. Instead, mirrors aspherically shaped are used with little more than marginal budgetary consequences. In fact, an optical system with a primary mirror with spherical shape and later optical elements correcting the resulting spherical aberration may well be more complicated, less productive and more costly than a corresponding optical system relying on an aspherical primary mirror.

Over many years, due to the favorable figuring techniques, spherically polished primary mirrors were used also for telescopes with larger apertures. These telescopes, of Schmidt-Väisälä or Maksutov type, were equipped with lenses or systems of lenses correcting the spherical aberration caused by the spherical primary mirrors. Some of the telescopes of type Schmidt-Väisälä were rather large, with primary mirror diameters up to two meters. In order not to introduce too much chromatic aberration, the corrector lenses of these telescopes had to be made as thin as possible.

In a Schmidt-Väisälä telescope, the primary mirror is spherical. This means that it is easy to figure but also that it delivers images with large effects of spherical aberration. To eliminate or at least to drastically reduce these effects, a correcting lens is mounted at the centre of curvature of the primary mirror. The lens is aspherically figured. So configured, the telescope has very limited effects of spherical aberration at the same time as it keeps effects of coma and astigmatism rather reduced. In consequence, a large field of view can be used.

Especially in the case of larger-aperture telescopes of Schmidt-Väisälä type, the attractive thinning of the corrector lenses could, unfortunately, often be achieved only at the price of lens deflections and, thus, secondary optical problems. For many reasons, such telescopes, of catadioptric construction, are today much less useful and popular than some decades ago. Still, no doubt, they often offer rather large usable fields, something that can be achieved also without use of catadioptric methods but then at the price of notably sophisticated figuring procedures.

While the normal measure to avoid spherical aberration in reflecting telescopes is to replace spherical mirror surfaces with aspherical ones, the corresponding exchange of lenses with spherically shaped surfaces for lenses with aspherically defined surfaces is a complicated way out, as aspherically shaped lenses are challenging to produce to high optical precision. The option regularly selected is instead to apply combinations of lenses with specially selected surface figures, positive and negative. As always with refractive optics involved, effects of chromatic nature have to be considered.

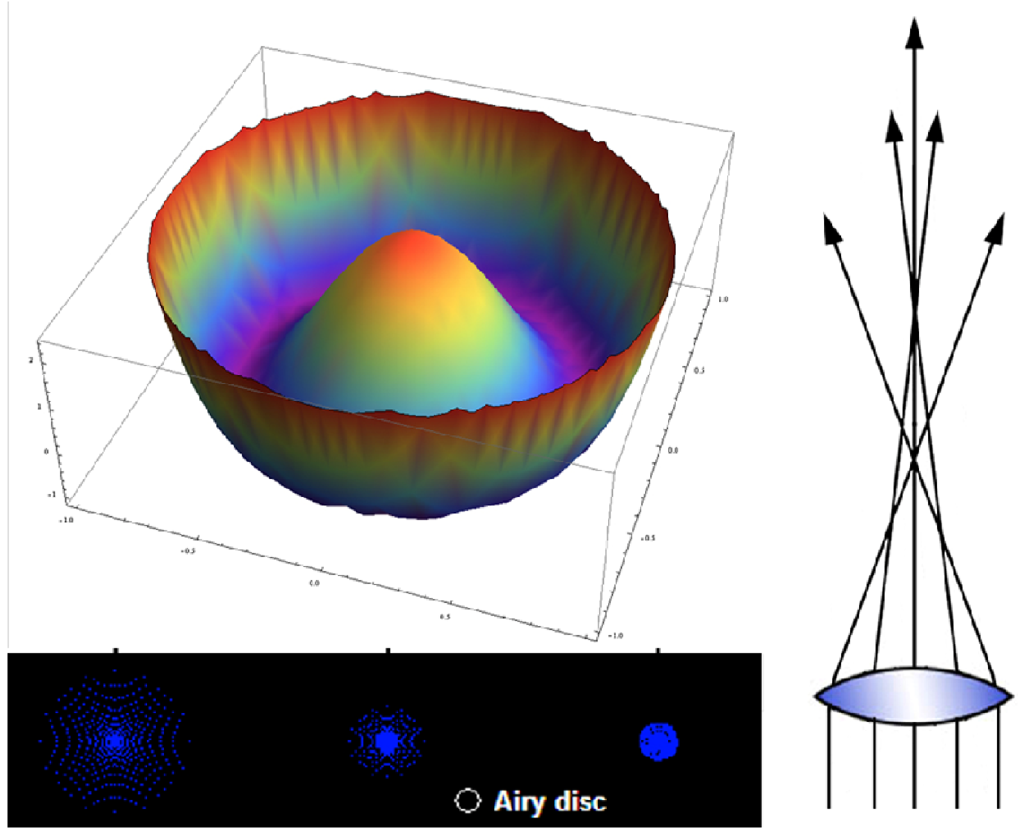


Figure 110 Spherical aberration is an image imperfection caused by the spherical shape of the optical surfaces. The right-hand image illustrates the aberration for a single lens. The focal length of a concentric set of rays depends on the distance from the optical axis of the set. The left-hand images show the corresponding wave-front shape and spot diagram.

Coma

In many ways, to avoid the effects of spherical aberration in mirrors, it seems rather natural to choose mirrors with parabolic surfaces, at least as long as the object is on the optical axis only. While somewhat more complicated to figure than their spherical counterparts, parabolic shapes are today relatively easy to achieve, even to high precision. The result is a mirror that is free from spherical aberration for light arriving along the optical axis (as well as from other directions). Light arriving at an inclination to the optical axis is, however, rather badly affected in a parabolic system, as it is asymmetric with respect to light from such directions.

As a consequence, parabolic mirrors are adequate for small fields of view but much less so for larger fields. In the latter case, in the centre of the field, the images are sharp, while, with increasing distance from the centre, the images get gradually more distorted. The distortion has a shape not unlike that of bright outflows from cometary nuclei. The fan-like distortions are directed out from the central position of the field of view.

Above, the elimination, or at least reduction, of effects of spherical aberration with telescope concepts like the Schmidt-Väisälä and Maksutov was mentioned. It is noted that optical systems of Ritchey-Chrétien type also, if well functioning, eliminate effects of spherical aberration without introduction of effects of coma. In addition, they do so without the other negative effects caused by catadioptric systems.

Effects of coma are not restricted to reflective elements and telescopes. Coma occurs also for lenses in much the same manner as for mirrors. Also in the latter case, the natural remedy is adoption of lens surfaces that are more sophisticatedly shaped than the spherical ones. As before with refractive optical elements, and as a complication compared to the case of reflective optical elements, chromatic aberrations have to be taken into account for lens systems.

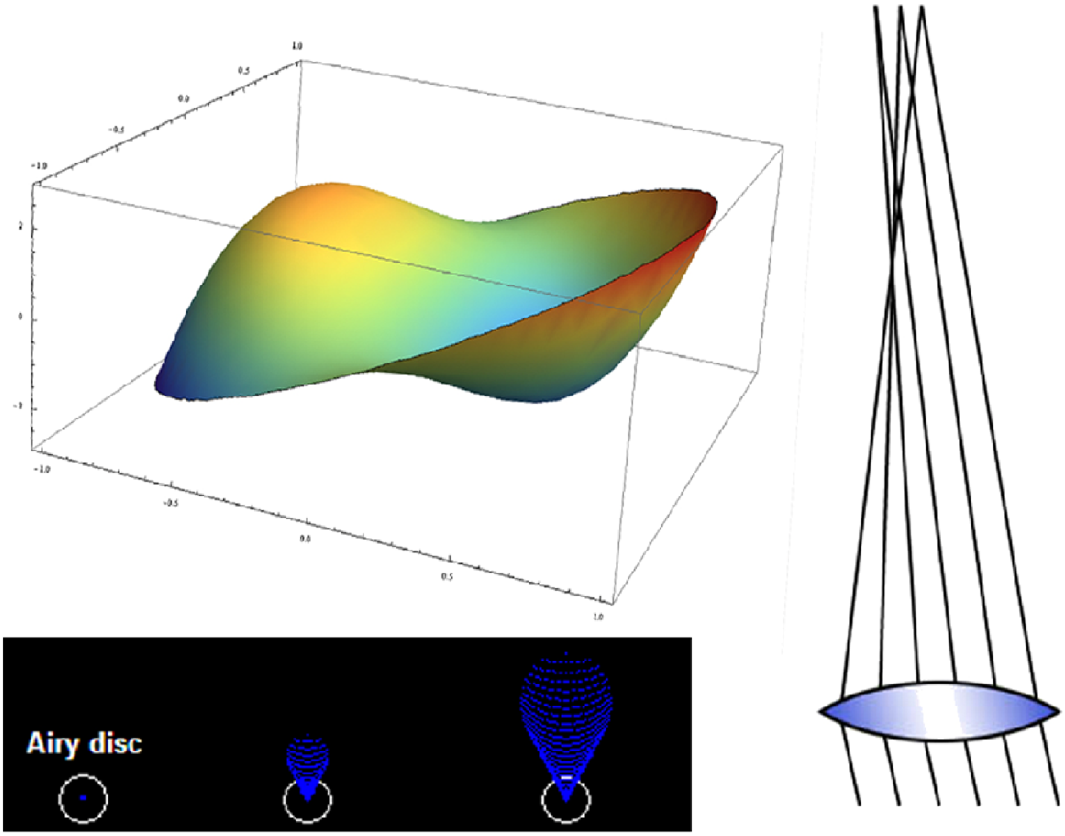


Figure 111. Coma occurs when the incident wavefront is tilted or decentered with respect to the optical surface. Hence, it affects off-axis image points but also results from axial misalignment of optical surfaces. See right-hand illustration. Comatic wavefront deviation has reverse symmetry along the axis of aberration, with one side flatter and the other more curved with respect to the perfect reference sphere. See left-hand illustration.

Astigmatism

In addition to spherical aberration and coma, astigmatism is a frequent optical aberration of considerable practical implications. This is not least the case for telescopes, especially not if high image quality is a priority. Once effects of spherical aberration and coma are eliminated, the image-quality performance of the telescope will normally be limited by astigmatism. Astigmatism can be divided into two types. These may be labeled system-independent astigmatism and system-dependent astigmatism, respectively.

System-independent astigmatism is not, in itself, caused by system asymmetry, misalignments or errors in design and manufacture. It occurs even in fully symmetrical and aligned optical systems of high quality. Further, it is not, in itself, an effect caused by light including a wide range of wavelengths. System-independent astigmatism occurs also for fully monochromatic light. Primarily, it is non-existent on the optical axis and a function of the distance from this axis.

System-dependent astigmatism can be seen and studied in optical systems that are not symmetric with respect to the optical axis. It is a natural consequence of certain asymmetric optical designs. Cylinder lenses are prominent examples of such designs. When system-dependent astigmatism occurs in systems symmetrically designed, this is most frequently due to either occasional or permanent misalignments. However, it may also have its origin in errors in the design and/or in the manufacturing process. This type of origin of the system-dependent astigmatism reveals itself through its occurrence also on the optical axis. It may be stated that significant signs of system-dependent astigmatism is a clear announcement of notable optical imperfections, with the exception of optical systems deliberately designed as asymmetric.

Common to both types of astigmatism, system-independent and system-dependent, is the special manner in which the effect of astigmatism manifests itself. Light rays that are seen propagating in two mutually perpendicular planes and is focused in two mutually perpendicular separated focal lines. The result is that there is no singular sharp focus.

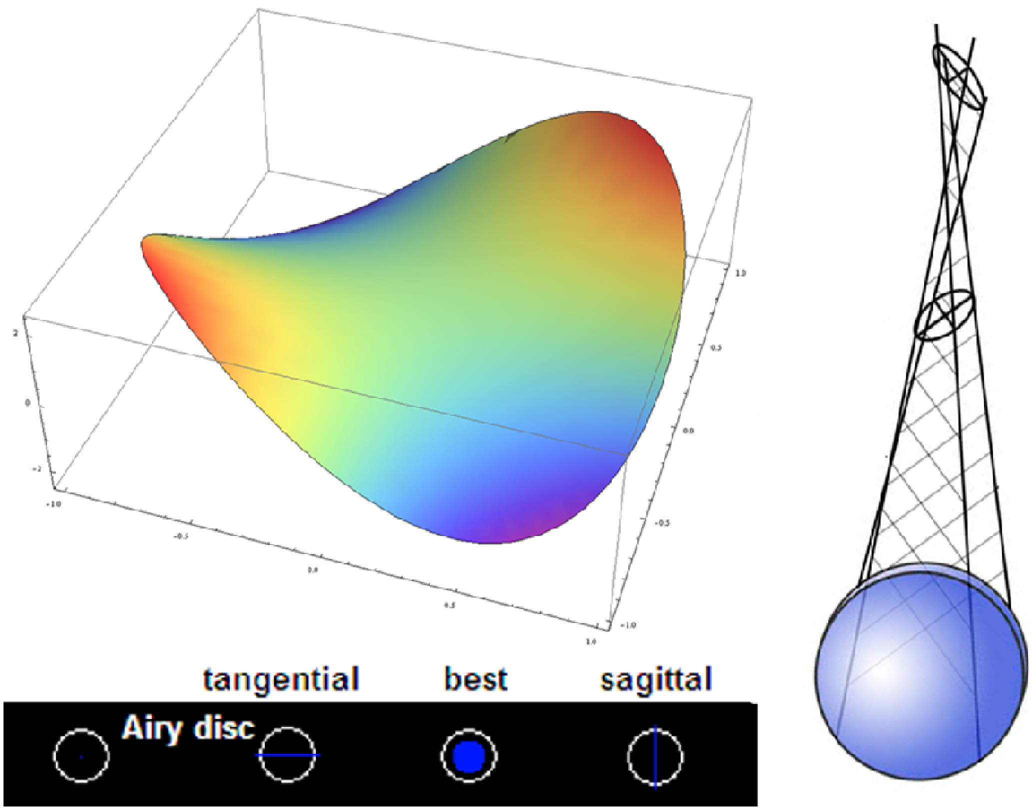


Figure 112. Astigmatism affects off-axis image points. It is caused by inclination of incident wavefronts relative to the optical surface. Astigmatism, in its simplest form, for mirror with the stop at the surface, results from projectional asymmetry due to wavefront inclination to the surface. The diameter of wavefront projection onto the surface varies from minimum in the plane of wavefront tilt - determined by the chief (central) ray and optical axis, defining the tangential plane, to the maximum in the direction orthogonal to it, the sagittal plane, in which it equals the aperture diameter.

Field curvature

Field curvature is an optical aberration affecting a large range of optical systems, refractive as well as reflective. It is normally described as an effect causing a flat object with its surface perpendicular to the optical axis to be imaged with its locus on a non-flat surface. The locus of the sharp focus is, at least in principle, rather well defined. All focal points are to be found on a surface the deviation of which from the plane perpendicular to the optical axis and placed at the on-axis focal point is equal to the cosine of the angle between the object point in question and the optical axis.

While conceptually serious, the effects of field curvature can, normally, be corrected with only smaller consequences for the resulting image quality. In the human eye, the architecture of the retina takes natural care of the effect of field curvature. Most cameras are designed and constructed to avoid the effect as much as possible, in better cameras normally with rather good results. In telescopes, similar results can be obtained with the help of field flatteners.

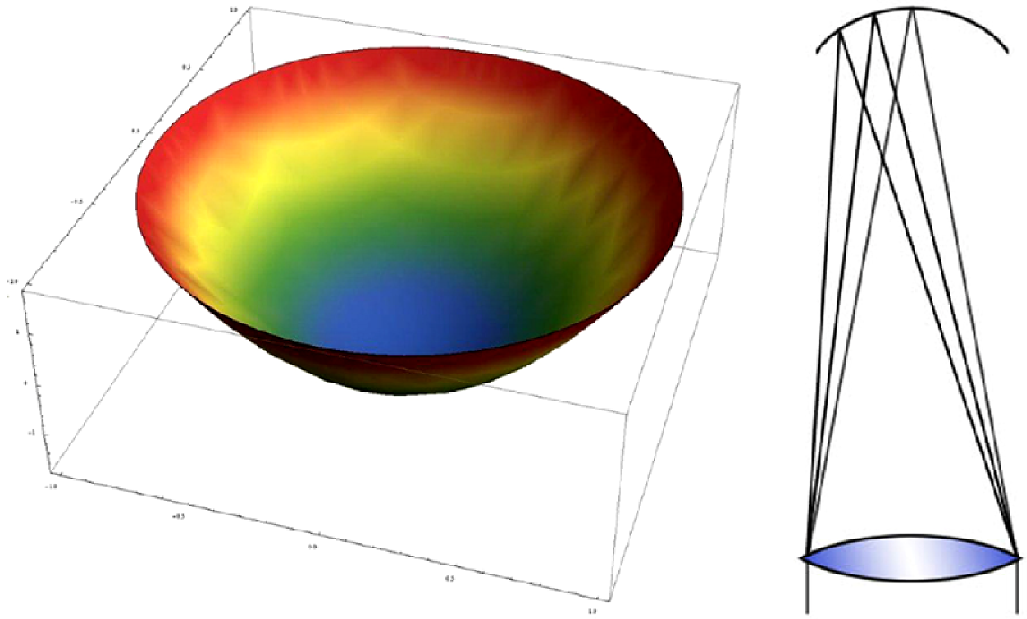


Figure 113. Most telescopes form images on a curved surface symmetrical around the optical axis. The radius of curvature of this surface, which can be approximated with a sphere, is called field curvature.

Distortion

Image distortion is considered as an aberration. It is a denomination often employed for a range of problems affecting imaging. Image distortion is defined as occurring as soon as straight lines in an object are imaged as non-straight lines. Illustrations of this imaging behavior are plentiful and often seen in wide-angle photographs. More strictly, image distortion implies field-dependent magnification but sharp images.

Occurring in an optical system that is symmetric, or at least nearly so, the image distortion is, as a rule, directly dependent on the distance from the optical axis. The mode of the distortion can, however, vary considerably. In practice, we often distinguish between barrel distortion and pincushion distortion, with complex distortion, often called moustache distortion, being a mixture of the two.

In an image affected by barrel-type distortion, the magnification in the image decreases with the distance from the optical axis. This effect is, with varying success, exploited in so called fisheye lenses. It is an effect helpful for the transformation of wide object planes into limited imaging areas.

Images affected by pincushion-type of distortion are affected oppositely of those affected by barrel-type of image distortion. In pincushion-deformed images, the magnification increases with the distance from the optical axis. Both types of distortion are quite frequent.

As the name indicates, complex distortion is more complicated that those due to barrel and pincushion distortion. In its normal behavior, complex distortion is similar, if not equal, to barrel distortion at smaller distances from the optical axis. With growing optical-axis distance, it gradually converts into pincushion-type distortion.

For telescope imaging, the effects of image distortion should neither be forgotten nor exaggerated. For smaller fields of view, the effects are normally not too disturbing, while their influence on large-field survey imaging can be considerable. Reducing the effects optically is a challenging undertaking. However, in practice, post-exposure rectification is normally rather satisfactory. Often, it is fully sufficient to use the images as is for photometric and similar purposes, while positions can be conveniently re-mapped.

Effects of image distortion can, to a considerable extent, be reduced with software methods. For this purpose, dedicated codes have been developed. In principle, the distortions imposed are reversed by image warping. In the case of lateral, chromatic aberrations, warping procedures can, with good results, be made for different wavelength bands separately. The total process is rather complicated but a considerable improvement of the image quality can often be achieved.

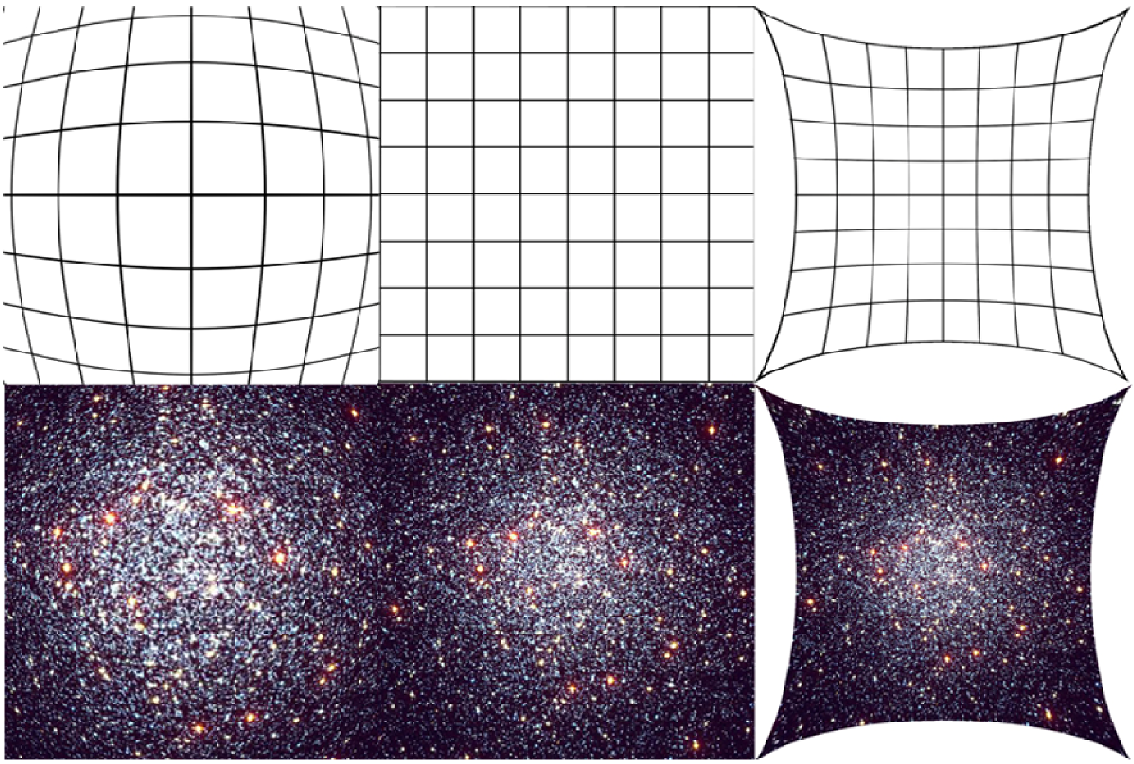


Figure 114. Distortion arises because the magnification of the peripheral part of the image is different from that of the central part. An optical system with distortion deforms a square image into a barrel shape or pincushion shape or a combination of both. The effect of distortion has been simulated for M51.

Chromatic aberration

Effects of chromatic aberration, also referred to as chromatic distortion, are image distortions occurring for refractive optical systems only. They are closely related to the nature of the lenses. These have refractive indices that are wavelength dependent, their value decreasing with increasing wavelength. There are two types of chromatic aberration. They are called axial, or longitudinal, chromatic aberration and transverse, or lateral, chromatic aberration, respectively.

As long as refractive-type telescopes were still seen as competitive in astronomy, chromatic aberration was a considerable concern. Over the latest century, refractive telescopes have largely been phased out and never attempted for apertures larger than 125 cm. Thus, in the community of astronomers, the importance of chromatic aberration has decreased rather much. Still, however, most telescopes and their auxiliary instrumentation contain refractive optical elements. Accordingly, the effects of chromatic aberration are still of significant concern in astronomy.

The type of chromatic aberration mostly illustrated and discussed is axial chromatic aberration. As the refractive indices of lenses depend on wavelength, so does the focal length of any given single lens. Thus, while light of shorter wavelengths defines focal points closer to the lens, light of longer wavelengths defines focal points further away from the lens. At lower image resolution, images appear unsharp, while at higher resolution they appear as colored layers. Axial chromatic aberration occurs all over the image plane, also on the optical axis.

Not only the refractive index but also the magnification of a lens depends on wavelength. Accordingly, light of different wavelength defines focal points that spread in the focal plain. This effect explains transverse chromatic aberration. The spread increases with the distance from the optical axis and is non-existant on the optical axis.

A number of methods have been used to minimize the effects of chromatic aberration in telescopes. Use of lenses with large focal lengths was an early remedy. Later, compound lenses were introduced, composed of materials with different dispersion. So called achromatic doublet lenses were composed of crown and flint glass. They provided large reduction of the effects of chromatic aberration, but, naturally, less so if the wavelength interval of use was enlarged. Through combination of more than two lenses, giving so called apochromatic triplets, the reduction of effects of chromatic aberration can be further reduced.

Even further improvements can be introduced through use of several different types of glass. Also, as an alternative to the use of achromatic and apochromatic compound optical elements, combinations of refractive and diffractive optical elements can, with significant effects, be employed. In the end, however, at least to some extent, the advantage of the reduction of chromatic aberration may well be lost due to the increase of complexity.

Today, even images significantly affected by effects of chromatic aberration may be successfully used for scientific purposes. As long as ultimate reduction of the effects is not a neces-

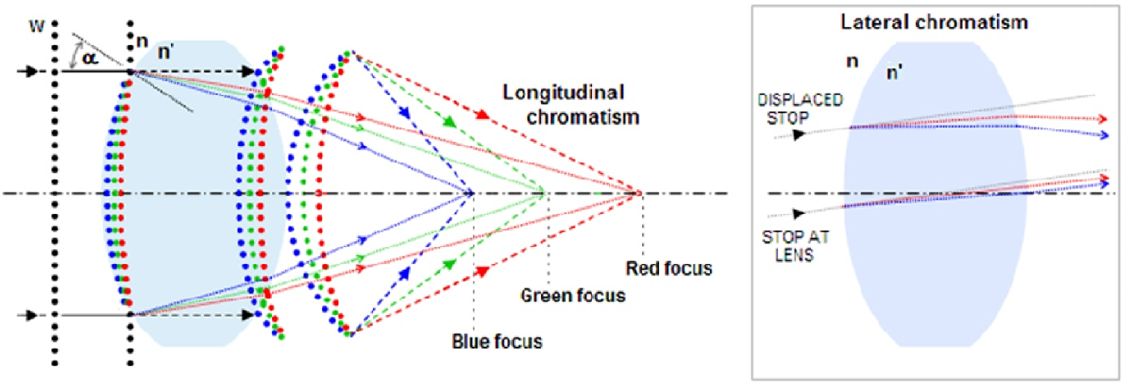


Figure 115. The wavelength-dependent refractive index of a lens causes chromatic aberration. White-light splits into component wavelengths and component wavefronts aree formed. This gives a focal length dependent on wavelength or longitudinal chromatism. See left-hand part of figure. The white-light chief ray, orthogonal to the centre of the incident wavefront at an angle to the optical axis, splits laterally into component-wavelength chief rays, causing lateral chromatism. The right-hand part of the figure demonstrates the implications of the stop location. Note the difference in colour spread in the two examples. Longitudinal and lateral chromatism have different origins and magnitudes, and, thus, correction of one of them does not necessarily imply correction of the other (Sacek, 2006).

sity, large improvement can be reached with post-facto processing of images. The operations required are far from trivial but considerable experience has been assembled. The results of post-facto image processing can be astonishingly good.

Conceptual optical design

As a consequence of its fundamental importance, initial, conceptual design of a telescope for observations in the range 325 - 2 500 nm has to be commenced in the form of an optical telescope design. Once the optical design is available in its tentative conceptual version, design of mechanical structures can be initiated. From there on, for optimum outcome, optical and mechanical elements should be designed in an iterative procedure. This is especially important, if the over-all telescope project includes ambition on high image quality.

Concentrating, at first, on conceptual optical design, a number of decisions have to be taken. Some of them can be modified during the progress of design, optical and mechanical, while other choices are more or less of definite nature, at least if a very extended design phase is to be avoided. Thus, definition of optical design parameters requires both a deep insight into the science case and science requirements forming the foundation of the design and construction of the telescope. The design parameters forming the basis of the conceptual optical design must be defined as early as possible, or a substantial amount of iterative design work has to be foreseen and accepted as has a considerable increase in project time and cost.

Optical concept

A large reflecting telescope, such as a telescope of 3 m class, can be designed along a number of optical concepts. The choice of concept should reflect the science case and its priorities but also technical, regarding optics as well as mechanics, and economical consequences. Thus, the adoption of optical concept is a decision of high importance. A recommendable procedure is to review advantages and disadvantages of all concepts possible and realistic, weigh them against science priorities, practical arrangements and the ease and cost of total design and construction. It should be remembered that the decision on optical concept for the telescope involves also the enclosure, its size, design and cost.

Optical concepts realistic and adequate for a 3 m class telescope are several. They include various versions of a limited number of solutions with respect to the focal stations of the telescope. Such solutions are of type Primary, Cassegrain, Gregory, Newton, Nasmyth and Coudé. To these, rather classical, focal-station alternatives can be added a fiber-fed floor station and a

Figure 116. Main optical concepts for reflective telescopes. a) Prime focus, b) Newtonian focus, c) Cassegrain focus, d) Gregorian focus, e) Nasmyth focus, and f) Coude focus. For a and b cases, a primary mirror with a focal ratio of 3.5 has been chosen and for rest f/2.

folded Cassegrain station. Some of the focal stations are illustrated in Fig. 116. All options mentioned have been used and all have presented both advantages and disadvantages, very much dependent on the use of the telescope.

Prime focus station

Choice of a prime focus station has some clear advantages. The telescope has only one reflecting surface, the primary mirror. The shape of this mirror depends on the requirements on field of view and image quality. See graphical representation in figs. 116 and 117. The concept implies, at least in principle, minimum optical complications and, at the same time, maximized throughput and simplest possible alignment procedures. It avoids construction of a secondary mirror, saving project time and cost. Further, the top ring of the telescope can be made in a relatively uncomplicated manner. In addition, choice of a prime focus station means that only one reflecting surface and a fast optical system are used. This sets the scene for maximum deep exposures for the aperture chosen. Further, large fields of view can be obtained.

Undoubtedly, a prime focus station also has a number of disadvantages. Relatively seen, it means a rather low over-all focal ratio for the telescope, in practice equal to that of the primary mirror, as long as no focal extender is applied. To avoid problems with too small a focal ratio as well as a focal extender, the primary mirror has to be given a high focal ratio. This gives a long telescope, which, in turn, implies mechanical instability, high weight and high cost. In addition, with only one reflecting surface, correction can be made for only one optical aberration, spherical aberration. Thus, image-quality problems are due. Of special concern are spherical aberration and astigmatism. Depending on focal ratio and effects of atmospheric turbulence, the corresponding difficulties may be more or less pronounced.

In practice, the low stiffness of the telescope tube structure translates into problems with high-precision pointing and tracking. Also, the instrumentation to be mounted in the prime focus has to be limited in size, or unacceptable obstruction ratios will effectively down-grade the potential of the telescope. In addition, a prime focus arrangement necessitates a large enclosure, further increasing project cost but also increasing enclosure turbulence and, thereby, decreasing the image quality.

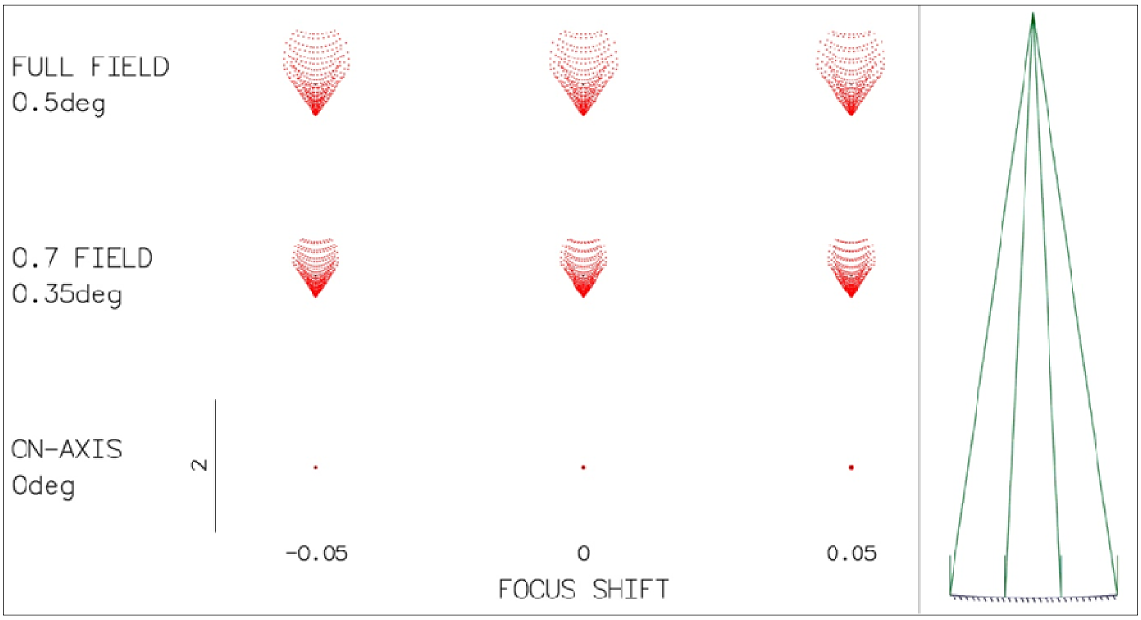


Figure 117. Spot diagrams for a prime-focus solution. Note the rapid deterioration of image quality with distance from the optical axis. Primary-mirror focal ratio is 3.5.

A further, and serious, disadvantage of the prime focus concept is the position of the auxiliary instrumentation. Mounted in the telescope top ring, it causes two problems. First, it is attached to the part of the telescope with largest movements. This gives serious stability problems. Further, it is highly complicated to service the instrumentation in prime focus. For telescopes with apertures larger than 1.5 m, normal service can be given only in a horizontal, or near horizontal, telescope-parking position. Reaching the instrumentation in an observational real-time mode is close to impossible.

Early large reflectors had prime focal stations. At that time, it was a rather natural choice. Today, the situation is very different. Requirements on pointing, tracking and image quality makes the choice of a prime focus station a doubtful option, unless the science case is of special nature. In addition, today's large emphasis on auxiliary instrumentation implies that its vulnerable and hard-to-service position in the top ring should, as far as possible, be avoided.

Cassegrain focus station

The Cassegrain focus-station concept is nearly as old as the reflecting telescope as such (Cassegrain, 1672). That, though, does not imply that it was chosen in early telescopes. Rather, while in itself an advanced concept, the Cassegrain solution required, at the time of its invention, a figuring of a level of sophistication not possible in practice. In addition, Cassegrain's proposal was strongly criticized by Isaac Newton, probably partly for reasons to be discussed.

In principle, the Cassegrain concept is rather straightforward. Two mirrors are used. The primary mirror has a concave shape, and the secondary-mirror reflective surface is convex. The secondary mirror is placed in a pre-focus position relative to the primary mirror. This is illustrated in Fig. 118.

Originally and classically, the shape of the primary mirror is that of a paraboloid. That is matched with a secondary mirror with the form of a hyperboloid. The two mirrors have a common focus. The final focus station is located below the primary mirror, which has a hole in its centre, the size of the hole and the secondary mirror normally chosen together. The optical concept gives a rather compact telescope, favourable in terms of weight and cost.

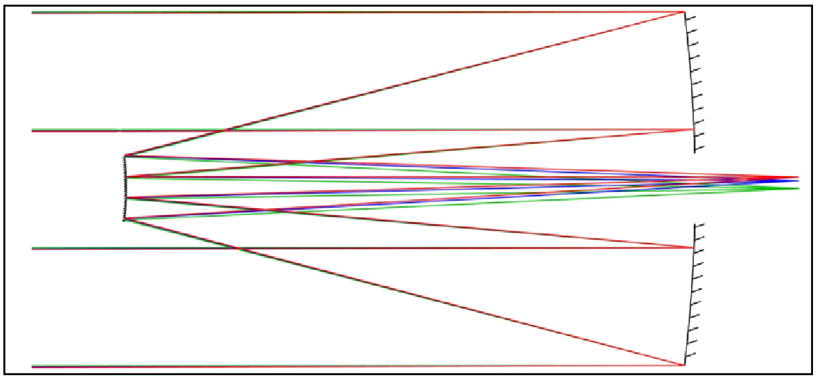


Figure 118. Ray-tracing for a Cassegrain telescope with a primary-mirror focal ratio of 2.0. Rays with different colours do not refer to light with different wavelengths. Instead, at the focus position, they indicate the footprint of the field of view, the corresponding deviations of the incoming rays being very small.

The form of the classical Cassegrain-concept primary-mirror surface, that of a paraboloid, was, in its time, chosen to minimize the effects of spherical aberration resulting with a spherical primary-mirror surface. The corresponding secondary mirror was a hyperboloid relaying the primary focus to its final position without introduction of spherical aberration. While this simple approach is perfect in theory, it is far from problem-free in practice. At the same time as the paraboloidal primary mirror eliminates spherical aberration along its optical axis, it collapses the many axes of symmetry inherent to a spheroidal mirror into only one axis of symmetry. Thus, outside the optical axis, image distortion, in the form of coma, is strong.

If, but only if, the telescope is intended for strict optical-axis observations only, the choice of a paraboloidal primary mirror can be recommended. This is very seldom, if ever, the case in practice. If a larger field of view is required, the solution is to figure the primary mirror to a higher order. The by far most popular mirror-surface shape is that proposed by Ritchey and Chrétien, the so-called Ritchey-Chrétien solution. In this approach, the reflecting surfaces of both the primary and the secondary mirrors have hyperboloidal form.

The Ritchey-Chrétion solution offers a relatively large field with both spherical aberration and coma eliminated. Moreover, and important in practice, if the primary and secondary mirrors have the same radius of curvature, the image field produced is flat. As long as photographic plates were used as detectors, the field flatness was a great asset of the Ritchey-Chrétien solution. The advantage of the flat field diminished when CCD detectors, normally small in physical size, took over after the photographic plates. Today, with the availability of much larger CCD detectors, and mosaics of such detectors, the field flatness is again a large advantage of telescopes with Ritchey-Chrétien-type optical solutions.

A prime advantage of the Cassegrain concept is its compactness. Thus, the telescope tube is short. This means a telescope that is relative light and, thus, in principle, economic. At the same time, the Cassegrain solution favours a small, compact enclosure. This, in turn, means an enclosure that is both economic and that produces a minimum of enclosure turbulence. These are the features that have made Cassegrain-type telescopes highly popular.

Nevertheless, the Cassegrain concept has a number of disadvantages. All the major disadvantages are caused by the convex secondary. This convex form requires an extra optical element for its polishing. Fabrication of this element, necessarily of high quality, and the polishing of a convex surface in itself, imply a secondary-mirror figuring process that is time consuming and expensive. Likewise, alignment of the optical system is far from trivial. The same is true for optical in-telescope testing.

There are a number of variations on the Cassegrain optical telescope theme. In the Dall-Kirkham Cassegrain concept, the concave primary mirror has an ellipsoidal shape, while the convex secondary mirror is spherical. This choice makes the Dall-Kirkham variant of the Cassegrain concept easier to figure. On the other hand, it has the distinct disadvantage of disability to correct for off-axis effects of coma.

A number of off-axis modifications of the Cassegrain optical principle have been both proposed and conctructed. In practice, they have had small success in terms of telescopes intended for use at optical and adjacent wavelengths..

Another variation of the Cassegrain concept rests on introduction of a combination of reflecting and refracting optical elements. Examples more seriously tried with larger telescopes are the Schmidt-Cassegrain and the Maksutov-Cassegrain telescope. However, non of these concepts has won any larger success in practice.

Gregory focus station

The Gregory optical concept can be regarded as an alternative to the Cassegrain concept. Rather early designed (Gregory, 1663), instead of a concave primary mirror and a convex secondary mirror, as in the Cassegrain solution, the Gregory concept has both the primary mirror and the secondary mirror concave. The primary mirror has a paraboloid and the secondary mirror has an ellipsoidal surface. Further, the secondary mirror is placed post-focus with respect to the primary mirror. Like in the Cassegrain concept, light from the secondary mirror is reflected to the telescope focus through a central hole in the primary mirror. The Gregory optical concept is illustrated graphically in Fig. 119.

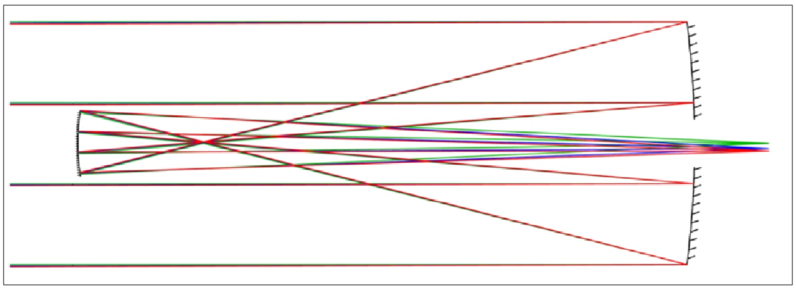


Figure 119. Ray-tracing for a Gregorian telescope with a primary-mirror focal ratio of 2.0. For the significance of the ray-tracing colours, see Figure 118.

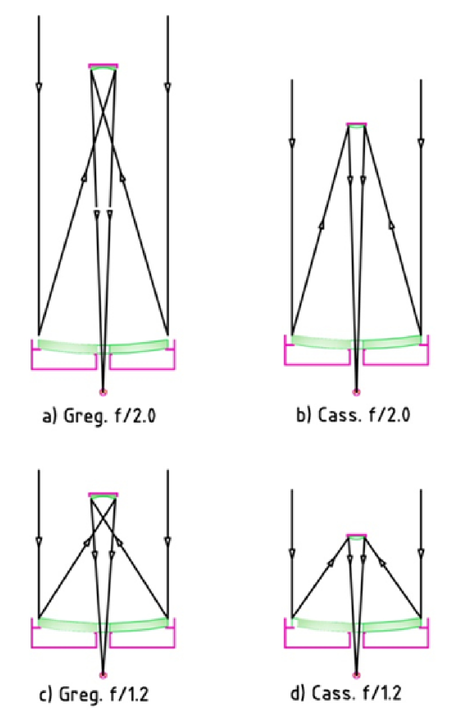
As the primary mirror has its focus in front of the secondary mirror, a field stop can be introduced, an advantage especially valuable for telescopes used for observations of the Sun. Another advantage is that the Gregorian telescope has a real exit pupil. This allows efficient stray-light baffling. Early in design, the first useful Gregory telescope came around five years after Newton's pioneering working telescope.

Compared to the Cassegrain concept, the Gregory solution has a distinct advantage. As both the primary and the secondary mirror are concave, figuring of the secondary mirror is much less demanding as figuring of the Cassegrain-concept secondary mirror. The surface to polish is concave, and no extra optical element is needed for optical testing. Both in terms of polishing time and concerning testing material, the Gregorian secondary mirror is more favorable than its Cassegrain counterpart. An additional advantage of the Gregorian telescope as opposed to its Cassegrain counterpart is that it delivers direct, non-inverted, images. However, in modern observational astronomy, this advantage is marginal at most.

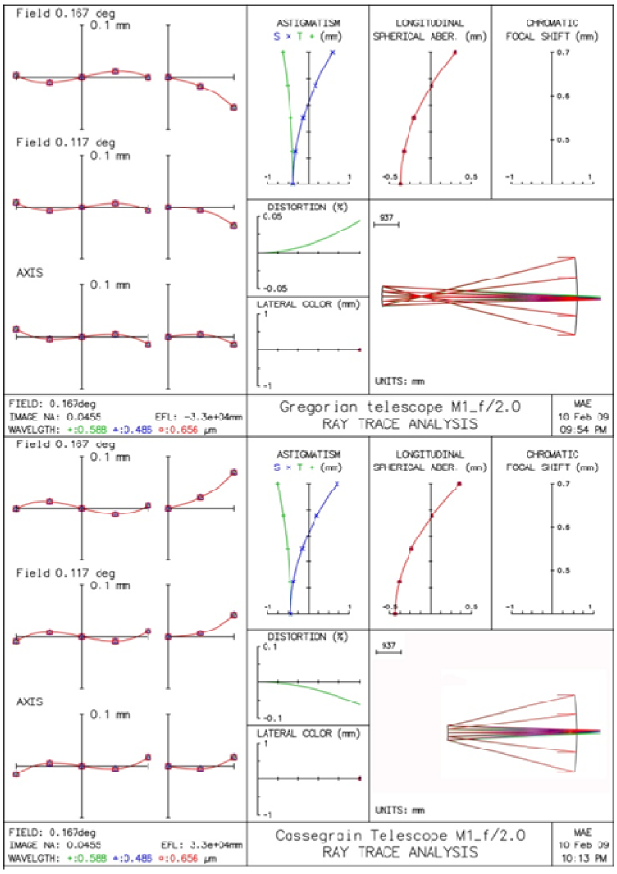
Again compared to its Cassegrain counterpart, the Gregory secondary mirror requires less aspherization. This implies a decreased polishing time and decreased costs. Logically then, a corresponding relation is valid for the two primary-mirror solutions, the Cassegrain and the Gregory. As the Gregorian secondary mirror is less aspherized than its Cassegrain counterpart, also the Gregorian-solution primary mirror requires less aspherization than the corresponding Cassegrain-type primary mirror. We refer to a Gregorian solution free from both spherical aberration and coma as an aplanatic Gregorian concept. The Advanced Technology Solar Telescope (ATST) is an aplanatic off-axis Gregorian telescope.

A considerable general disadvantage of the Gregorian concept compared to its Cassegrain counterpart is its significantly longer physical length. Thus the Gregorian-type telescope is longer than the corresponding Cassegrain-solution telescope. This makes the former type telescope larger and heavier. As a result, the Gregorian telescope has smaller stiffness than the corresponding Cassegrain telescope. In addition, the Gregorian-type telescope is more expensive than the Cassegrain-solution telescope. Further, the Gregorian telescope requires a larger enclosure than the Cassegrain telescope, with higher cost and stronger enclosure turbulence as inevitable negative consequences. A comparison of Cassegrain and Gregorian arrangements is given in Fig. 120.

It is interesting to compare in some detail the optical parameters of Cassegrain and Gregory approaches. The results of such comparisons are shown in Fig. 121. The figure demonstrates that the Gregory concept is slightly superior to the Cassegrain concept. However, the diagrams in the figure also show that the differences are, in practice, not significantly affecting the image quality resulting.



Comparing Cassegrain vs. Gregorian telescopes' tube length with different primary mirror focal ratio
D = 3000 mm



Figures 120 and 121. Comparison of Gregorian and Cassegrain concepts for two different primary-mirror focal ratios, 2.0 and 1.2, both representing fast optics. Figure 120, to the left, illustrates ray tracings and Figure 121, to the right, shows the corresponding optical aberrations.

Newton focus station

The Newtonian concept was the optical solution of the first reflecting, practically useful telescope, Successfully demonstrated by Newton in 1668. In its most construction-friendly version, the Newtonian telescope has a spheroidal primary mirror, followed by a flat secondary mirror and the focus outside and close to the telescope tube. While this version of the Newtonian telescope, for reasons of optical aberrations, has to have a large focal ratio, higher image quality can be reached with a paraboloidal primary mirror.

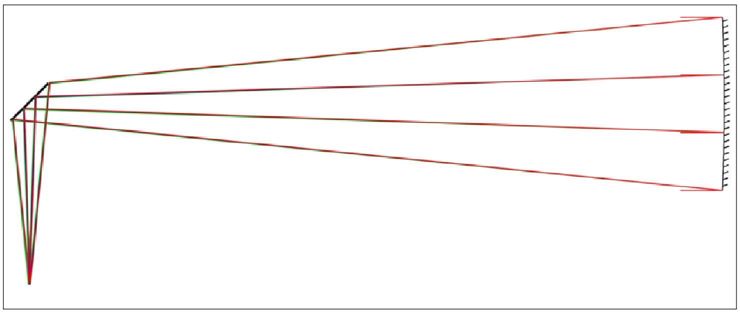


Figure 122. Ray-tracing for a Newtonian telescope with a primary-mirror focal ratio of 5.0.

Some telescopes for scientific use have been constructed as Newtonian reflectors. For larger apertures, however, the position of the focal station is rather cumbersome in practice. On the contrary, for smaller telescopes, the Newtonian principle can be highly practical. At any rate, a Newton focus station, with its 45 degrees folding mirror, is not a good choice for polarimetric measurements as the state of polarization is affected by an oblique reflection. A telescope of Newtonian type is illustrated in Fig. 122.

Nasmyth focus station(s)

A telescope with a Nasmyth focus, or two Nasmyth foci, can be regarded as an optional variant of the Cassegrain optical concept. Following the primary and secondary mirrors, both with surfaces of Cassegrain type, albeit the centre hole in the primary mirror can be omitted, a flat mirror is introduced. The focus is directed out from the tube at right angles with the telescope optical axis and exiting through the altitude axis. Fig. 123 illustrates this.

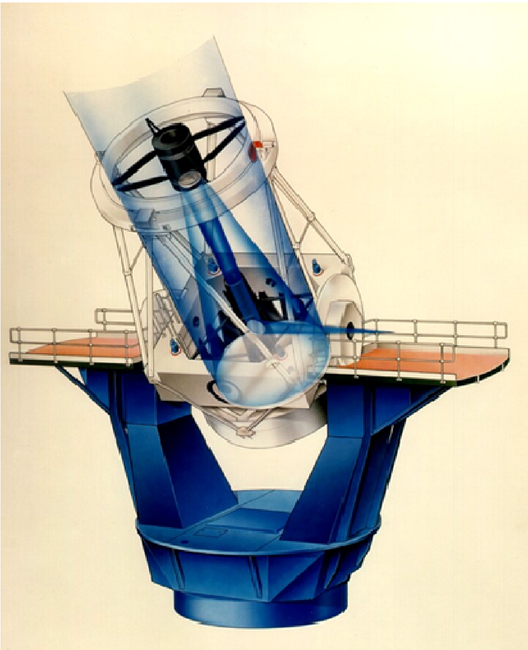


Figure 123. William Herschel Telescope in a position demonstrating its two Nasmyth focal stations. Photo Isaac Newton Group of Telescopes, La Palma.

A clear advantage of the Nasmyth solution is the possibility to construct large and stiff focal stations. Thus, also large and heavy auxiliary instrumentation can be allowed with relatively small negative effects on the operation of the telescope. Another highly important advantage of Nasmyth focal stations is that they rotate around a vertical axis only. Thus, effects of gravitational deformation of the instrumentation are neutralized. In addition, a Nasmyth focal station is favorable for direct access during observation.

To serve their purpose of stability and rigidity, the Nasmyth focal stations have to be placed in the prolongation of the altitude axis of the telescope. This sets the scene for an often hard-to-solve dilemma. In order to place the focus, and the auxiliary instrumentation, outside the aperture range, it is attractive to place the flat Nasmyth mirror at a relatively large distance from the primary mirror. Then, however and unfortunately, severe telescope-balancing problems are unavoidable.

To have the telescope properly balanced, an important ingredient in a telescope required to point and track with high precision, it is natural to place the flat Nasmyth mirror relatively close to the primary mirror and the corresponding heavy mirror cell. While ideal from a balancing point of view, however, the latter solution seldomly brings the telescope focus outside the aperture beam of light. Thus, a relay-optics arrangement becomes necessary and, inevitably, with it, also decreased optical throughput.

Unfortunately, the Nasmyth optical concept also implies some other rather non-negligible disadvantages. The Nasmyth stations, to offer the advantages of stability also for heavier instrumentation, have to be rather large constructions. This gives a telescope that is both heavy and expensive to construct. In addition, the construction implies unfortunate thermal inertia. Further, large Nasmyth platforms require a large enclosure. The price of this is high cost and enlarged enclosure turbulence.

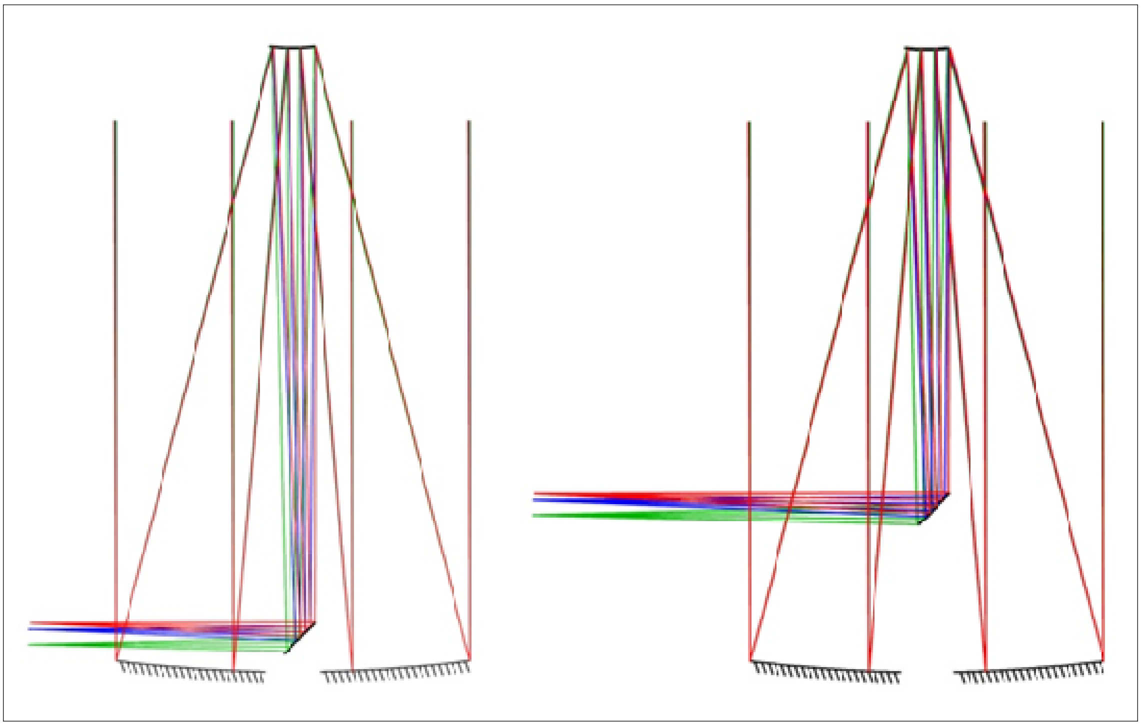


Figure 124. Comparison of two Nasmyth-configuration options, one with smaller, the other with larger distance between the primary and tertiary mirrors. Note the difference in focus position, in the left-hand case favouring mechanical balance, in the right-hand case the convenience of focus location. In both cases, the focal ratio of the primary mirror is 2.0.

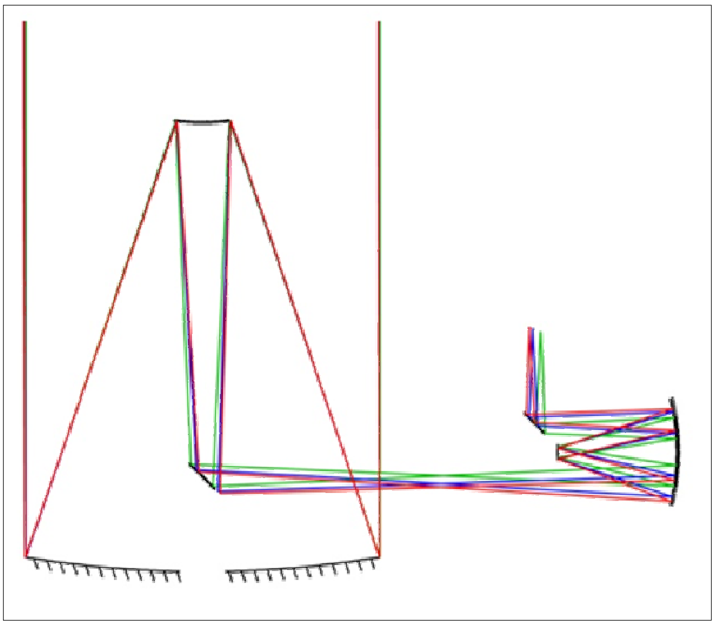


Figure 125. A Nasmyth configuration with an Offner relay-optics configuration.

To avoid problems with the field of view and vignetting, the altitude axis has, for Nasmyth foci, to have a generous light-pass space. This implies a requirement for larger altitude bearings than otherwise necessary. As a result, further increases of the weight and cost of the telescope have to be accepted.

Not uncommon is a combination of a classical Cassegrain arrangement and an optional Nasmyth solution. Among other advantages, such a combination of focal station allows simultaneous readiness for observation of at least three sets of auxiliary instrumentation. Especially in case of a telescope intended for a broad field of activities, this versatility can be a large advantage.

As a basis for a Nasmyth solution, in principle, a Gregory arrangement can be chosen as well as a Cassegrain concept. Combining Gregorian and Nasmyth concepts, however, gives a rather large and heavy telescope. Thus, such an approach is highly uncommon.

Coudé focus station

With a Nasmyth arrangement, an important advantage is the limited movement of the focal station, a rotation in a horizontal plane only. Further, a Nasmyth focal platform can take large and heavy instruments and provide easy access for observers and technical staff. All these advantages can be offered in an even better manner with the introduction of a Coudé focal station.

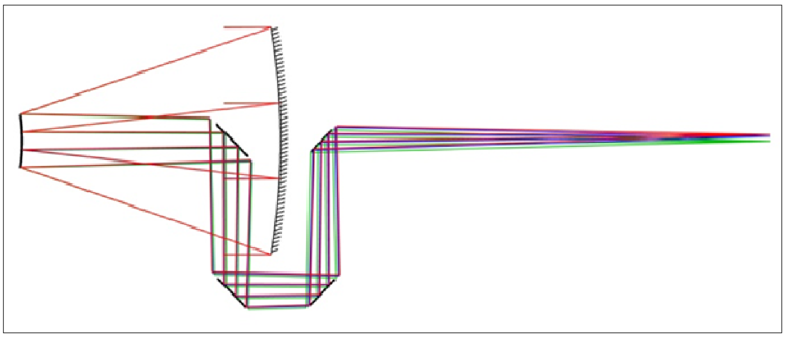


Figure. 126. Ray tracing for a Coudé arrangement, using a Cassegrain telescope with a primary-mirror focal ratio of 2.0. For the significance of the ray-tracing colours, see figure 118.

As the Nasmyth concept, the Coudé solution builds on a Cassegrain (or, possibly, a Gregorian telescope). Also as with the Nasmyth arrangement, the Coudé optical train follows via the primary and secondary mirrors plus a flat tertiary and exits through the altitude axis. From here, the light path normally proceeds to a separate Coudé laboratory. This laboratory has no mechanical connection with the telescope and is, thus, not affected by its movements. To provide large focal lengths, in practice, for Coudé arrangements, special secondary mirrors must be used. Coudé instruments can have close to unlimited sizes and weights. Moreover, they can be kept highly stable. A Coudé arrangement is shown in Fig. 126.

While highly stable, a Coudé focus station is a choice with a number of problems. The number of reflections required implies reduced throughput. The change of secondary mirror and Coudé -focus alignment are non-trivial procedures. The rather large focal ratio implies a small field of view. Also, the image scale tends to be rather extreme. Thus, the objects to be observed with the Coudé instrumentation have to be much brighter than those observable at other foci. In practice, only single, or crowded multiple, objects can be successfully observed in Coudé focus. Finally, but certainly not negligible, a Coudé arrangement is an expensive solution, sometimes needing a budget comparable to that of the telescope.

Coudé focus stations were popular with telescopes equatorially mounted. Nearly all Coudé focus platforms were dedicated to high-resolution spectrographs. With the introduction of echelle spectrometers, high-resolution spectroscopy over larger wavelength ranges became accessible with limted instrumentation in, for instance, Cassegrain focus. As a result, the popularity of the rather elaborate and expensive Coudé stations decreased.

When altitude-azimuth-mounted telescopes rapidly became the rule, the Coudé era came close to its end. However, for requirements on ultimate stability, still Coudé arrangements are without competition. As an illustration, the European Extremely Large Telescope (E-ELT) has a Coudé room planned for its ultra-stable high-resolution spectrograph working at optical and adjacent wavelengths and dedicated to the CODEX cosmology programme. CODEX is a cosmic-dynamics experiment, aimed at providing a direct measure of the cosmological expansion (Gilmozzi and Spyromilio, 2007; Quartin, 2010).

An alternative to Nasmyth and Coudé focal solutions

An important reason for the choice of a Nasmyth or Coudé focal arrangement is a desire for stability, or freedom from influence of telescope movements. Other reasons refer to a wish for large space around and possibilities for high weight of the instrumentation without a penalty on the stability of the instrumentation and the telescope. All these advantages can be obtained with an alternative solution. This alternative is an instrument station on the observing floor. In this case, the price to be paid is a necessity for fiber-cable use instead of fixed optics. While this is a limitation serious for photometric purposes, it is much less so for spectroscopy, for which it can even be of advantage. Fig. 127 illustrates a fiber-coupled instrument mounted on the observing floor.

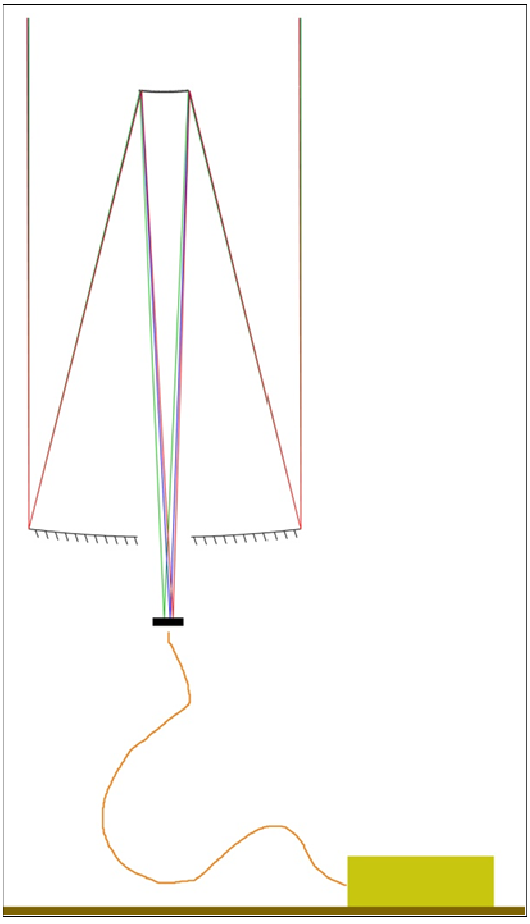


Figure 127. An instrument mounted on the observing floor and fibre coupled to the focus of a Cassegrain telescope with a primary-mirror focal ratio of 2.0

Centre-Section Focal Station(s)

If priority is given to availability of more than one instrument at any time, there is an alternative to the possibilities so far discussed. In this option, the centre section of the telescope is used for focal platforms. A tertiary mirror directs the light to instrumentation attached to the outer shell of the centre section. This focal-station alternative allows 2-6 auxiliary instruments to be ready for use at the same time. However, both dimensions and weight of these instruments are restricted. With a turning-mirror arrangement, a shift of instrument can be made very swiftly.

Other focal arrangements

In addition to the focal stations discussed, other arrangements are possible and have been used. However, these alternative solutions for instrument platforms are, in practice, rather rare. Most of them have been chosen for special reasons. Here, they are not further commented.

Relation between Cassegrain and Gregory focus stations

For many reasons, it seems natural to settle upon the key optomechanical parameters already at an early phase in the tentative optical telescope design. The key parameters are telescope aperture, the primary-mirror f ratio, the telescope F ratio and the back-focal distance. Once the aperture and the system length as well as telescope F ratio and back-focal length are given, choice of a Greogory concept will imply a smaller primary-mirror f ratio than the corresponding Cassegrain solution.

Telescope concept - what to choose?

For a 3 m class telescope intended for use at visual and adjacent wavelengths and with high image quality as a priority, it seems reasonable to limit the practically attractive possibilities for optical concepts. For many reasons, the choice could be limited to the Cassegrain, Gregorian and Nasmyth solutions. For practical reasons, as discussed above, a Cassegrain option seems more adequate than the Gregorian counterpart. Further, it seems advisable not to choose a Nasmyth concept alone but rather as a complement to a Cassegrain-type telescope. In any case, an observing-floor focal station should be seriously considered, either as a replacement for a Nasmyth station or as an additional option.

Primary mirror

Once the optical concept of the telescope has been fixed, it is natural to proceed to its primary mirror. This optical element is defined by a number of parameters defining its material and material quality, size, weight, shape, structure and finish quality. The first-mentioned parameters, material and material quality, are determined by the mirror substrate or the mirror blank. The quality of the substrate material is of fundamental importance for the quality of both the primary mirror and the total telescope. Further, the mirror substrate defines a considerable part of the total cost of the telescope.

Mirror substrate

In the absence of special and different requirements on the primary mirror and the following mirror or mirrors, it seems a prudent manner to choose the mirror substrate for all optical elements of the telescope with the aim to obtain best possible total performance. For a 3 m class telescope with high image quality as a priority item, the requirements on the substrate are, and have to be, very strong. Items to take care of are substrate homogeneity, elasticity, coefficient of thermal expansion, bulk stress birefringence, striae, frequency of bubbles and inclusions and freedom from contaminations but also density and brittleness.

First mirror substrates

The earliest telescope mirrors were made of metal alloys. They were reasonably manageable to produce and figure. Their reflectivity was, however, far from ideal. Already newly polished, these mirrors had a reflectivity of only around 60 %. Moreover, this reflectivity rapidly decreased. Repolishing had to be made several times per year, or the telescopes got performed less than reasonable. Further, the pioneer mirrors deformed very much under influence of temperature changes.

Window glass and pyrex glass

With George Ellery Hale, glass was introduced as the mirror material for large telescopes. The new mirror material was essentially equal to ordinary window glass albeit treated to be of as good quality as possible. While these mirrors caused smaller problems than their metal predecessors, they still had rather disturbing weaknesses. The glass had a substantial thermal expansion coefficient. Even when ambitiously temperature stabilized, as in the Hooker telescope, the material deformed under diurnal and other temperature cycles. Further the size and abundance of bubbles and inclusions were disturbingly high, making decent figuring a rather difficult undertaking. Later, glass materials have improved in the form of float glass, soda-lime glass and borosilicate glass.

Next step ahead in terms of mirror material came with pyrex glass and the Hale telescope. Compared to earlier glass materials, the Hale-telescope primary-mirror pyrex material had a rather low coefficient of thermal expansion and, in addition, it had considerably lower frequency of bubbles and inclusions. Still, with its around 40 tons mass, hardly ever relaxed thermally. Thus, regularly, it deformed regrettably much as a result of diurnal and other temperature variations. Even much worse was the performance of the primary mirror of the Bolsjoj 6 m telescope. The ceramic material, astrositall was rather inhomogeneous, had a high frequency of bubbles and inclusions and deformed very much with changing temperature.

Lately, borosilicate glass has, to some extent, regained interest as a substrate for mirrors in telescopes. This interest is primarily concentrated on mirrors equipped with active and, not least, adaptive optical systems. Borosilicate glass can be produced in large yet very thin sheets. These sheets can be figured to high precision. Stability defects causing serious problems in case of passive optical elements can today be eliminated with active and adaptive optics. Reference is made to Ardeberg et al. (2006) and Andersen et al. 2006).

Ceramic glass material

Around 1990 came a remarkable breakthrough concerning mirror material. The glass-ceramic material Zerodur, produced by Schott, Mainz, Germany, showed impressive qualities. Not least did the results from the Nordic Optical Telescope (NOT) testify to the excellence of Zerodur. NOT, with its 2.6 m Zerodur primary mirror, was, over a long time, one of very few Earth -based telescopes regularly producing sub-arcsecond images, frequently with FWHM below 0.6 arcsec. Competing with Zerodur were other more or less similar new materials, an improved version of Astrositall, from LZOS, Lytkarino, Moscow, Russia, fused quartz from various sources and Cervit from Corning, New York, USA. In 2010, these are still competing materials with qualities further improved.

Generally, the best available glass-ceramic materials are excellent mirror substrates. While composed of different materials, they show rather high homogeneity or very low over-all variation in terms of their refractive index. Correspondingly, their striae, or spatially short-range, over the order of a millimeter, variations of the refractive index, are low. Both the number and the sizes of bubbles and inclusions can be kept rather low.

The glass-ceramic materials have very low and highly spacially homogenous thermal expansion. Also, the thermal conductivity is favourable. Bulk stress birefringence is favourably low. The density of the materials is, at room temperature, typically around 2.5 gcm^{-3}, and they are easily figured to very high precision. Further, glass-ceramic materials are favourably easy to coat with aluminium as well as with silver.

While producers of mirror substrates in the form of glass ceramics for smaller apertures are reasonably many, the market concerning mirror blanks for 3 m class mirrors is, globally, rather limited. Applying strict quality criteria, there are, in 2010, three well known companies producing mirror substrates with diameters around 3 m and larger. These companies are, in alphabetical order, Corning Incorporated, New York, USA, Lytkarino Optical Glass Factory (LZOS), Lytkarino, Moscow region, Russia and Schott, Mainz, Germany. All three companies have delivered mirror blanks to large telescope projects. Further, all three companies know the market as well as their place in it. It is not discouraged to hope for a high-quality mirror substrate at bargain price, but it might well end in frustration.

Silicon carbide

Silicon carbide, also labeled carborundum, is a material in high regard for telescope mirrors. It has low density. Yet, it is rather hard and very stiff. Its thermal conductivity is favourably high and its coefficient of thermal expansion is very low. Until relatively recently, silicon carbide could not be produced in discs sufficiently large for a 3 m class telescope. However, this is now history and mirror blanks for astronomy have been produced with diameters well over 3 m. Reference is made to Petrovsky et al., 1994. In addition to a certain brittleness, the only substantial disadvantage of silicon carbide as mirror material is its relatively high cost.

Beryllium

Especially for mirrors that have to be light yet stiff, beryllium has, during later years, been a substrate much discussed. For aircraft and space-based telescope and telescope enclosures, beryllium is especially interesting and has been used in many space applications and will most certainly be so also in the future. The material is light. At the same time, it is rather stiff. Further, beryllium has a favourably low coefficient of thermal expansion. A disadvantage is a considerable brittleness. Beryllium is a rare element and, thus, expensive. Another, serious, disadvantage of the material is its high toxicity. As inhalation of beryllium is especially dangerous, figuring has to be accompanied by a high degree of safety measures, further increasing the cost.

Borosilicate

Within telescope technology, borosilicate is a well-known mirror substrate. It is relative light and it has a low coefficient of thermal expansion. At the same time, borosilicate is somewhat btittle. Higher grades of the material show relatively low degrees of bubbles and inclusions as well as striation.

Aluminium

During many years, with varying intensity, the use of aluminium mirrors for large telescopes has been discussed. Reference is made to Forbes (1992), Rozelot (1992a, 1992b), Ardeberg et al. (1992), Aluminium as a mirror substrate has many positive features. It is light. It is stiff. It can be figured to very high aspect ratios. It has a high thermal conductivity. It is easy to control thermally. It is easy to handle and figure (Ruch, 1992). The risk of fractures is low. It is relatively cheap. While dimensional stability of larger aluminium mirrors might be doubted, this should be a minor problem with active optics. Still, larger aluminium mirrors are rare in telescopes. One reason might be that of coating problems. While aluminium is, itself, an often-used coating material, nickel is quoted as coating for mirrors of aluminium (Pasquetti, 1992). However, the coefficients of thermal expansion are rather different for these two materials.

Carbon fibre-reinforced polymer (CFRP)

For construction of telescopes as for a very large amount of other purposes, carbon fibre-reinforced polymer (CFRP) has drawn considerable attention and interest. Compared to all other substrates considered for telescope mirrors, CFRP has some very high advantages. It is exceptionally light. At the same time it is very stiff. Its coefficient of thermal expansion is very low. Further, CFRP can be formed to very thin sheets, still easy to handle. It should be possible to fabricate it in sizes adequate for large telescopes.

CFRP has been very much discussed as telescope mirror material. Yet, little has, in this direction, happened so far. There seems to be at least two reasons for that. First, for high-precision polishing, the fibre reinforcement is a clear problem. Second, CFRP is a rather expensive material, even for real-size tests and assessments.

Size of primary mirror

The size of the primary mirror is a most important factor. It determines the (maximum) collecting power of your telescope. If and when you use your telescope with full active and adaptive optics, the diameter of the primary mirror also determines the diffraction limit, or the spatial resolution reachable. In combination, the collecting power, determining the amount of light caught, and the spatial resolution, determining the concentration on the detector, define the detection limit of the telescope.

In principle, you may feel free to choose the size and shape of your primary mirror. In real life, things are somewhat more restricted. A mirror substrate of a size adequate for your wanted primary mirror must be available. Further, it must hold a quality acceptable for your purpose. It must have a weight and also otherwise be able to handle in a safe manner, and it must be offered at a price you can afford.

The best mirror materials, as discussed above, are normally not available in an off-the-shelf manner. They are too complicated to fabricate and too expensive to keep in store for may-be customers. Thus, these mirror blanks are normally made on demand. This in turn, implies that the substrate of the favourite mirror has to be ordered. This requires time, especially taken into account the high prices of the market and the corresponding requirements on quality assurance, contract and insurance. Including also final testing and delivery, a realistic time span from first contacts with the substrate company to delivery for figuring is somewhere between 10 and 20 months.

Weight of primary mirror

For the performance, not least regarding image quality, the weight of the final primary mirror is a parameter of prime importance. It determines the weight of the mirror cell as well as the approximate weight of the total moveable parts of the telescope. Thus, to a considerable extent, the weight of the primary mirror also influences the cost of the telescope. Moreover, it is of high importance for the stiffness and adaptivity of the primary mirror as well as of its thermal relaxation time.

One way to secure a primary mirror that is both reasonably light and stiff is to choose a mirror of light-weighted type. Such a mirror has a thin, conventional type of surface. Beneath this surface, there is a support structure guaranteeing high rigidity while, at the same time allowing a substantial weight reduction. The support structure can be in the form of ribs but also be made as smaller and distributed structural elements. This form of light-weighting can cut the total weight of the mirror by as much as 80 % while maintaining its original stiffness. Fig. 128 illustrates light-weighting with a rather modest factor.

A light-weighted primary mirror implies a lighter and less expensive telescope. In addition, the thermal relaxation time decreases dramatically with light-weighting. This favors a short time of cooling after casting but also a decreased thermal relaxation time of the final mirror. In addition, as discussed above, the decreased weight of the primary mirror implicit reduced weight and cost of the total telescope. As an extra bonus, the free volume of a light-weighted mirror behind its surface can be conveniently used for measures of temperature control, for example with the help of some temperature-controlled liquid. However, such an arrangement, convenient as it might be for temperature stability, adds weight to the mirror.

Pioneer work on large light-weighted mirrors was met with great interest and hopes. However, while meeting many of its original goals very well, the technique has a clear disadvantage. The total mirror is stiff but not homogeneous in its structure. Thus, it is not flexible enough to deform in a fully controlled manner. Accordingly, light-weighted mirrors are far from ideal for use with systems of adaptive optics.

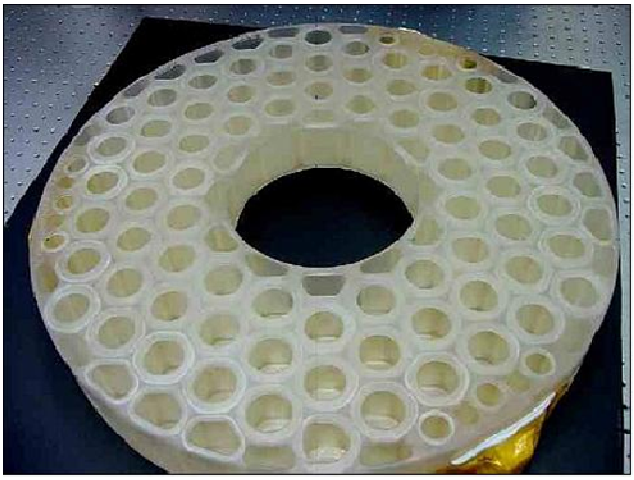


Figure 128. Light-weighted mirror substrate for SOFIA telescope.

An alternative way to achieve a large mirror that is, at the same time, light, is to make it thin. The thinner it is, the lighter it is. At the same time, a thinner mirror means a mirror with a decreased thermal relaxation time. In these two respects, the thin mirror has similar qualities as its light-weighted counterpart. The similarity also holds concerning reduction of the weight and cost of the entire telescope.

The similarity between the thin and the light-weighted mirrors does not, however, hold for the stiffness of the mirror. While the light-weighted mirror is very stiff, the thin mirror is not. For a modern telescope with a large primary mirror this can, clearly, be seen as an advantage, as it sets the scene for adaptive optics, dicussed under other title in the present publication. As a result, thin primary mirrors have been adopted with high success in terms of image quality. Wile early tin primary mirrors were of concave-flat form, advances in optical processing now allow them to be of meniscus type.

Aspect ratio

In many ways, it might be seen as natural to choose a primary-mirror diameter as large as possible and a corresponding mirror thickness as small as possible. Taking safe function and handling into account, things are slightly more difficult. Generally, the deflectivity of mirror is proportional to the fourth power of its diameter and inversely proportional to the square of its thickness. Thus, in practice, we should choose the diameter and the thickness of the primary mirror in a matching manner, with due regard to all relevant practicalities. These concern, primarily, applicability of active high-precision and real-time control of the mirror surface as well as safe mirror handling routines.

As a relevant and adequate measure of mirror flexibility, with special importance for use of active-optics systems, we use the aspect ratio of the mirror. It is the ratio of the diameter to the thickness of the mirror. While less well defined for older, concave-flat primary mirrors, the aspect ratio is perfectly well defined for mirrors of meniscus type.

A well-chosen aspect ratio should take into account both the requirements of the active-optics system and those of safe handling. Safe handling has to be guaranteed for delivery, routine maneuvers, mirror-surface cleaning and mirror washing and coating. An aspect ratio below around 12 implies difficulties to implement a high-quality system of active optics. On the other hand, an aspect ratio significantly higher than 20 is a challenge with respect to mirror handling.

Mirror figuring

Optical high-precision figuring of large-surface telescope mirrors has always been, and still is, a major technical challenge. Over time, figuring tools have become gradually more sophisticated and practical to use. Today, grinding and, especially, polishing tools are highly advanced pieces of equipment. Real-time assessment and feed-back procedures are equally well developed. However, in parallel, requirements on the precision of optical surfaces for telescopes have increased even more. As a result, high-quality figuring of a large telescope mirror is a combination of advanced techniques and art.

A modern figuring facility capable of delivering high-quality primary and following mirrors to large telescopes is limited in its achievable precision. One important limitation is often the mirror substrate. A mirror blank of low quality can hardly be converted to a final mirror of high or even reasonable quality. Another limitation is the adequacy of the support pads used during figuring. If they do not match the aspect ratio of the mirror and/or the support system to be implemented in the telescope, they will cause problems. Time is a further limiting factor. High -accuracy figuring is not a quick job. Finally, and ultimately, the professionality of the figuring team determine the outcome of their work.

There are large numbers of figuring places for mirrors of smaller size. For mirrors of 3 m class there are only very few facilities. In Europe, there are four well-known companies that can figure such mirror surfaces to high precision. They are, in alphabetical order, Advanced Mechanical and Optical Systems (AMOS), Angleur, Liège region, Belgium, LZOS, Lytkarino

Optical Glass Factory (LZOS), Lytkarino, Moscow region, Russia, Sagem, with several facilities in France and world-wide, and Opteon, Tuorla, Turku region, Finland. They all accept to figure large mirrors to a precision of around 15 nm, or, possibly, better, at higher spatial frequencies. All of them except for AMOS have figured telescope mirrors with diameters of 3 m and larger.

Optical design

Before embarking on final choice of optical design parameters, it is convenient to have a look at a general telescope optical layout. For such a layout, we make some decisions and some tentative assumptions. Based on the discussion above, it is decided to opt for a 3 m class telescope according to a Cassegrain concept. Here, to promote a more concrete and qualitative discussion, we confirm an aperture of 3 000 mm. Further, it is decided to adopt a Ritchey-Chrétien configuration, the latter choice intended to provide a combination of high image quality with a reasonably large field of view.

In addition, tentatively, we opt for a primary mirror with a focal ratio of f/1.5. For the over-all telescope focal ratio, we assume f/11. Further, we define the back-focal distance as 1 200 mm. These parameters serve to freeze the telescope design. The hole of the primary mirror is set to 600 mm. This should give a first-hand field of view (diameter) of somewhat more than 20 arcmin. Graphically, this is illustrated in Fig. 129, in which the symbols adopted are explained. The same symbols are used in continuation. The entrance pupil is located on the primary mirror.

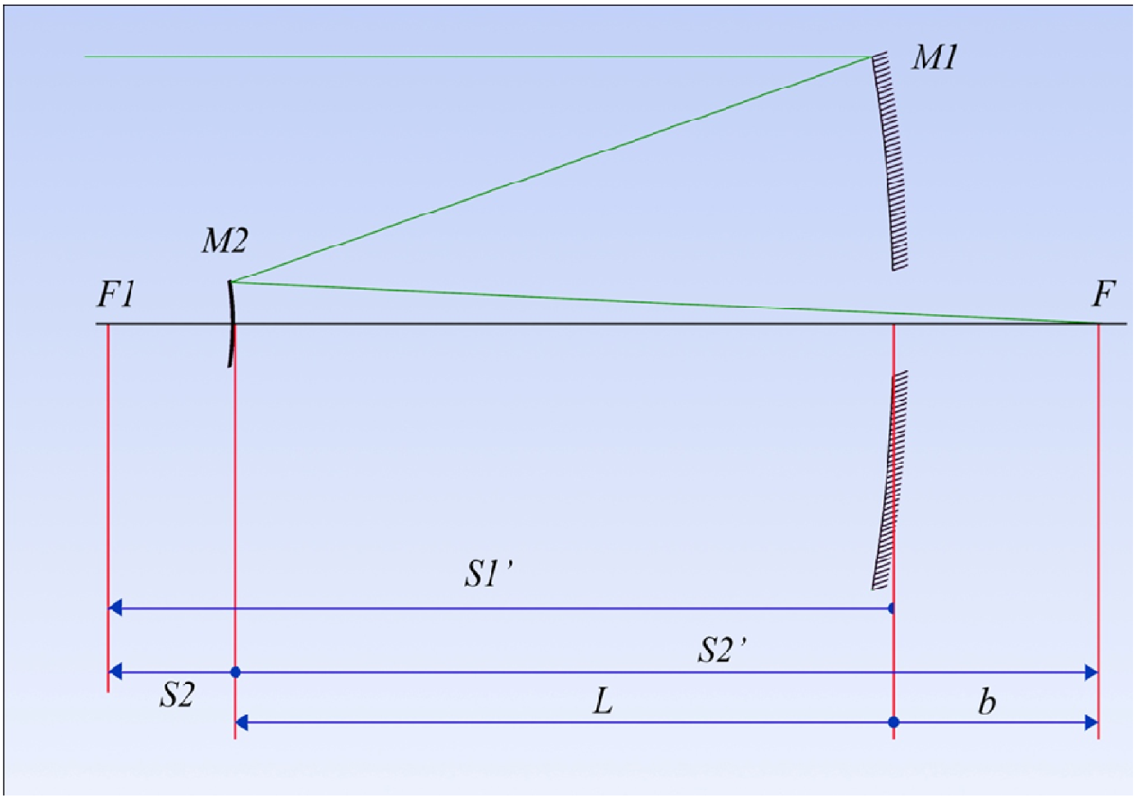


Figure. 129. Graphical representation of a tentative layout of a Cassegrain-concept, Ritchey-Chrétien-type 3 m telescope. M1 and M2 denote the primary and secondary mirrors, respectively. F denotes the telescope focal point, F1 the joint foci of M1 and M2 and L the distance between the reflecting surfaces of M1 and M2. S1' is the focal length of M1, S2 is the object distance, S2' is the image distance for image formation in M2 and b is the back-focal distance.

For clarity, it is noted that, in Fig. 129, M1 has a diameter of 3 000 mm and M2 a diameter of approximately 500 mm. L is around 4 000 mm. S1' is 4 500 mm, S2 500 mm and S2' 5 200 mm. Using the figure as a design illustration, the scale can be seen as set by M1 being, as decided above, 3 000 mm.

In the final phase of optical design, the parameters given above can be seen as first tentative input specifications. During design, (some of) these parameters can be modified in a trial-and-error manner. In this process, a number of factors have to be taken into account. These factors may be defined as referring to science requirements, science competitiveness, technical feasibilities, operation-mode realities, cost considerations (referring to installation as well as operation), and, in addition, a number of practicalities of a wide range. Thus, optical design is a demanding undertaking. Shortcuts might seem attractive. However, such easy ways out will, nearly always, back-fire once the telescope is ready for regular use.

Two focal ratios

There are two focal ratios to determine for a telescope as discussed. In both cases, the focal ratio refers to the ratio beween the focal length and the diameter of the primary mirror. Both focal ratios are highly important for the design work as well as for the scientific-technical operation and functioning of the operating telescopes and its relation to auxiliary instrumentation. One of these focal ratios refers to the primary mirror as such, the other to the telescope as an optical ensemble. The primary-mirror focal ratio determines, to a large extent, the over-all geometry of the telescope. The total, telescope focal ratio defines two important imaging features, the physical resolution and the field of view. Both features have to be compatible with the priority set of science requirements.

Focal ratio of primary mirror

The most straightforward of the two focal ratios is that of the primary mirror. This focal ratio determines the curvature of the primary-mirror reflecting surface as well as the distance from this surface to the corresponding focus, equal to half the radius of curvature. Thereby, it is of prime importance for the distance between the primary and secondary mirrors and for the total length of the telescope tube. At the same time, the choice of primary-mirror focal ratio has substantial implications on mirror figuring.

Classical reflecting telescopes had large primary-mirror focal ratios. The reasons were, to a large extent, two-fold. First, it was highly challenging, if not impossible, to figure a large mirror to required optical precision, if the focal ratio were below a certain limit. Second, even if such a figuring precision could be achieved, the results of operation were hard to guarantee. The reason was that the smaller the focal ratio, the more were the telescopes prone to give poor image-quality results due to the small margins available for fully correct focus setting. With the often highly inadequate temperature circumstances and changes, this was very often a highly important source of malfunction.

Thus, classical large reflectors had, typically, primary mirrors with focal ratios of the order of 5 to 10. Unavoidable, while giving focal positions with relatively manageable margins, the resulting telescope tubes were rather long. Thus, they were of less than desirable stiffness with secondary image-quality problems a normal plague. In addition, the size of the telescope tubes forced their mountings and enclosures to be correspondingly large, heavy and expensive. In addition, huge enclosure volumes normally severely degraded the image quality obtainable.

Only recently has it been possible in practice to drastically decrease the focal ratios of large mirrors for telescopes intended for work at optical-visual and adjacent wavelengths. The most important reason is a rapid increase in the sophistication of optical polishing. Not least have new tools and real-time computer-controlled combined polishing and evaluation implied entirely new dimensions. It should be noted that, except for much improved flexibility in terms of mirror focal ratio and surface quality, the development has, in many situations of high importance, implied entirely new possibilities concerning higher-order and/or off-axis figuring of large mirrors.

From around 1970 to 1990 representative focal ratios of the primary mirrors of larger telescopes for the optical-visual and adjacent wavelength range converted from normally in the range 5 - 8 to a corresponding range of 2 - 3. The effects were as obvious as positive. More compact and less heavy telescopes set the scene for smaller effects of alignment problems, mechanical relaxations and thermal inertia. At the same time, enclosures could be drastically reduced in size as could their adverse influence on observed image quality. As an important extra bonus, telescopes, enclosures and control facilities could be, not only increased in quality, but also, at the same time, decreased in cost.

In 2010, the tendency described has given further improvements and benefits. Current large telescope primary mirrors are, dependent on their priority programs, given focal ratios of 2.0 and below. At this point of the development, limits are not any more defined entirely, nor always to a major extent, by considerations of optical polishing. Rather, astronomers, opticians and mechanical engineers are left with a range of choices that are rather favorable but also challenging due to their often quite extreme nature.

Further, while the resulting sizes of telescopes were to a very large extent determined by the focal ratio of the primary mirror, this is today no longer so. Gradually, for example, the back-focal distance has taken, and takes, an important role, a situation in which it requires new and careful consideration. Referring to Fig. 129 and its notations, it is seen that the length of the telescope tube is L, where $L = f1(b-f) / (f1-f)$. Here, $f1$ and f are the focal lengths corresponding to the foci $F1$ and F. Note that $f1$ is negative whilst f is positive.

Towards the end of the 20th and in the beginning of the 21st century, larger primary mirrors were, to some extent, made as segmented surfaces. Segmentation has a notable influence on the concept of primary-mirror focal ratio. In a primary-mirror concept relying on segmentation of the surface, the over-all primary-mirror f ratio can be made very small as the figuring is done for the segments as individual pieces.

Primary-mirror focal ratio - some consequences

As has been discussed above, the final choice of the primary-mirror focal ratio will have some consequences necessary to take into account in practice. A smaller focal ratio will shorten the telescope tube and decrease the tendency for mechanical deformations. On the other hand, a smaller focal ratio also implies a higher sensitivity to focus misadjustments. In addition, when the primary-mirror focal ratio reaches rather small values, polishing, supporting and handling of the mirror approach critical limitations. See Schroeder (1978). Also, scattered light and baffling imply considerable challenges for faster optical telescope systems. At the same time, a small focal ratio gives a more compact and lighter telescope and, as a consequence, a more compact enclosure generating less enclosure turbulence. Further, the smaller dimensions of telescope and enclosure are positive in terms of project budget.

In 2010, f/2.0 should be regarded as a relatively conservative focal ratio for a new 3 m class telescope for optical-visual and adjacent wavelengths. On the other hand, f/1.0 must, for the same telescope, be seen as rather extreme. This is especially the case, as with such a primary-mirror focal ratio, the telescope length will, to a large extent, be determined by other factors.

The back-focal distance is an obvious example as is the need to provide space in Cassegrain focus for auxiliary instrumentation of reasonable size. While the primary-mirror focal ratio must be chosen individually for each telescope project, a focal ratio around 1.5 seems a good

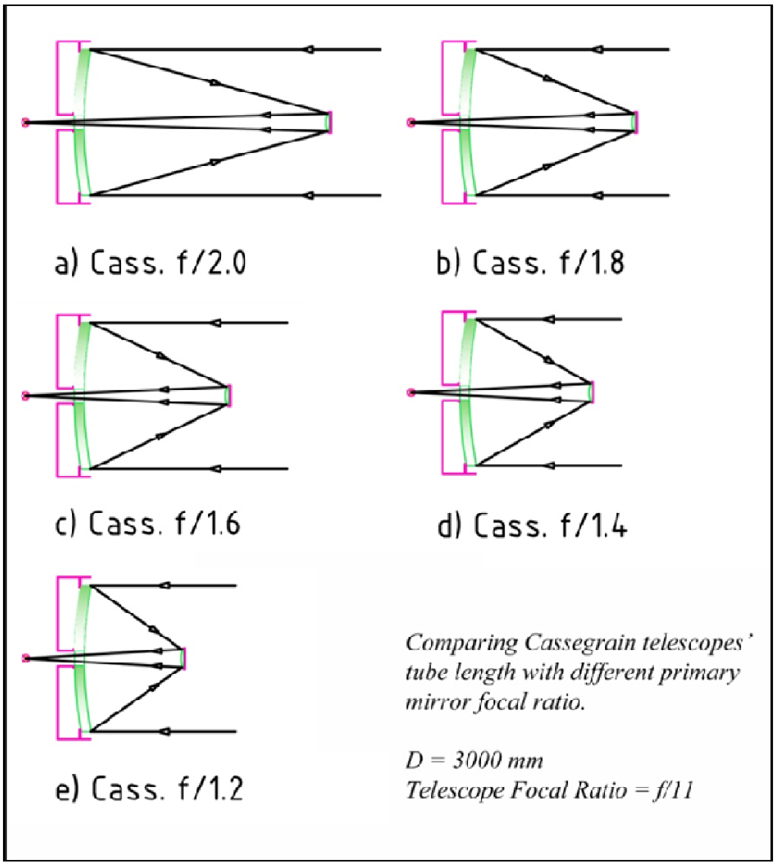


Figure 130. Primary-mirror focal ratio and tube length in a Cassegrain configuration.

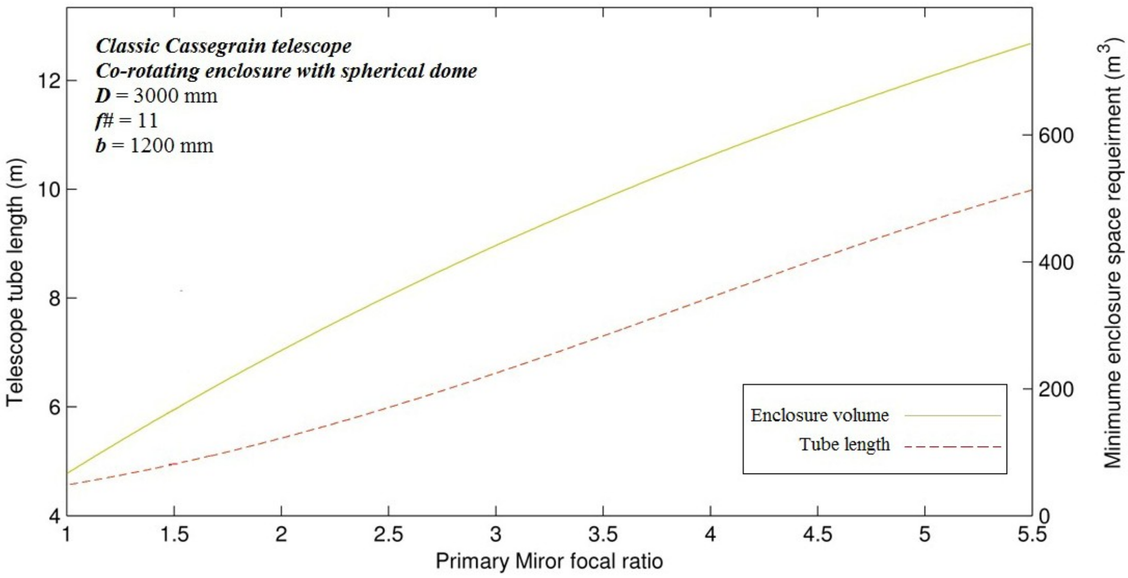


Figure 131. Relation between primary-mirror focal ratio and enclosure volume. For details, refer to data given in the upper left-hand corner of the figure and to Figure 129. The dome diameter has, for simplicity, been set equal to the telescope tube length, L, with L = F1(b-F)/F-F1), symbols as defined in Figure 129. Some space for the M2 cell and telescope top ring has been added.

Figure 132. Nordic Optical Telescope and Hooker telescope, both with approximately 2.5 m apertures but with different primary-mirror focal ratios, 2.0 and 5.0, respectively. The two telescopes and their enclosures are compared. In both cases, the same scaling is applied.

starting point. In figs. 130 to 132, comparisons are made of Cassegrain telescope concepts with different primary-mirror focal ratios and their consequences on telescope and enclosure size.

Telescope focal ratio

The over-all focal ratio of the telescope has a number of implications. Like the primary-mirror focal ratio, it affects the telescope tube length, albeit only marginally so. The telescope focal ratio must be taken into account concerning the diameter of the central hole of the primary mirror. Further, the telescope focal ratio influences the size and, thus, the weight, of the secondary mirror, a fact of importance when pre-focus adaptive-optics systems are of interest.

In principle, the telescope focal ratio is important for the field of view. However, in practice the latter quantity is defined by off-axis aberrations as functions of distance from the optical axis. Important for instrumentation is the influence of the telescope focal ratio on the size of the corresponding optical entrance pupil. Highly important is the direct influence on image scale. This is a fact closely related to the choice of pixel size and requirements for relay optics.

It is good practice to keep reminded of the need for pixel-size optimization. On the one hand, the pixel size of the detector surface should be small enough to allow adequate handling also of images at the limit of resolution. On the other hand, the pixel size has to be kept large enough that also faint objects can create a significant response and that image processing is not unnecessarily hampered by excessive numbers of pixels. Basically, it is good practice to keep reminded of the Nyquist criterion as applied to the pixel size. With the limiting resolution, in radians, denoted *r(rad)*, the corresponding resolution in arcseconds denoted *r('')*, the equivalent linear resolution denoted *L*, and with the pixel size p, the wavelength λ, the telescope aperture *D* and the telescope focal ratio *f*, we have

$r(rad) = \lambda/D \qquad r('') = 206265\lambda/D \qquad L = f\, r(rad)$

and, $\quad p = 1/2\, L = 1/2\ f\, \lambda/D$

There are a number of practicalities to be noted for the final choice of telescope focal ratio. In addition to those discussed here, it is of interest to attempt to stay compatible with the auxiliary instruments normally available in the communities of astronomers. A choice of a more or less odd telescope focal ratio may imply compatibility difficulties for instruments otherwise easily available. In practice, most modern telescopes for optical-visual and adjacent wavelengths, and corresponding auxiliary instruments, have over-all focal ratios in the range f/8 to f/15.

Back-focal distance

A telescope, even if ever so sophisticated, is of real scientific use only together with a compatible piece of instrumentation. Thus, for a Cassegrain or Gregororian telescope, the back-focal distance is a parameter of utmost importance. Still, regrettably, it is often given small attention. The result is often a necessity to adjust the geometry of the auxiliary instrument to the back-focal space available rather than to that best serving the science goals of the instrument.

In any given situation, there is a minimum requirement for the back-focal distance. This is defined by the totality of the elements unavoidably needing space below the surface of the primary mirror. In the case of a normal Cassegrain configuration, we have the primary-mirror body, the support and actuator system, the primary-mirror cell, the field rotator, the instrument adapter and flanges. Fig. 133 illustrates the ensemble of these parts.

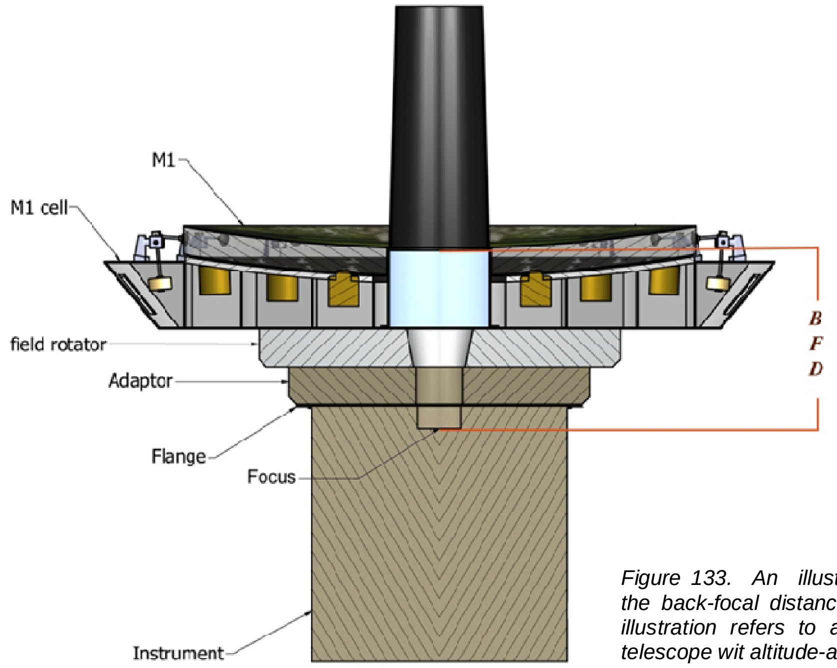


Figure 133. An illustration of the importance of the back-focal distance, here denoted BFD. The illustration refers to a Cassegrain or Gregorian telescope wit altitude-azimuth mount.

While sufficient space for the telescope units mentioned is normally provided, there is often a clear temptation to minimize the back-focal distance by adding only a smaller space for the part of the auxiliary instrumentation in front of the focal point. This is a quite common cause not only of problems for the instrument designer but also of unfortunate limitations in terms of best possible use of the instrument in scientific terms. Thus, it is highly recommendable to treat the back-focal distance with certain generosity, even if it adds somewhat to the size of the telescope and the enclosure. In addition, it is of importance to design the telescope mounting with due regard to the total size of the auxiliary instrumentation expected and also, and important, to the need for sufficient space between the instrument back-side and the fork floor when the telescope is in zenith position.

For a 3 m class telescope, it is prudent to allow for a back-focal distance of at least 1.0 m and, in more general terms, 1.1 to 1.2 m. In addition, it seems wise to count on instrumental extensions of the order of 1.5 m. Finally, the free space in zenith position between the instrument back side and the fork floor should, normally, be at least 0.25 m.

Optical relations

For a summary of some optical relations, reference is made to Fig. 129. In accordance with this figure, the following denotations are used throughout.

D Primary-mirror diameter in meters

$f_/$ Primary-mirror focal ratio (negative)

S_1 Object to primary-mirror distance (negative)

S_1' Primary-mirror focal length in meters (negative)

R_1 Primary-mirror radius of curvature in meters (negative)

R_2 Secondary-mirror radius of curvature in meters

S_2 Object distance in meters

S_2' Image distance for image formation in M2 plus inter-mirror distance in meters

f# Telescope focal ratio

F Telescope focal length in meters

B Back-focal distance in meters

L Distance in meters between reflecting surfaces of primary and secondary mirrors

Referring to Fig. 129, and with D = 3000 mm, f/ = -1.5, f# = 11, and b = 1200 mm; we get:

$$S_1^{'} = R_1 / 2 \rightarrow S_1^{'} = -4500\,mm$$

$$R_1 = -2Df_/ \rightarrow R_1 = -9000\,mm$$

$$F = Df_\# \rightarrow F = 33000 \quad mm$$

$$L = \frac{S_1^{'}(F-b)}{F-S_1^{'}} \rightarrow L = -3816mm$$

$$S_2^{'} = b - L \rightarrow S_2^{'} = 5016 \; mm$$

$$S_2 = S_1^{'} - L \rightarrow S_2 = -684\,mm$$

$$R_2 = \frac{2S_2S_2^{'}}{S_2 + S_2^{'}} \rightarrow R_2 = -1584\,mm$$

If a classical Cassegrain concept is chosen, the primary mirror is a paraboloid. It has a conic constant δ_1, for which

$$\delta_1 = -\left(\frac{S_1^{'} - S_1}{S_1^{'} + S_1}\right)^2 = -1$$

In the same concept, the conic constant of the secondary mirror is δ_2, for which

$$\delta_2 = -\left(\frac{S_2^{'} - S_2}{S_2^{'} + S_2}\right)^2 \rightarrow \delta_2 = -1.7313$$

The diameter of the secondary mirror is D_2, where

$$D_2 = D_1\left(k + 2\theta\, f_{/}(1-k)\right) \rightarrow D_2 = 508\ mm \quad with \quad k = \frac{R_2(S_2^{'} + S_2)}{R_1 S_2^{'}} \quad and\ \ when\ \ \theta\ is\ FOV$$

Returning to the Ritchey-Chrétien design, reference is made to Fig. 129. For this design, the correction terms to the conic constants of the primary and secondary mirrors, δ_1 and δ_2, respectively, get $\Delta\delta_1$ and $\Delta\delta_2$, where

$$\Delta\delta_1 = -\frac{2\Omega\left(1 - m_1^2 m_2^2\right)}{m_2^2(1-\Omega)(1-m_1)^3} = -0.0066$$

and

$$\Delta\delta_2 = -\frac{2m_2\left(1 - m_1^2 m_2^2\right)}{(1-\Omega)(1-m_2)^3} = -0.0680$$

Here,

$$\Omega = \frac{s_2}{s_1^{'}} = 0.152$$

is the marginal ray height ratio, and

$$m_i = -\frac{S_i^{'}}{S_i} \rightarrow \begin{cases} m_1 = 0 \\ m_2 = 7.33 \end{cases}$$

is the magnification. Thus:

$$\delta_{1rc} = \delta_1 + \Delta\delta_1 = -1.0066 \quad and \quad \delta_{2rc} = \delta_2 + \Delta\delta_2 = -1.7993$$

Ritchey-Chrétien system, spherical aberration, coma and astigmatism

From ray-tracing inspection and analysis, it can be shown that the Ritchey-Chrétien system is free from both spherical aberration and coma. It has, however, some effect of astigmatism. The plane of best focus is mid-way between the sagittae and tangential astigmatic image planes.

Denoting the radius of curvature of the so accepted image plane r, we have

$$r = \frac{S_1^{'}F^2(S_1^{'} - L)}{FS_1^{'2} + L(F^2 - S_1^{'2})} = -706\ mm$$

Thus, the Ritchey-Chrétien version of the Cassegrain telescope concept, with a curved image plane, is free from both spherical aberration and coma. Then, two problems remain. They are the curved image plane and astigmatism, the latter demonstrated in Fig. 136. This is shown in figs. 134 and 135.

In a two-mirror telescope, astigmatism cannot be completely removed. However, while it defines a limiting image-quality factor in principle, in practice, with adequate care taken, it can be brought to a level compatible with very high image quality. Still, it should be noted that permanent elimination of significant image-quality degradation due to astigmatism is an item of priority for telescope operation.

A curved image plane, accepted as an escape from effects of mirror curvature and astigmatism, was seen as a rather acceptable price in the era of photographic emulsions. The reason was that both glass plates and, especially, film as detector bases could, in their holders, be forced to follow the curvature of the image plane. Also during the first decades of CCD imaging, the image -plane curvature was quite acceptable, as the CCD detectors of the time were too small in extension for the curvature degradation to be noticeable.

Today, the situation is different. CCD detectors, and especially mosaic versions of them, cover substantial fields. Thus, the image-curvature degradation is fully noticeable. The high attention on image quality, significant for later years, makes the problem even more obvious. In addition, the CCD detector units cannot, as the photographic plates and films, be forced to comply with the curved image plane. However, field flattening is a relatively uncomplicated measure.

Compared to the classical Cassegrain concept, the Ritchey-Chrétien version has clear advantages. It is, however, as sensitive as its classical counterpart to effects of misalignment. This is emphasized in projects with high ambitions concerning image quality. Also rather small focus mis-matches can introduce significant effects of spherical aberration. In addition, it causes variations of the image scale. The latter effect can cause problems not only if astrometry is attempted but also for photometry adopting image-stacking routines.

Deficient alignment of the primary and secondary mirrors is a problem as common as serious. Both de-centring and tilt result in effects of coma. With an active-optics system properly designed and operated, however, effects of de-focus as well as of de-centring should be easily eliminated via the secondary mirror mount with its five-degrees-of-freedom movement pattern.

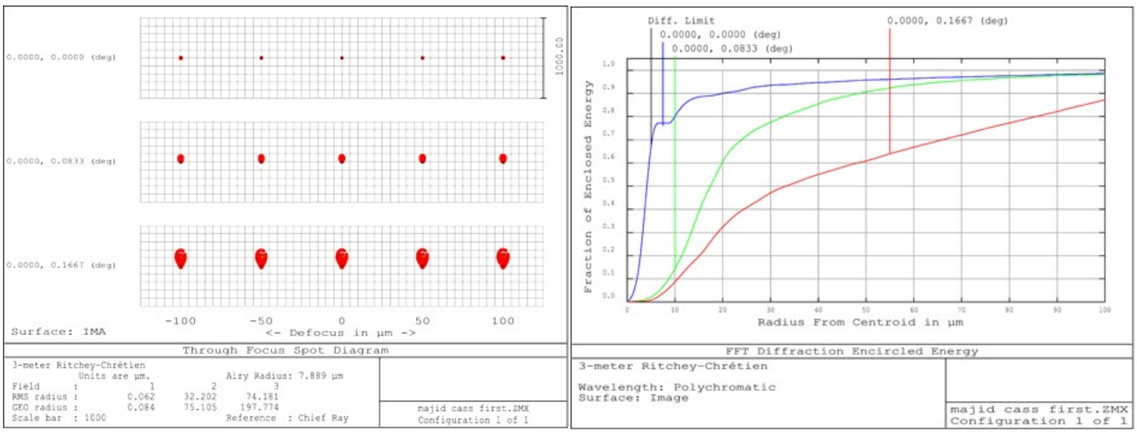


Figure 134. Spot diagram, left, for a classical Cassegrain telescope shows strong coma and spherical abberation increasing the encirled-energy diameter as a function of distance from the optical axis, right.

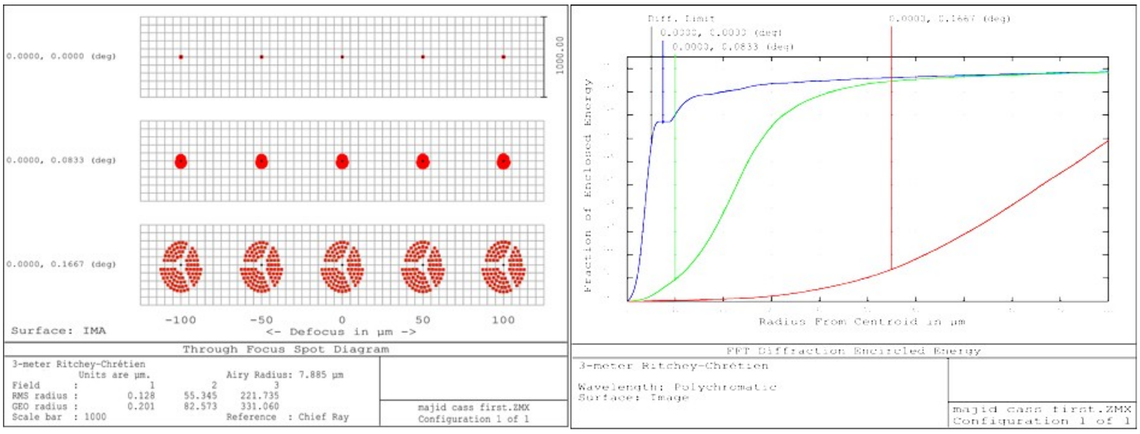


Figure 135. The same Cassegrain concept as in Figure 25 but in a Ritchey-Chrétien version. Now, field curvature and astigmatism are the only aberrations remaining, left. The encircled-energy diameter over a flat image plane increases rapidly with increasing distance from the optical axis, right.

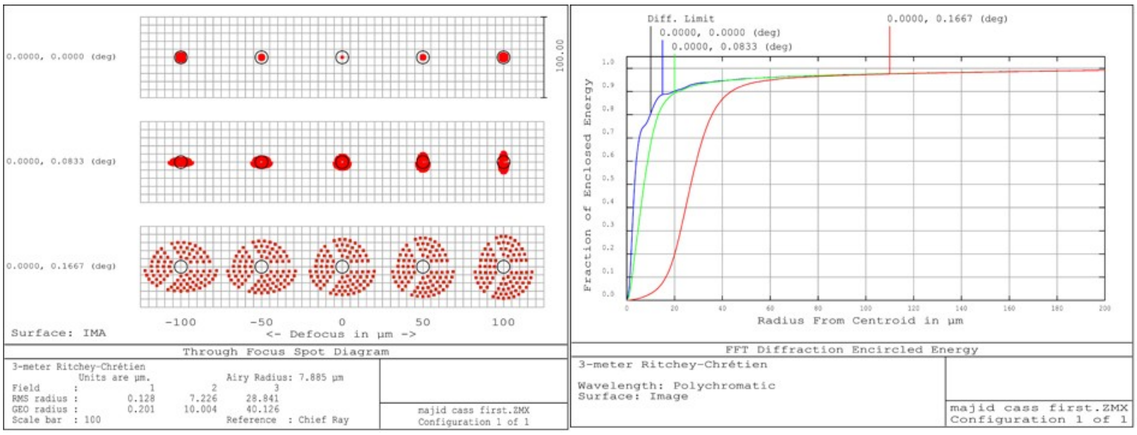


Figure 136. The same concept and version as in Figure 26 but now with a curved image plane with an image-quality optimised curvature. Now, astigmatism is the only aberration remaining, left. The encircled-energy diameter is small and the corresponding image quality very high even at larger distances from the optical axis, right. While the image scale in the left-hand parts of figures 134 and 135 is the same, here it is increased by a factor of 10.

Tolerance analysis

Currently, in most fields of astronomy, for observations in the visual and adjacent wavelength regions, expectations on modern telescopes to a very large degree are centered on image quality. Until recently, the very hardest demands on image quality were a privilege for astronomers using telescopes in orbit, while their colleagues using ground-based telescopes did not really have the same expectations as they knew that they anyhow were limited by atmospheric turbulence. The space telescopes had as their most ambitious demand an image quality limited by effects of diffraction only at the same times as the ground-based counterparts did quite well as long as their contributions to the observational FWHM were significantly below those from atmospheric turbulence. In practice, expectations were even lower, as it was well known that effects of gravitation and temperature changes on the shape of both the primary mirror surface and on the telescope structure and optical alignment in practice always were at least as negative for the resulting image quality as the effects of the atmosphere.

The introduction of active optics changed the picture to a significant extent. Practice has demonstrated that sophisticated active-optics systems are fully capable of a performance implying that the contributions to the observational FWHM values from the telescope can be kept well below those of the atmosphere even in good atmospheric conditions.

At the same time, ambitious site-selection campaigns have identified higher mountain sites with a quality allowing observations with FWHM values well below one arcsecond. Some of the best sites allow even such values below half an arcsecond during significant part of the nights available. Thus, telescopes should be designed for optomechanical qualities high enough not to add more than marginally to such image-diameter data.

As long as ambitions include even adaptive optics, of lower or higher order, telescope designs have to be even more sophisticated. A 3 m class telescope has, in visual light, a diffraction limit of around 0.04 arcseconds. For a system of adaptive optics to be meaningful, the basic optomechanical quality has to be very high, even though feedback procedures are used. As a result, massive efforts have to go into suppression of a range of sources of optical aberrations. Important challenges concern errors due to mirror deformation and misalignment as well as to deficiencies of mirror mounts and supports. With the image-quality expectations currently prevailing, such errors can not be prevented to the extent required but have to be compensated in real time.

In many ways, a Cassegrain telescope is a rather good choice concerning high image quality. Its optical train offers special advantages, as its alignment is that of two mirrors only and these mirrors must have a common optical axis. The efforts can concentrate on the form of these two mirrors and maintenance of their alignment.

Keeping the surface of the primary mirror close enough to its theoretical form requires high-quality figuring over higher spatial frequencies but also corresponding high-quality real-time support over lower spatial frequencies. Axial and lateral support systems of high sophistication are a necessity. In addition, the cell of the primary mirror has to be designed with matching sophistication.

In a telescope performing with active optics only, not including adaptive optics, the secondary mirror can have a relatively moderate aspect ratio. Being much smaller than the primary mirror, maintenance of its correct surface should not be a major problem. However, its alignment is far from simple. Depending on elevation, the telescope tube deforms. This brings the secondary mirror out of altitude alignment at the same time as it tilts in the same orientation. In addition, its distance from the primary mirror changes. In practice, these displacements are often, if not normally, accompanied by corresponding azimuthal displacements and tilts. While the inter-mirror distance is relatively easy to maintain via focus monitoring, the other displacements require a secondary-mirror cell with high-quality real-time corrections in four degrees of freedom. This is illustrated in Fig. 137.

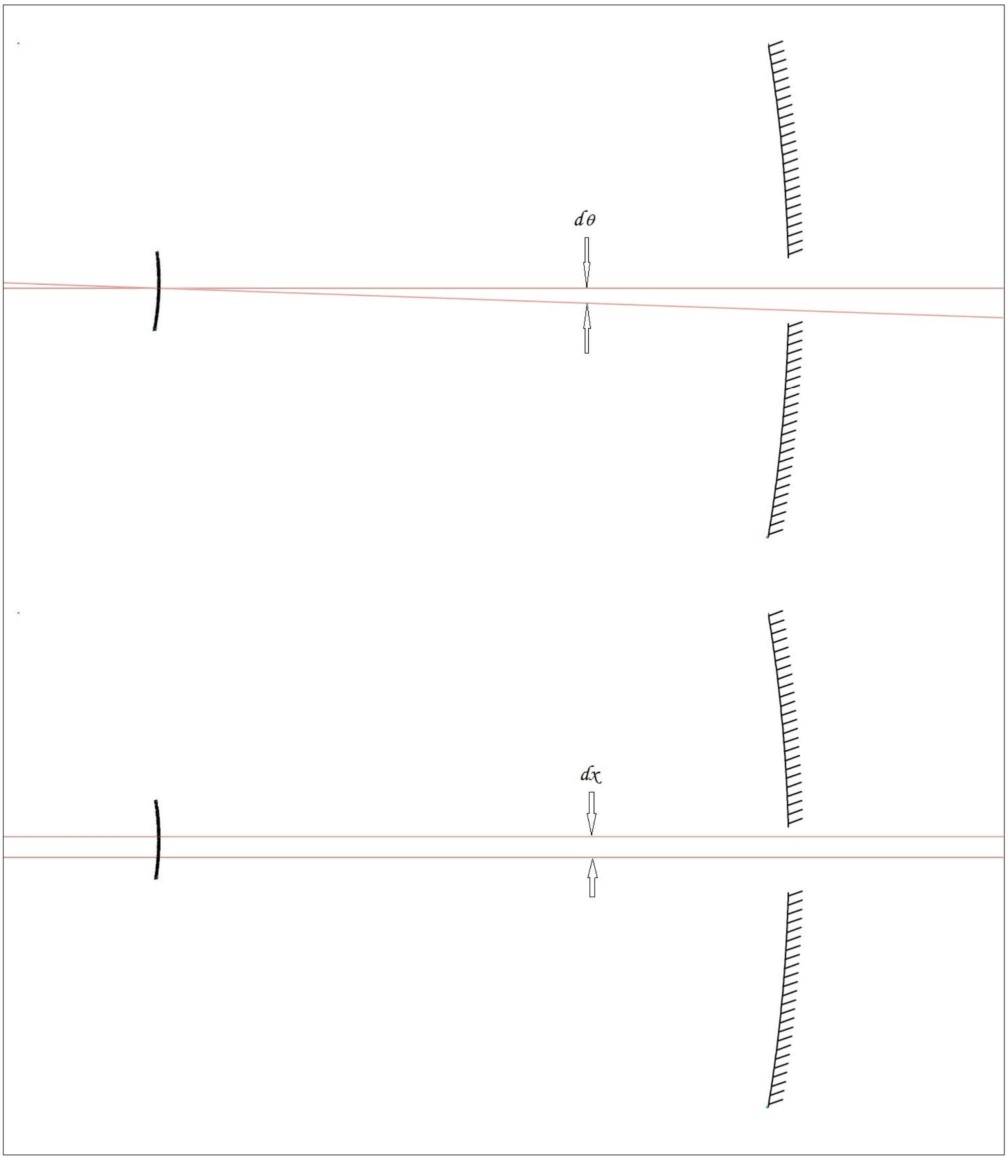


Figure 137. Errors of alignment and displacement in a Cassegrain telescope. For clarity, deviations are strongly exaggerated.

For a 3 m class telescope, the diffraction limit, and the limiting FWHM value, is, in the visual wavelength range, between 0.04 and 0.05 arcseconds. With a telescope focal ratio of 11, this corresponds to approximately 7 micrometres in the image plane. If we assume a site image quality of 0.5 arcseconds, a point source produces an image with an FWHM value of around 80 micrometres. Thus, in order not to influence site image quality, we can derive a maximum tolerable misalignment of the secondary mirror with reference to the framework provided by the primary mirror. While a detailed tolerance analysis can be made, here a trial and error calculation with optical software seems fully sufficient for an order-of-magnitude conclusion.

An iterative calculation with dedicated software showed that, for a 3 m class telescope as discussed above, the maximum allowable decentering misalignment of the secondary mirror, in the elevation or azimuthal direction, is around 100 micrometres. The corresponding maximum allowable tilt deviation is approximately 35 arcseconds. See figs. 138 to 140. Thus, adjustments as discussed of the secondary-mirror ensemble have to be accurate to within around 50 micrometres and 20 arcseconds, respectively. It is noted that site image qualities can, at least over limited periods, be even better than 0.5 arcseconds, possibly of the order of 0.3 arcseconds. Accordingly, for maximum performance, adjustment precisions of around 30 micrometres and 10 arcseconds, respectively, are required.

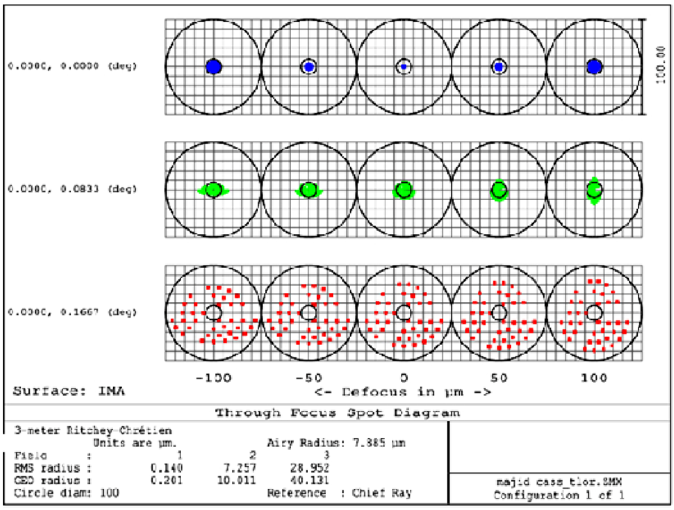


Figure 138. A well-designed and constructed Ritchey-Chrétien telescope shows only astigmatism aberration around the diffraction limit.

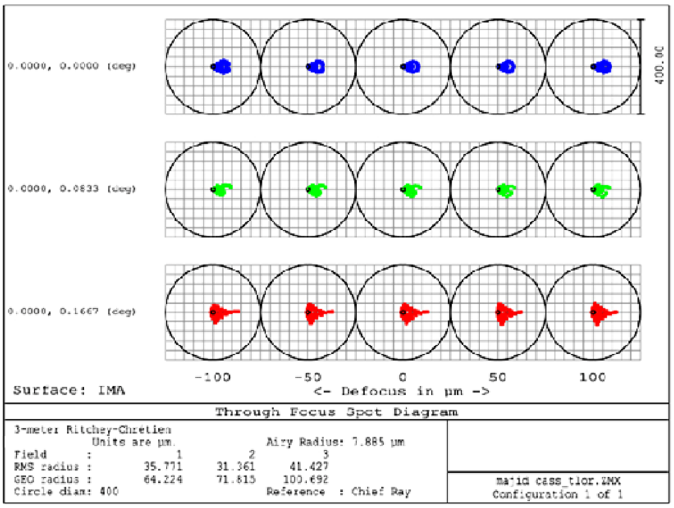


Figure 139. Decentering the secondary mirror gives strong coma. Due to spherical symmetry, the direction of decentering is unimportant for the result..

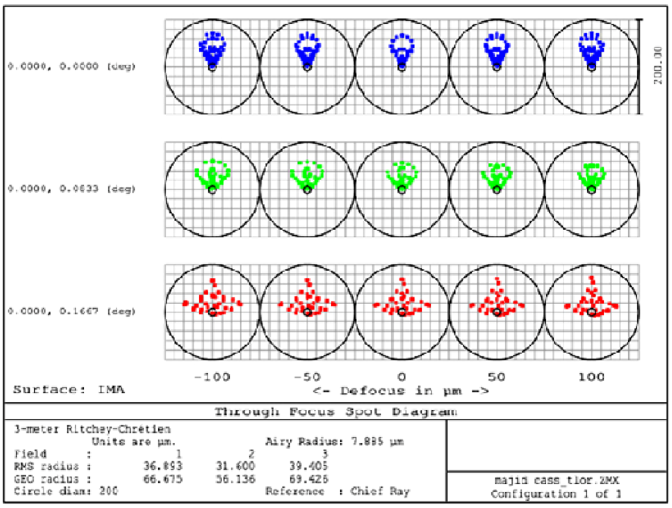


Figure 140. Misalignment of the secondary mirror gives strong coma. Compare results of corresponding decentering as shown in Figure 30.

Stray light and light baffles

If no special precautions are taken, a telescope will, nearly without exception, record light not only coming directly from the target object or objects but also from other, unwanted sources. The light from the latter sources is called stray light. It is, in practice, the sum of the contributions of a number of, celestial and environmental, off-axis light sources, the flux of which reaches the detector due to scattering and diffraction of and in various surfaces. Not to forget, one of these unwanted light sources is provided by light from the target object or objects that takes paths other than the adequate one. To this, we have to add flux due to thermal emission from the sky, the telescope, the instrumentation, the telescope enclosure and various ambiental structures.

A practical and, in practice, also rather efficient manner to decrease the effects of stray light, is to block the light unwanted, deviating it away from reaching the detector. For this purpose, a number of mechanical light-blocking devices are available, such as light baffles, aperture stops and field and Lyot stops. In a two-mirror telescope, it is recommendable to install two light baffles, one for the primary mirror, another for the secondary mirror. This is illustrated in Fig. 141.

Designing sky baffles is an undertaking far from trivial. This is emphasized by the fact that there is no formal analytical solution of the sky-baffle geometry in a Cassegrain telescope (Wilson, 2001). Nevertheless, routines are available assisting the identification of initial parameters for light-baffle design. Reference is made to figs. 141 and 142 as well as to previous optical-design parameters for the Cassegrain telescope concept. Adopting these routines as illustrated, it is possible to find optimal values of both the length and the widths of the light baffles required (Bely, 2002).

Figure 141. Tube assembly and locations of the primary-mirror and secondary-mirror light baffles.

Figure 142. Indicative positions and radii of light baffles in a Cassegrain telescope (Bely, 2002).

Light-baffle parameters

Referring to Bely (2002) and with the same denotations as used above, in Fig. 129 and 142, we have:

$$x_u = \frac{-b_0 - \sqrt{b_0^2 - 4ac}}{2a} \quad , \quad r_u = x_u(\theta - \theta_0) + \theta_0 f_1$$

$$x_l = \frac{-c_1 b_2 + b_1 c_2}{a_1 b_2 - a_2 b_1} \quad , \quad r_l = \frac{-c_1 a_2 + a_1 c_2}{b_1 a_2 - b_2 a_1}$$

Here, θ is the half of the field of view in radians and the other constants are as follows:

$$\theta_0 = \frac{D}{2f_1}$$

$$a = \theta_0^2(f_1+b)^2(m+1) + \theta_0\theta(f_1+b)\big(mf_1(m-1) - b(m+1)\big)$$

$$b_0 = -(f_1+b)^2\theta_0^2\big((2m+1)f_1 - e\big) - \theta_0\theta(f_1+b)\big((mf_1)^2 + b^2\big) + f_1\theta^2\big(f_1^2(m^3-3m^2) - 2f_1b(m^2-m) + b^2(m+1)\big)$$

$$c = \theta_0^2(f_1+b)^2 f_1(mf_1 - b) - f_1\theta^2\big((mf_1)^3 + 2f_1^2b(m^2-m) - f_1b^2(m^2-m) - b^3\big)$$

$$a_1 = \theta_0(f_1+b) - \theta(m^2f_1 + b)$$

$$b_1 = -(f_1+b)m$$

$$c_1 = \theta_0(f_1+b)b + \theta(m^2f_1^2 - b^2)$$

$$a_2 = \theta_0x_u - \theta_0f_1 - \theta f_1$$

$$b_2 = -f_1$$

$$c_2 = -\theta_0f_1x_u + \theta_0f_1^2$$

Inserting corresponding telescope design values as discussed above, the result is

θ_0 = 0.3333 rad, b=1200 mm, θ =0.0029 rad, m = 7.3333, and f_1 = 4500 mm

x_u = 3700 mm, r_u = 270 mm and x_l = 2100 mm, r_l = 140 mm

Mechanical concepts

Large telescopes and optomechanics

Large telescopes are optical and mechanical, or optomechanical, systems, often rather complicated. As a rule, at least for telescopes, advanced optics relies to a large extent on mechanical functions without which it would not be able to have the telescopes perform as expected. The mechanical outfits in turn, to a considerable degree depend on the action of control systems. It may well be argued that the border lines between optics, mechanics and control systems are fuzzy. Nevertheless, it is beyond doubt that a high-performing telescope has to have a mechanical structure of considerable sophistication. Such structures are the topics of the current section.

Somewhat simplified, it may be stated that the primary role of the telescope mechanics is to maintain as far as possible the figure and relative alignment of the optical elements of the telescope. In this spirit, a very large range of mechanical configurations have been designed and constructed. Further, for the purpose, a variation of materials has been adopted. While many different constructions have been adopted, a number of fundamental limitations apply.

Large mechanical structures

Large mechanical structures imply large weights. This, in turn, sets the scene for structural deformations due to influence of both the gravitational field and changing temperature. In addition, large-size structures are prone to suffer from effects of wind buffeting. High performance, not least in terms of image quality, is impossible as long as such deformations cannot be kept to a minimum, ideally eliminated through compensatory measures. Finally, and importantly, the heavier the telescope, the higher its cost. Thus, reductions of size and weight of telescopes are important parts of the efforts aiming at high-performance yet affordable telescopes.

Until relatively recently, the way to reduced telescope deformation was purely through optimization of the mechanical structures. The result was heavy telescopes and, thus, an unavoidable requirement to counter large effects of deformations driven by gravity and varying temperature. In addition, the structures drew rather high costs.

Today, the policy regarding mechanical structures is rather different. Light structures inevitably deform in the field of gravity. However, in a light-weight structure the same deformations can also be counteracted. In addition, it has, generally, a lower cost than its heavier, old-fashioned counterparts.

Active optics play a major role in modern, light-weight telescopes. The ultimate goal of such a system is to make the image quality limited by the turbulent activity of the atmosphere only. This requires a system maintaining the figure of optical elements as well as their relative alignment within error limits not significantly surpassing those inherent to the system as such. The design and action of active optics has been discussed under separate heading.

Material

For the choice of material for the mechanical structure of a telescope, a major consideration is specific stiffness, or the ratio of Young's modulus to density. Another important issue is cost. Today, the materials of choice are steel, aluminium and carbon-fibre reinforced polymer (CFRP). While experience with steel and aluminium is rather solid, the performance of CFRP is still not known to any comparable extent.

In table 4, a comparison is provided of steel, aluminium and CFRP. Included in the comparison are Young's modulus, expressed in GPa , density, expressed in kg/m^3 and cost, expressed in relative terms.

Material	*Young's modulus in GPa*	*Density in kg/m^3*	*Relative cost*	*Remarks*
Steel	200	8 000	Low	
Aluminium	70	2 700	High	
CFRP	Around 150	1 600	Very high	Young's modulus can be increased.

Table 4. Comparison of steel, aluminium and CFRP.

All three materials provide high stiffness. For steel and aluminium, the ratio of Young's modulus to density is approximately the same. While a structure of aluminium is potentially lighter than a corresponding structure of steel, at the same time, it has a lower stiffness. Hence, aluminium and steel have the same gravity performance and steel is preferred for cost reasons.

The combination of high specific stiffness and low density has made CFRP a rather interesting alternative. Clearly, choice of CFRP allows a rather light yet stiff telescope structure. On the other hand, the detailed behaviour of CFRP, not least its humidity performance, is still not well known. Further, the cost of CFRP is quite high. As a result, while often discussed and chosen for structures for which low weight is a critical factor, CFRP is still not a very popular material for telescope structures in general. Thus, still, for telescope structures, steel is the rule.

Operational static and dynamic loads

The requirements on the design of the mechanical structure of a telescope are critically dependant on the tolerance levels defined for telescope operation. More specifically, for a telescope intended for a site with favourable atmospheric turbulence, the figure and alignment of optical elements must remain within limits that match the quality of optical figuring. While the high spatial frequency precision of the primary mirror is determined by the polishing quality, the corresponding low spatial frequency precision has to be guaranteed by the mechanical structure contained in the primary-mirror cell.

Static loads on the telescope are imposed by gravitational forces and preload forces. Semi-static loads come from low-frequency wind forces. Dynamic loads are caused by wind buffeting. Effects of temperature variation, expansion and contraction, smooth and non-smooth, can be seen as slowly-acting dynamic loads. The time scales of thermal variations are many and depend on diurnal and seasonal cycles as well as on operational conditions.

The gravitational forces are highly predictable and easily modelled. Thus, they are, at least in principle, easy to compensate. This is also the case for preload forces. With a distributed monitoring system for temperature variations, of the ambient and enclosure air as well as of structural elements, basic effects of these variations can be partially calculated and compensated. Still, due to unavoidable structural imperfections, second-order effects of gravitational and preload forces plus those of temperature variations must, for high-efficiency compensation, be measured, analysed and taken into account in real time. For effects of wind forces, such real-time counteraction is a necessity.

Wind forces

While wind forces are of utmost importance for very large telescopes, they are of considerable importance also for telescopes in the 3 m class. This is not least due to the

wind power spectrum. This spectrum can provide substantial energy at frequencies around and below 1 Hz, which is, normally, not so far from the natural frequencies of the telescope structure and the enclosure. Thus, effects of wind (gusting) can be rather high, direct as well as via the enclosure and its vibration effects on the telescope via its foundation, the ground and the telescope pier.
In the static, or semi-static, regime, wind loads imply a force on the telescope structure that is proportional to the square of the wind velocity and the cross-section interface area of the structure. This is often labelled direct wind drag force. In the dynamic regime, we have to take into accounts effects of vortex shedding and wind gusting. Vortex shedding is a fluctuating flow causing varying low-pressure vortices behind obstructions, in our case parts of the telescope structure. These parts tend to move in the direction of the low-pressure air cavities created. This is especially serious if the vortex-shedding frequency equals structural resonance frequencies. Wind gusts are short increases in wind speed which can be as strong as and even stronger than the base wind.

Primary mirror

For a modern 3-m class telescope designed for high image quality, unavoidable static and dynamic loads imply, first, that the primary mirror has to have an adequate aspect ratio, in practice in the range 15 and upwards, the higher limit being set by considerations of safe handling. Further, an active-optics system with axial and lateral supports as well as with hard points, wave-front sensing and analyzing equipment plus a control system is a requirement. Equally necessary is a mirror cell of sophisticated design providing the basis for the entire primary-mirror ensemble. In the design phase, this ensemble is a unity.

Telescope structure

While a flexible primary mirror with a sophisticated real-time support system is a necessity for high image quality, it is far from a guarantee for high imaging performance. The entire telescope structure and its tube are affected by gravity and effects of preload, temperature variations and wind buffeting. The result is bending, twisting and deformation, of the mechanical structures and the optical elements. These effects have to be counteracted, which is discussed below.

Stresses, acceleration, deceleration and seismic activity

Requirements on normal operation define the degree of stiffness due for the telescope structure. Requirements regarding safe operation and survival define the constraints on the maximum permissible stress of these structures. Of prime concern are effects of telescope acceleration and deceleration as well as of seismic activities.

Acceleration and deceleration impose dynamic loads on telescope structures that are proportional to their distance from the axes of rotation. These effects are essential for azimuth and elevation movements and for field rotation. While the slewing speed of the telescope is a dominant factor regarding the time necessary for changes of position, the restrictions on acceleration and deceleration are highly essential for corresponding times needed for smaller changes of position. As an illustration, the maximum acceleration and deceleration allowed for the Gran Telescopio Canarias (GTC) is 0.31 and 0.15 $^{\circ}/s^2$, respectively, with the corresponding maximum for field rotation being 0.15 $^{\circ}/s^2$ (GTC System Specification, 2005).

Most sites of modern telescopes for optical and adjacent wavelength regions are subjected to effects of seismic activity, some of them rather much. Such activity can impose high dynamical loads on the telescope structures, including the telescope pier. It is important to design the telescope (and the enclosure) for safe survival also of stronger earthquakes. The ground-level earthquake, three-dimensional, response spectrum sets the scene of the event threatening the telescope and enclosure. The essential parameters are velocity, acceleration and displacement. The peak response of the telescope structure is determined by the corresponding natural frequency and the level of the earthquake ground response spectrum at this frequency. Typically, when the damping ratio is small, the earthquake ground acceleration is amplified by a factor of three or more within the frequency range 2 - 10 Hz. This is illustrated in Fig. 143 (Haskell, 1986).

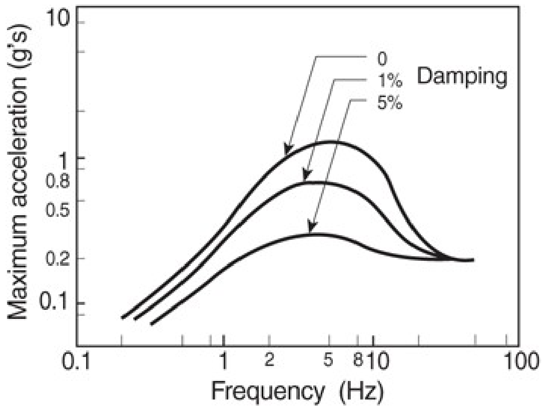


Figure 143. A typical earthquake acceleration response spectrum. (Haskell, 1986)

When telescopes (and enclosures) are designed, normally, two levels of seismic loads are considered. The first is the load which the telescope should be able to sustain without losing its proper functionality. It is often called the operational base earthquake. The second load taken into account is that for which the telescope remains intact as a structure and basically operational albeit with no guarantee for proper function without corrective measures. This level is often labelled the maximum likely earthquake.

M1 Assembly

The primary mirror, M1, of the telescope is supported in a dedicated mechanical structure. We refer to this structure as the mirror cell or the M1 Assembly. It is a multiple-purpose structure including a range of devices connected to the primary mirror. The M1 Assembly is a key part of the telescope.

Among the functions of the M1 Assembly are:

- Maintaining the correct shape of the primary mirror irrespective of its orientation and other observing conditions, all within certain limits.
- Allowing smaller adjustments of the basic figure of the primary mirror.
- Maintaining the primary mirror correctly oriented and safely attached.
- Supporting and protecting the primary mirror.
- Providing adequate Cassegrain-focus interface to auxiliary instrumentation.

M1 surface and image quality

For a telescope aimed at high-quality imaging, a natural requirement is that it should have an optomechanical performance guaranteeing that the resulting quality of images is limited by atmospheric conditions only. This has to be the case even in conditions of lowest atmospheric turbulence (or best possible seeing). At the best sites, we refer to regular conditions characterized by point-source images having full width at half maximum intensity (FWHM) less than an arcsecond and best conditions providing FWHM values below half an arcsecond. Thus, the image-quality performance of the telescope must be well below these levels.

For a telescope equipped with active optics but not with adaptive optics, a commonly accepted image-quality criterion is that 90 % of the image energy should fall within the best-quality seeing disc. This is roughly the same as stating that 80 % of the energy received should enter within a diameter of between 0.15 and 0.30 arcseconds. For the practical assurance of such an image quality, the primary mirror is a key element (Wilson, 1996).

For a telescope equipped with or being prepared for later inclusion of adaptive optics, the requirements on telescope image-quality performance are considerably higher than for telescopes with active optics only. Dealing with high-order adaptive-optics system, the natural target is an image quality restricted by effects of diffraction only. That implies that details of the Airy pattern should be resolved. In more practical terms, for a 3 m class telescope, the primary-mirror surface rms error should be smaller than around 2.5 % of the wavelength. The corresponding target image quality should be approximately 0.02 arcseconds. More details regarding active and adaptive optics are provided under special headings.

In principle, the optical figuring defines the optical quality of the primary mirror. However, this surface quality is unavoidably restricted to higher spatial frequencies. At lower spatial frequencies, effects of gravity, temperature and wind load, but also of mirror-substrate manufacture and polishing as well as accidental errors due to friction and slippage, imply, if uncorrected, surface distortions far above those acceptable for a telescope image quality limited by effects of the atmosphere only.

At any given time, the quality of the mirror surface is defined by the ensemble of the distances between the actual surface and the corresponding ideal surface. Conveniently, the mirror-surface or wavefront error is expressed as the root mean square (rms) of these distances. Statistically adjusting the actual surface to a best-fit position, the rms value is the standard deviation of the distance errors. Alternatively, we may refer to the square of the rms value, or the variance.

For an axially symmetric telescope aperture, the Strehl ratio of the images may be defined as

$$S_t \cong \exp\left[-\left(\frac{2\pi}{\lambda}\sigma\right)^2\right]$$

Here, S_t is the Strehl ratio, λ the wavelength and σ the wavefront rms error. This is the so called Maréchal approximation (Hardy, 1998).

With double reflection, the wavefront error is twice the error of the mirror surface. Accepting a Strehl ratio of around ⅔, we define a largest permitted mirror-surface rms error of around 0.05λ or 0.025λ (see above). Notably, the requirements on observing-conditions mirror-surface quality depend linearly on the lower limit of the wavelength range defined for observations, as does, consequently, also the quality of mirror figuring. This, in itself, implies that choice of an observing wavelength range approaching that of the atmospheric limit, around 325 nm, sets the scene for ambitious efforts concerning mirror substrate, mirror polishing and mirror support as well as maintenance of an adequate telescope alignment. At the same time, logically, it prepares for corresponding competitiveness, especially if the telescope site has a higher altitude.

Primary-mirror support system

A complete primary-mirror support system should guarantee a telescope image quality free, or at least close to free, from effects depending on elevation, temperature variations and wind forces. At the same time, it should correct fixed-pattern figuring errors. The support system includes both so called positioning and floating components as well as a combination of axial and lateral supports.

The position of the mirror is defined by a small number of so called hard points. These positioning supports and the related displacement actuators carry only a rather small part of the total weight of the primary mirror. Practically all of the weight is carried by the floating-component supports. The floating, or astatic flotation, supports have to act in a manner as similar as possible to that of a liquid with a density equal to that of the mirror substrate, in which the mirror floats.

Depending on the elevation angle of the telescope, the gravitational forces change direction and relative influence with respect to the mirror surface. In general, telescopes are supposed to cover the sky above around 15 degrees from the horizon, sometimes having 10 degrees above the horizon as their lower limit. At the same time, at least conceptually, the basic requirement on the mirror surface is that it remains unaltered by the elevation of the telescope position. Thus, the mirror needs efficient support both over its backside and along its circumference.

Axial support system

Traditionally, primary mirrors were made rather thick, in order not to deform under the influence of varying forces of gravity. When they, inevitably, anyhow deformed, under gravity and due to changing temperature, no remedy was available but waiting for the effects to diminish. Today, the concept has changed drastically. While traditional primary mirrors had aspect ratios of five to six, modern mirrors, say of 3 m class, have aspect ratios of around 15 and larger, in some cases much larger. The result is that they, on the one hand, are very prone to deform but, on the other hand, have forms that can be handed via active-optics systems. In addition, being thin, they have rather favourable thermal relaxation times. Clearly, the support systems play an important role for the resulting quality of images.

Conceptually, we have to support a flexible substrate disc to maintain, at all times of observation, in any given direction (see above), the mirror surface adhering to the corresponding ideal surface within a given rms error. The architecture of the support-point system has to be determined. We have to define the distribution and number of support points. Further, the sizes of the support pads and their forces have to be determined. At the same time as we need a support architecture with sagging between the support points being small enough to meet our requirements on surface precision, we want to have a support system as simple as possible.

Design of axial support systems

At least to a first approximation, the surface deformation of a thin telescope mirror with an axial support system can be predicted from classical thin-plate theory. Under the thin-plate assumption, the deformation of the mirror disc is an approximate function of its diameter and thickness. This is referred to as the scaling law of mirror-support design. More precisely, the scaling law states that, for a given support architecture, the rms value of the mirror-surface deformation is proportional to the fourth power of the mirror diameter and inversely proportional to the square of its thickness (Cheng, 2009). To determine the constants of the scaling law, a mirror with a given support system and well-studied surface deformations can be used.

For other thin telescope mirrors with similar support structure, the surface deformations can then be predicted.

To serve their best purpose, the axial supports have to be evenly distributed over the back side of the mirror. For practical reasons, they are normally distributed along a number of concentric rings. For an adequate approach to the number of rings and support points, the finite element method (FEM) is a highly adequate tool.

An illustration of different sets of support structures is shown in Fig. 144 (Cheng and Humphries, 1982). Support structures are shown with support points distributed over one, two, three and four concentric rings. Mirrors with diameters from one metre to 10 metres are included. The data also cover aspect ratios from 4 to 50. Adhering to the 3 m class telescope discussed in this paper, it can be found from Fig. 144 that a 3 m mirror with an aspect ratio of around 15 can be adequately supported with support points along a three-ring structure. At any rate, this should be taken as an indication only. For proper support-architecture definition, detailed calculations are a clear requirement. It is added, that full adequacy implies that final decisions on the axial-support architecture have to take into account also the corresponding system of lateral mirror supports. These supports are discussed below.

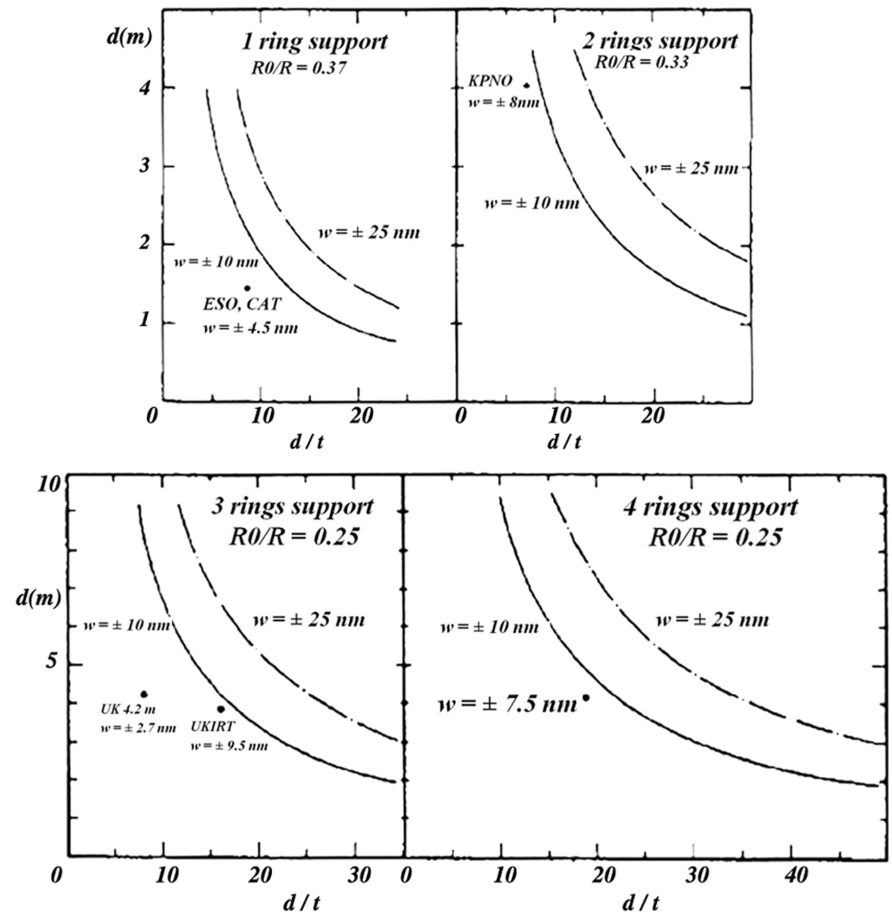


Figure 144. Overview of axial-support structure architectures for primary mirrors. Apertures in the range 1 – 10 m are shown as are aspect ratios in the range 4 to 50. Both equatorial and altitude-azimuth mounts are included (Cheng and Humphries, 1982).

With respect to the data presented in Fig. 144, it seems correct to make a remark concerning the lower range of mirror diameters. From thin-plate theory as well as from practical experience it seems not exactly evident that active optics are a requirement for telescope primary mirrors with diameters smaller than around two metres. For such an aperture, a passive mirror with an aspect ratio of approximately six may well perform rather adequately if well mounted and supported.

Some details of axial-support structures

Modern telescopes for optical and adjacent wavelengths are, with few exceptions, designed and constructed, as well as sited, with image quality as a prominent, or even first, parameter. This makes the optomechanical systems prime concerns. In these systems, primary-mirror support systems, not least the axial sub-systems, are of key importance. Thus, some detailed discussion of these systems seems well in place.

The value of the rms error of the mechanical surface of a mirror disc (not the wavefront error) provided with an axial support system can be expressed in a manner rather convenient for support-system optimisation. As given by Nelson et al. (1982), we have

$$\delta_{rms} = \xi \frac{q}{D} A^2$$

Here, δ_{rms} is the rms error of the mechanical mirror surface, ξ a constant (see comments below), q the areal density of support points, D the bending stiffness of the mirror disc and A its surface area. The value of ξ is a reflection of the mirror-support condition. It is labelled the support efficiency.

Assume that there are N axial support points at the back of the mirror disc. Then, the average support efficiency of all these points can be expressed as

$$\gamma_N = \xi N^2$$

Here, γ_N is the support efficiency, while ξ and N have the significance given above.

Final solution of the axial-support system

The design of the axial support system has a number of more or less free parameters. The supports may all be given equal force, in itself a decision implying some advantages, but they may also have differing forces. Of importance is to take care of the support of the edge parts of the mirror disc, as this part of the disc implies restrictions concerning the distribution of forces. It is essential that the final solution takes the total distribution of the axial supports into account. Again, it is noted that the final solution also includes the action of the lateral mirror supports.

The final support-system solution has to strive to reach a support efficiency of all given support points as close to the ideal value as possible, even if, in practice, this value cannot be realised in practice. In principle, the ideal value of the support efficiency is reached when (Cheng, 2009)

$A \rightarrow \infty$ and $N \rightarrow \infty$

In this, idealised, case, the mirror-disc deformation is determined by two factors only. They are, first the architecture of the support points and, second, the area of the disc supported by each support pad, the latter area being A/N.

Triangular, square and hexagonal grids

Under the assumption given, the ideal support efficiency of all support points can be derived for three fundamental arrangements of these points. They refer to a triangular grid, a square grid and a hexagonal grid. With the help of linear superposition, the deformations resulting from application of these three grids can be derived analytically. This implies that the average support efficiency of the pad points can be derived for the three arrangements of the support points. In terms of the rms surface error, these average support efficiencies are (Nelson et al., 1982):

$\gamma_{triangular} = 1.19 \times 10^{-3}$, $\gamma_{square} = 1.33 \times 10^{-3}$, $\gamma_{hexagonal} = 2.36 \times 10^{-3}$ $\qquad \delta_{rms} = \gamma_i \frac{q}{D}\left(\frac{A}{N}\right)^2$

Here, γ, δ_{rms}, q, D, A and N have the same significances as noted above.
For the mirror disc, the efficiencies discussed are independent of Poisson's ratio. In our case, this ratio is between 0.2 and 0.3. Considering the maximum or peak surface deformation, the average support efficiencies are for the triangular grid 4.95×10^{-3}, for the square grid 5.80×10^{-3} and for the hexagonal grid 9.70×10^{-3}.

Mirror-disc deformation

The over-all deformation of the mirror disc results from superposition of the local disc deformations introduced by the ensemble of support pads. In our case, with a circular mirror disc, the support points are distributed along concentric rings. In this situation, we have (Nelson et al., 1982):

$$\delta_{rms}(r,\theta) = \sum_i^n \varepsilon_i \delta_i (k_i, \beta_i, r, \theta - \Phi_i)$$

Here, δ_{rms} is defined as above, r and θ are polar coordinates, n is the number of concentric support-system rings, ε_i is a weighting factor, δ_i is a function that can be expressed in the form of a Zernike polynomial, k_i is the number of support points on support-system ring i, β_i is the relative radius of support-system ring i, and Φ_i is disc-centre angle defined by adjacent support points along support-system ring i.

Providing the factor δ_i in the form of a Zernike polynomial, δ_{rms} can be derived and the radii of the support-system concentric rings can be optimised. The larger the value of n is, the more difficult is the optimisation of the architecture of the support system.

Basic support-system architecture

The simplest support-system architecture is defined by a single ring. This case involves two variables only. These are the relative radius of the support ring and the number of support points included. It is noted that this basic architecture in practice is adequate only for telescopes with smaller apertures. Reference is made to Fig. 144.

In Fig 145, some details are demonstrated for some different applications of one-ring support-system architectures. The variation of the rms error of the mirror-disc surface with respect to the radius of the support-system ring and the number of support points is shown both over a larger range of the two variables and, in more detail, over a selected part of the variability space. The over-all rms surface error varies smoothly in all cases and has well-defined minima. At the same time, obviously, there is an optimum value for the number of support points. Adding further support points has little effect, saturation occurring already for 6 support points. At the same time as it seems obvious that one-ring support-system architectures have a very restricted applicability for real telescopes, the system-oriented message delivered by the data in Fig. 145 is well worth noting.

In the case of axial support systems based on two or more concentric rings, the deformation of the mirror surface depends on the Poisson ratio of the mirror material. As an example, if we assume a value for the Poisson ratio of, say, 0.25, we find that a nine-point two-ring system is the best among possible two-ring support approaches. However, nine support points cannot form an integrated triangular arrangement. The average support efficiency of each point decreases very much, as can be seen from Fig. 146. In contrast, a 12-point two-ring support system forms a well-defined integrated triangular grid. Under the latter condition, the rms mirror-surface error is decreased and the average support efficiency of each point is increased.

If we add even more support points, we find that a 15-point two-ring system has an even better average support efficiency than the corresponding 12-point system. Proceeding to an 18-

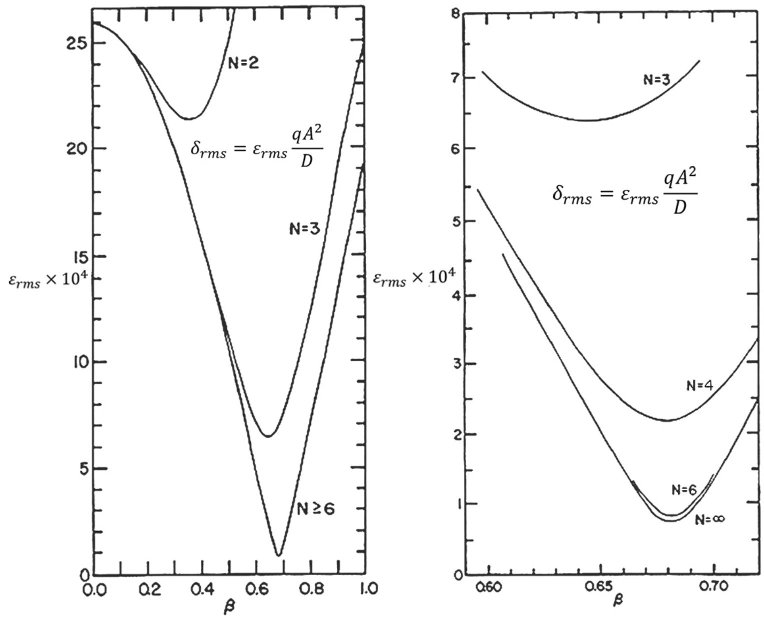


Figure 145. The dependence of rms errors of mirror surface on relative support-ring radius and number of support points for different one-ring support architectures. Left-hand box shows over-all dependence, right-hand box shows enlarged details (Nelson et al., 1982).

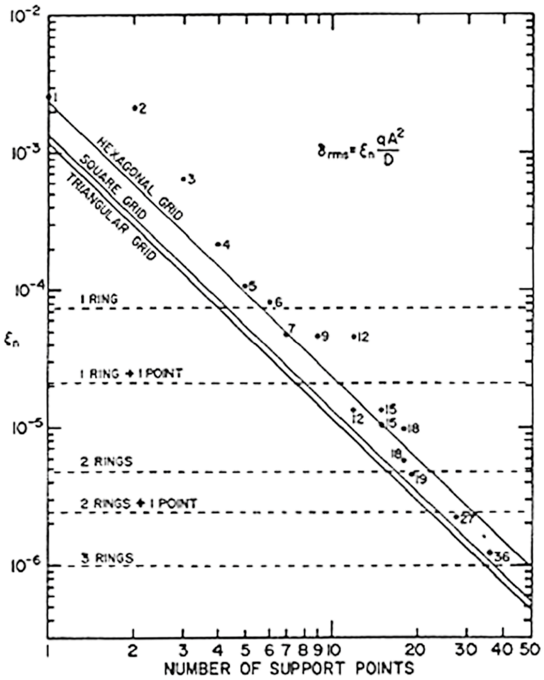


Figure 146. Axial support efficiency as a function of the number of support points for different support systems . (Nelson et al., 1982).

point two-ring support system, we obtain a support system of even higher efficiency. If we, however, add an additional support point, the 19th, at the centre of the latter system, both the over-all support efficiency and the average support efficiency per support point decrease significantly. Also, addition of further support points results in production of many more variables in the system optimization. Thus, dedicated and careful calculation is necessary, as a minute change of parameters can result in large variation of the over-all mirror-surface rms error.

For a mirror with an aspect ratio adequate for active support, the number of support points, N, is, generally, inversely proportional to the average support area per support unit. If the mirror thickness is *t*, the following relationship is due for triangular-distribution support points, δ_{rms} and *N* having the significances given above (Nelson et al., 1982):

$$\delta_{rms} \approx \frac{1}{(tN)^2}$$

It follows that, in principle, to improve the precision of the mirror surface, we have to either add more support points or use a thicker mirror. In practice, and as has been discussed above, both the number of support points and the thickness of the mirror have upper limits.

For the same mirror-surface precision, the thinner the mirror is, the higher the number of support points that are required. However, increasing the number of rings and support points increases the number of variables in the system and makes the optimisation procedure complicated even with FEM calculations.

Table 5 lists some modern telescopes, in operation, in commissioning and under preparation, Details are shown concerning their primary-mirror f ratio, the material of the primary mirror and its shape and aspect ratio as well as the number of axial support points and the number of corresponding concentric rings plus the hard points.

Name	D (m)	year	f/	material	structure	D/t	N. Sup.	N. Rings	N. fix points
SOAR	4.2	2005	1.75	ULE	Meniscus	42	120	5	3 tan
DCT	4.2	U.C.	1.9	ULE	Meniscus	42	120	5	3 tan
VISTA	4.1	U.C.	1.0	Zerodur	Meniscus	24	84	4	3
NTT	3.5	1989	2.2	Zerodur	Meniscus	14.9	75	4	3
TNG	3.5	1997	2.2	Zerodur	Meniscus	14.9	75	4	3
VST	2.61	U.C.	2.2	Astrosital	Meniscus	19	84	4	3

Table 5. Data for the primary mirrors of some modern telescopes. Details are shown for the primary mirror diameter, its f ratio, material, shape and aspect ratio plus the year of completion. For the axial support system, the number of support points and the corresponding number of concentric rings are given together with the number of hard points.

Lateral support system

The axial support system suffices in the zenith position only. Thus, also a lateral support system is necessary. When the telescope points to positions close to the horizon, the lateral support system takes the major load and responsibility for the surface precision of the primary mirror. Reference is made to Fig. 147. At the same time, it is noted that, in practice, most telescopes discussed have software stops excluding pointing below typically 15 to 20 degrees of elevation plus hardware stops posing limits a couple of degrees closer to the horizon.

Even when the telescope points at the horizon, the major mirror deformation is along the axial direction *z*. There may well be a strain in the *z* direction, due to the Poisson effect of the support forces, but this is significant only for more conventional mirrors with smaller aspect ratios and not for meniscus mirrors with higher aspect ratios.

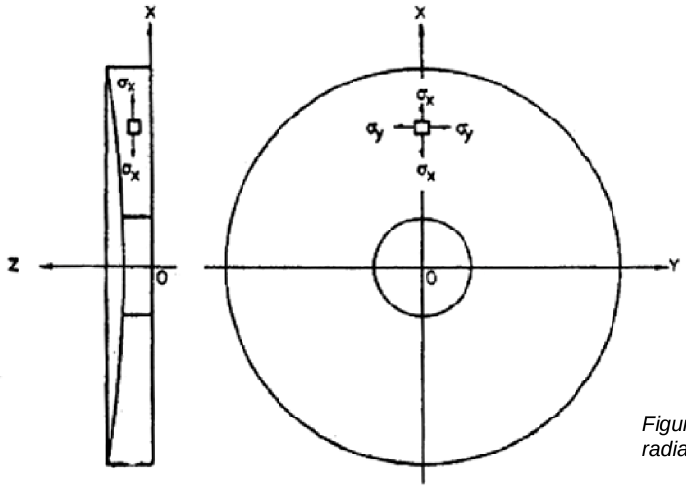


Figure 147. Mirror stress distribution under the radial mirror support system (Cheng, 2009).

We can consider three radial mirror-support systems and their force conditions. They are illustrated in Fig. 148. Fig. 148a shows the force conditions resulting with a so called mercury belt, or a rubber torus filled with mercury and with a fixed inner contact area. In Fig. 148b, the force conditions are given for a cosine radial support system, or a counterweight and cantilever system in the radial direction. Fig. 148c, finally, demonstrates the force conditions resulting with a vertical push-pull support system of which all supporting forces are parallel to the vertical axis (a counterweight and cantilever system in the vertical direction).

The stresses along the y direction of these three radial support systems are σ_{ya}, σ_{yb} and σ_{yc}, as given by (Cheng, 2009)

$$\sigma_{ya} = -k_a(1 - \cos\theta)\sin\theta$$
$$\sigma_{yb} = k_b \cos\theta \sin\theta$$
$$\sigma_{yc} = 0$$

Here, θ is the polar angle in the mirror plane (see Fig. 148) and k_a and k_b are positive constants.

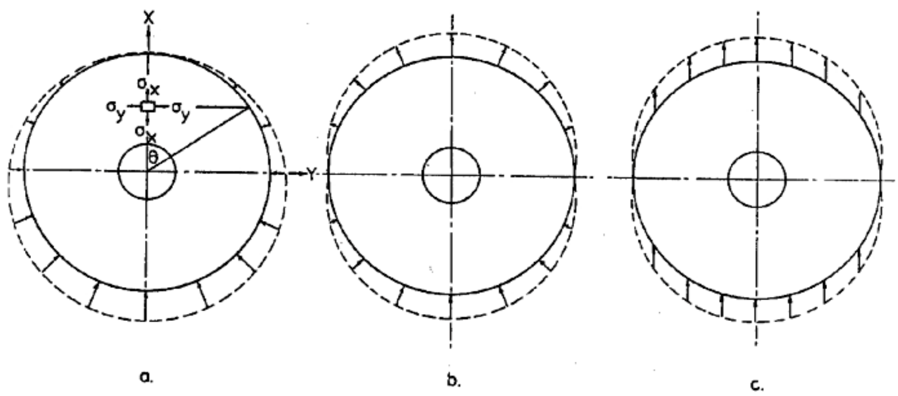


Figure 148. Force conditions of (a) a mercury belt radial support, (b) a cosine lateral force radial support, and (c) a vertical push-pull radial support (Cheng, 2009).

We find that the stresses along the *y* direction in System a and in the bottom part of System b have the same sign as the stresses in the vertical direction. The contributions from these stresses to the surface error in the *z* direction are added to those from stresses in the vertical direction. Thus, the minimum mirror surface deformation along the *z* axis is encountered only in System c in which stresses in the *y* direction vanish.

Plane-concave and meniscus mirrors

A plane-concave primary-mirror substrate is easier to produce and to handle than the meniscus counterpart. In addition, it requires less substrate volume to start with. Also in the process of figuring, the plane-concave substrate has many practical advantages. They include general handling, turn-table support and application of support pads.

Still, the end-product advantages of a meniscus mirror are considerable. First, with normal machining and figuring processes, the meniscus mirror has a lower weight than the plane-concave mirror. Thus, in the first case, the mirror-cell unit and the over-all telescope can be made lighter and less expensive than if a plane-concave mirror is chosen. With a compact construction, that is a small focal ratio and a large sagitta, the difference can be considerable.

Second, a meniscus mirror has a constant thickness. This implies that its thermal inertia is constant over its surface, while it is a function of the distance from the centre for a plane-concave mirror. Thus, the thermally induced stress is lower for the meniscus mirror than for the plane-concave counterpart. Also, the corresponding time of relaxation is shorter.

Third, the concept of the axial support system is more straight-forward in the case of a meniscus mirror than for a plane-concave mirror with its more complicated figure. In this case, however, there is a practical complication regarding the meniscus mirror. It refers to the support systems.

For a meniscus mirror, the axial supports may in some cases have their forces directed along the radius of curvature. This requires some special arrangements for their assemblage in the mirror cell. The lateral supports must, together, have their forces directed towards the centre of gravity of the mirror section supported. The corresponding constellation results in a bending moment.

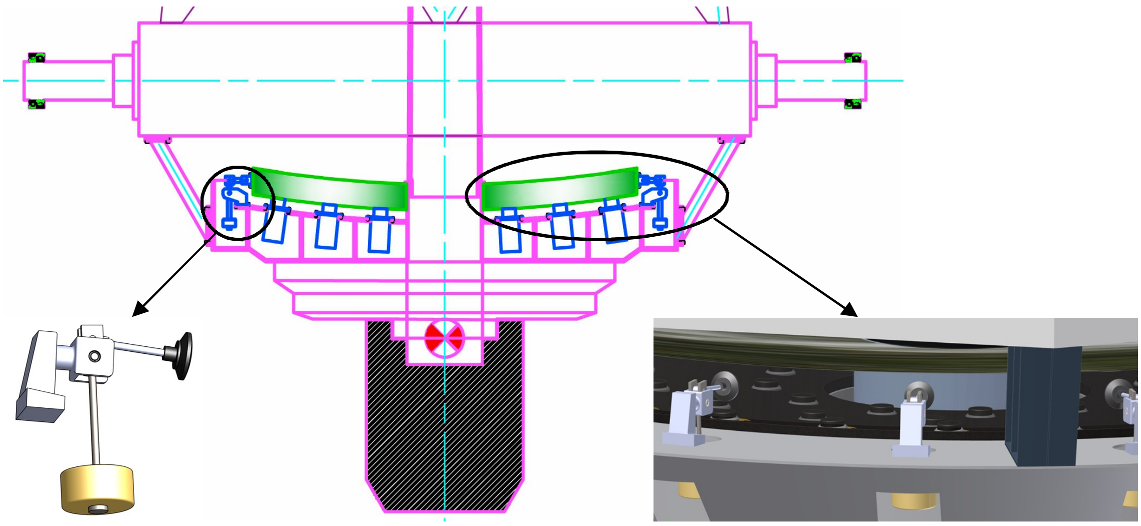


Fig. 149. A mirror-cell slice showing the axial and lateral supports (middle), a simplified version of a lateral support unit (left) and a 3D model edge view of a 3m primary-mirror lateral support configuration (right).

While deformations caused by the Poisson effect are normally rather small, those resulting from the bending moment are larger. Further, while the Poisson-effect deformation largely varies with the distance from the support point, this is not the case for those caused by bending moments. The latter vary with the distance from the support point in a non-linear manner. One way to reduce the lateral-forces bending moment is to insert the lateral supports in small cavities over the back of the mirror. This reduces the distance between any given lateral support point and the corresponding local mirror-section centre of gravity.

The bending moment caused by the lateral support of a meniscus mirror is proportional to both the mirror diameter and thickness but inversely proportional to its focal ratio. The deformation caused by this bending moment is proportional to the mirror area but inversely proportional to the focal ratio and to the square of the mirror thickness. Thus, when the mirror aspect ratio increases, the design of the mirror lateral support system becomes increasingly important to the mirror surface deformation. In Fig. 149, aspects of lateral mirror support systems are illustrated.

Positioning support points for primary mirror

A rigid body has six degrees of freedom, three translational and three rotational. Thus, a so-called kinematic mounting has many advantages as it is able to take care of the six degrees of freedom. This is, with certain restrictions, a useful point of departure for the concept of the positioning supports of the primary mirror. These supports are often labeled hard points, that term in a more general context often being understood in terms of attachment points. If we can discard the axial rotation of the primary mirror, the number of practical constraints is reduced to five.

The support functions can, in principle, be joined in a single point. However, considerable stress will occur around this point. Alternatively, the support functions can be located in three or more points, giving a more or less distributed stress pattern. The axial and the lateral positioning support points can be treated as an ensemble or separately. In most applications, the positioning support points can be chosen either at the outer edge of the mirror, close to the half -radius circle or at the inner mirror edge, the latter option valid only for mirrors with a central hole.

A three-point mirror support can evolve into a six-point, or nine-point, or even more-point mirror support through a whiffle-tree design. A whiffle-tree is a beam, or plate, structure, that distributes the support force from one point to two, or three, ends of a beam, or a plate. This force redistribution can be cascaded as a tree structure. Still, the degrees of freedom involved are kept the same as with the single-point support.

In general, the mirror and the mirror cell are made of different materials. In practice, primary mirrors for modern telescopes are made of glass-ceramic material, while the corresponding mirror cells are made of steel. This implies that the mirrors and their cells have different thermal expansion coefficients as well as different thermal inertia. With temperature changes that are impossible to avoid, these are non-trivial considerations.

The effects of differential thermal expansion or contraction increase with the support radius chosen. The effects are highly decreased in a positioning support system applied to the inner edge of the mirror, while they are larger when larger support radii are chosen. At the same time, location of the positioning support points at the outer edge of the mirror has important advantages. First, the outer edge of the mirror offers better practical options than its inner edge. Second, application at the outer edge of the mirror will result in a higher natural frequency than application of the points at its inner edge.

In general, it is a good policy to try to minimize effects of thermal expansion and contraction as much as possible. Most modern ceramic mirror substrates have only minute effects of this type. Thus, the harder challenge is to bring down the thermal effects coming from the mirror cell to a minimum while retaining its other important qualities. Still, with a ceramic mirror substrate and a mirror cell made of steel, differential effects of thermal expansion and contraction are unavoidable, as are the resulting forces of radial shear.

Actuators

With a properly functioning mirror-support system, most of the mirror weight is taken up by floating support mechanisms. There are four types of flotation support systems. These are mechanical, pneumatic, hydraulic and electromagnetic actuators.

A mechanical mirror support system usually involves a counter-weight and cantilever mechanism. The support force generated by this system follows a sine law with the elevation angle of the mirror as variable. This law is the same as that governing the variation of the axial force component of the mirror weight. Thus, no force adjustment is necessary in a normal passive support system. The cantilever length ratio produces a magnification of the load applied to the mirror. This sets the scene for a relatively reduced counter-weight.

A mechanical flotation support system can be used for both axial and radial support. The system involves mainly two problems. One is the friction involved. The other, due for use with active systems, is the heat created by the corresponding motor drives.

Air cushions or air cylinders are the hearts of pneumatic flotation mirror-support systems. In practice, they are mainly used for axial support. The support force of these systems is proportional to the mirror-contact area. Thus, this contact area should remain constant during telescope operation.

To obtain, at any moment, the support force required, the air pressure of a pneumatic bellow is adjusted by a pressure regulator. This process can be controlled via monitoring of the motion of the telescope and its pointing, thus producing the required sine-law governed air pressure. Rather than relying on a model support, a more precise and real-time oriented approach is to use force sensors, such as strain gauges, in the support points, to provide signals to control the air pressure. The air cushions are soft allowing height and tilt adjustments, producing rather small friction forces. When the pneumatic-bellow system is not pressurized, the mirror rests on a set of soft pads.

Using hydraulic actuators may, at least in principle, allow more exact pressure control than the application of pneumatic bellows. However, as compared to pneumatic bellows the hydraulic counterparts have more friction, and they are more expensive. They same applies largely to electromagnetic actuators.

Radial bumpers

The lateral support system is based on astatic lever supports surrounding the circumference of the primary mirror. The stiffness of this system is very low. Thus, oscillations of the mirror inside its cell, induced for instance by an earthquake, are little restrained by the astatic lever system. Rather, it acts like a series of masses attached to the mirror and oscillating with it.

Three tangential fixed points are applied to define the position of the primary mirror in the plane set by the mirror cell. The fixed points have a limited load capacity. Thus, when the mirror displacement in the mirror-cell plane tends to increase, the fixed-point forces are limited.

Fig. 150 shows a primary mirror inside its cell and surrounded by a lateral support system and equipped with a safety system, or anti-earthquake system, as described.

A common manner to investigate earthquake-related stress and deformation conditions for a structure is to perform a response-spectrum analysis. This procedure, linear in its nature, may not be sufficient while designing the telescope primary mirror safety-device system. A major reason is that introduction of nonlinearities in the real system (gaps and nonlinear springs) can affect the real stress and deformation field.

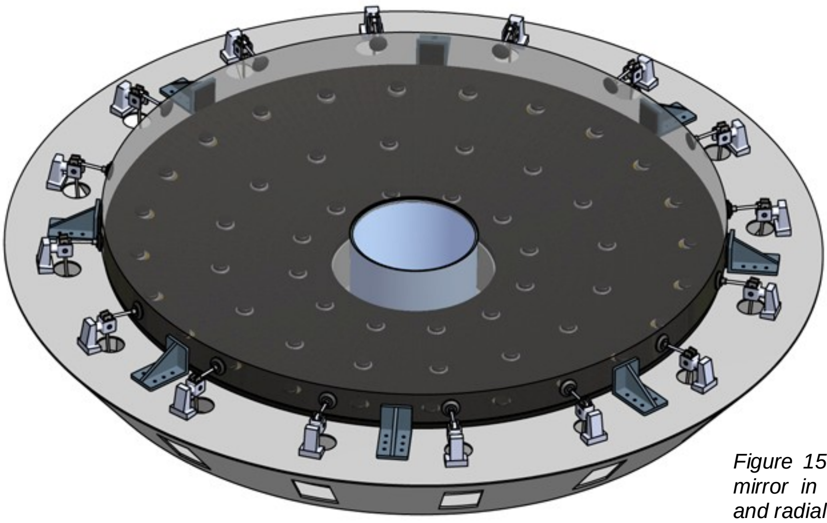


Figure 150. An example of a primary mirror in its cell with lateral supports and radial bumpers.

Primary-mirror cell

The primary mirror and its support systems are embedded in the corresponding mirror cell. This cell is, on its preferential upper side, attached to the centre section of the telescope. On its lower side, it carries the science instrumentation, as well as other components, normally via a field rotator, an instrument adapter and an attachment flange.

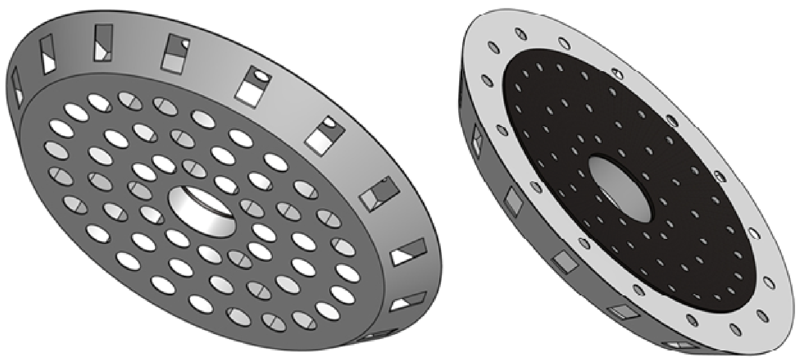


Figure 151. A modern mirror cell, stiff yet light-weighted and providing space for components, cables and pipes.

The cell for the primary mirror must provide space for the mirror, its support systems and adhering equipment. That includes adequate space and facilities for cables and pipes. Also, the mirror cell should be as light as possible. At the same time, it is of major importance for the design of the primary-mirror cell that its deflections under forces of gravity are limited. These deflections should not exceed the range acceptable for the actuators, typically of the order of a millimetre. Also, the natural frequency of the mirror-cell mode along the optical axis of the telescope should be high enough not to be excited by wind gusts.

Another concern regarding the primary-mirror cell is its thermal expansion coefficient and heat capacity, which should be as limited as possible. Further, and of special importance when high image quality is a priority, it should carry the primary mirror in a manner exposing its surface to free air flushing, thereby allowing efficient elimination of mirror-surface air convection. This latter criterion has to be supplemented with optimum protection of the mirror, avoiding wind shaking. An illustration is provided in Fig. 152.

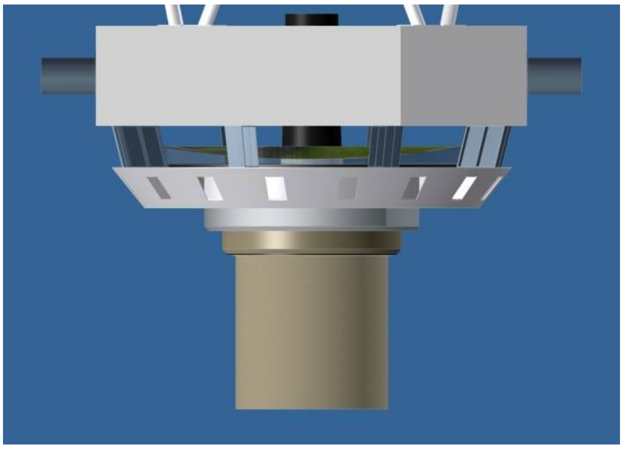


Figure 152. The primary-mirror cell below the centre section and carrying the field rotator, the instrument adapter and flange plus the instrument. Note the exposure to free-air wind flushing of the mirror surface.

Secondary-mirror size

Choosing the diameter of the secondary mirror, a number of considerations are due. They regard the field of view to be available, emission in infrared light from the mirror cell, obstruction of the light available for the primary mirror and the weight of the secondary mirror and its cell. In practice, a combination of science and technical priorities has to be made for final decision.

For the telescope design in general, the maximum field of view to be used is an important parameter. Considerations of science use have to be merged with those of the optomechanical system. In addition, the image quality ambitions have to be matched with the atmospheric quality of the site of the telescope.

If significant amounts of observations in infrared light are considered, some special arrangements may be in place. An under-sized secondary mirror and an even more under-sized secondary-mirror unit are helpful to minimise the infrared emission resulting from these elements.

Obstruction of the light available for the primary mirror is a natural concern at the same time as it, normally, does not define any serious restrictions. Two considerations are due in this case. They are reduction of the light collected by the primary mirror and the transfer of light regarding the Airy disc. Even with a relatively large secondary/primary diameter ratio, the influence in terms of light collected is rather limited. The same is essentially true concerning the Airy-disc light-transfer influence (Mahajan, 1991).

Traditionally, for telescopes with passive optical systems, the weight of the secondary mirror has been a concern of somewhat reduced importance. In practice, the major restrictions in terms of this weight have been in regard to handling. The latter consideration has sometimes been emphasised by requirements for exchange of secondary-mirror units. Of special concern has the weight of the secondary mirror been for telescopes intended at least partly for observations at longer wavelengths. Faster mirror chopping, several and even tens of Hz, and larger throw angles, an arcminute or more, have often prompted rather special designs of the secondary-mirror units.

As soon as any form of pre-focus adaptive optics system is considered with the secondary mirror as the adaptive unit, the weight of this mirror becomes a critical issue. This is clearly the case already for low-order adaptive optics. The best example is low-order adaptive optics including only tip-tilt corrections, focusing and centring. The improvement of the image quality possible very much depends on the tip-tilt frequency achievable. To provide significant image-quality enhancement, this frequency should exceed 10 Hz, preferably more than that.

The tip-tilt frequency viable depends on the weight of the total structure to be actuated. When the weight of the secondary mirror increases, so does the weight of its mechanical support systems, motors and control units. As an illustration, we can consider a secondary mirror with a diameter of 600 mm. To allow sufficient stiffness, it should have a relatively low aspect ratio, say below ten. Depending on the choice of material (see below), the weight of such a mirror falls typically between 20 and 35 kg. The indicative total weight of the secondary-mirror unit could be between 40 and 80 kg.

To provide safe tip-tilt corrections with a mirror unit with a weight between 40 and 80 kg is a task far from trivial. The challenge increases significantly with the maximum tip-tilt frequency to be available. The situation can be very much improved, if a light-weighted secondary mirror is chosen. With a solid front plate backed by a rib structure, a weight reduction of a factor of four can be achieved without significant loss of stiffness. For the SOFIA secondary mirror, with a target chopping frequency of 20 Hz, Fig. 153 gives an illustration of such mirror light-weighting.

Figure 153. SOFIA secondary-mirror blank (backside on the left and frontside on the right. This mirror vibrates with a frequency of 20 Hz in chopping mode (Erikson, et.al, 2004).

Secondary-mirror material

Under separate heading, materials for mirrors have been discussed. While the choice of material for the primary mirror is of prime importance, the corresponding choice for the secondary mirror is, normally, somewhat more relaxed, at any rate if a passive optical system is considered. However, if any form of pre-focus adaptive optics is considered with the secondary mirror as the adaptive unit, the selection of mirror material is of importance. We note that a modest thermal-expansion coefficient and a low material density are both highly advantageous. In this context, we refer to the discussion of mirror materials.

Secondary-mirror and top-ring assembly

The secondary-mirror assembly unit has a number of functions, as partly indicated above. It must provide a stiff location and support platform for the secondary mirror. It should be as small and light as possible yet providing adequate space for all components required. In modern telescopes with active optics, it must include moving and tilting mechanisms acting in a five degrees of freedom mode to assure, at all times, an adequate optical alignment of the telescope. In case a low-order adaptive-optics system is included in the design of the telescope, the secondary-mirror unit must also support the corresponding tip-tilt mechanisms. A conceptual secondary-mirror and top-ring assembly is illustrated in Fig. 154.

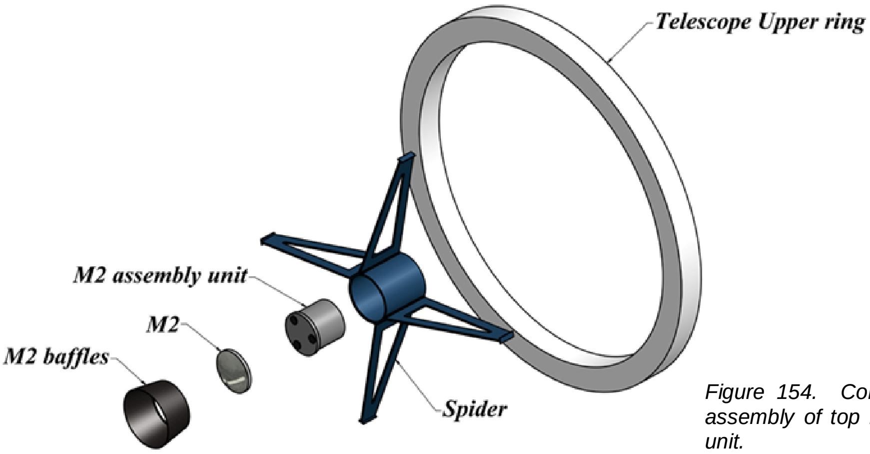


Figure 154. Conceptual illustration of an assembly of top ring and secondary-mirror unit.

Secondary-mirror mounting, alignment and active motion

The secondary mirror is mounted on a mirror cell. Alignment and motions of the mirror as described above are provided via a dedicated mechanism unit. At its lower end, this unit is attached to the mirror cell, at is upper end to a counterweight system. The alignment and motion unit as well as the counterweight system are comprised in a secondary-mirror-unit container, attached to the top-ring spider vanes. This is illustrated in Fig. 155 with a hexapod mechanism for alignment and motion of the secondary mirror (see below).

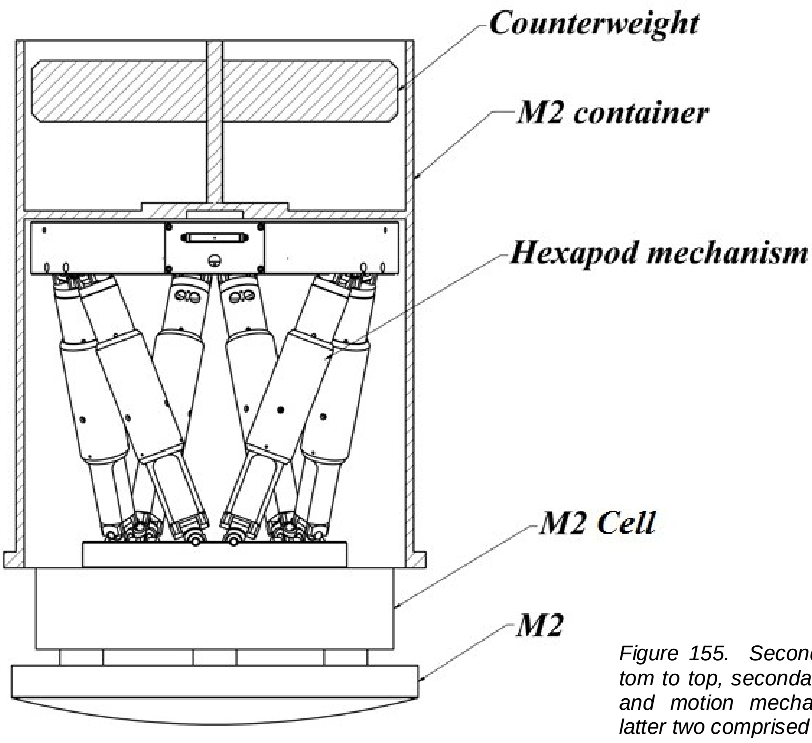


Figure 155. Secondary-mirror unit with, from bottom to top, secondary mirror, mirror cell, alignment and motion mechanism and counterweight, the latter two comprised in a common container.

The arrangement shown in Fig. 155, is rather straightforward as long as no adaptive function is required. In this case, efficient functioning in terms of alignment and motion can be provided with a gimbal mechanism or a pivoted support that allows rotation around an axis. Well equipped and functioning, the same arrangement, in dual version, a dual-axes gimbal with orthogonal axes, can, however, serve also in the case low-order adaptive optics are run.

When adaptive optics, with emphasis on tip-tilt correction, is a target, an interesting option for the alignment and motion mechanism is a Gough/Stewart platform, often labelled a hexapod. As illustrated in Fig. 155 , it is a mechanical arrangement featuring six jacks mounted on a level surface in three pairs and crossing to three mounting points on a plate intended to provide movements in six degrees of freedom. Currently, such arrangements are often, due to their straightforward and light construction and high reliability, used for mountings for secondary mirrors intended as moving units in pre-focus adaptive-optics systems.

Hexapod platforms have been used also for entire telescopes, in replacement of altitude-azimuth arrangements. From early proposals (Schmidt-Kaler, 1992) the concept has gone into realisation of a relatively modest telescope for optical and adjacent wavelengths (Chini, 2000). Designed for microwave-background observations, the (Yuan-Tseh Lee) Array for Microwave Background Anisotropy (AMiBA), is a radio-wavelength telescope atop a hexapod mount (Koch et al., 2009). In addition, a hexapod arrangement is discussed for the James Webb Space Telescope (JWST).

Spider

The mechanical structure connecting to and supporting the secondary-mirror unit via the top-ring is labelled spider. For an optimum spider design, some optical and mechanical issues have to be considered. In the case of modern telescopes such studies have been relatively detailed.

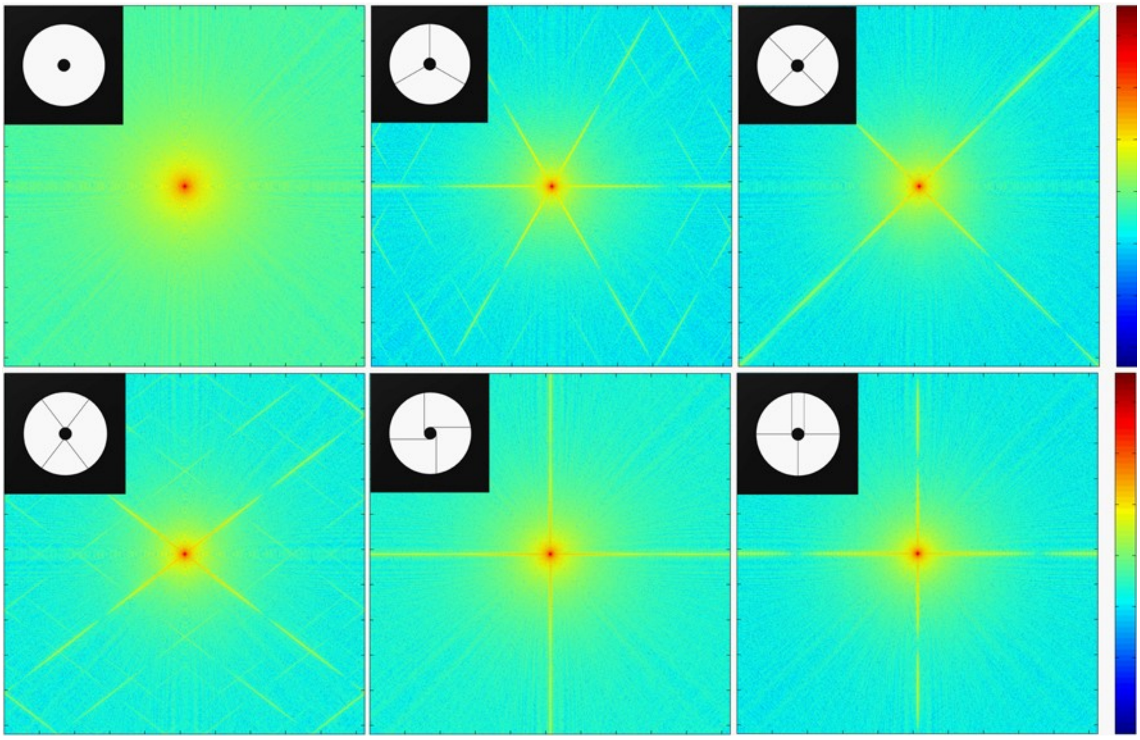


Figure 156. Visual appearance of a point-source object (a bright star) without spider and with five different spider forms. While the spikes caused by spider vanes can be visually distracting, the amount of energy lost from the disc is usually negligible for general observing.

Optically, the spider vanes act as pupil obstructions. While the light obstruction in itself is normally negligible, the vanes interfere with and modify the emitting area of the wavefront and, thus, cause effects of diffraction. Reference is made to Fig. 156. Still, in general, the effects of diffraction are, while present, of no significant concern for the contrast level.

Treating the effect of the spider vanes in a manner analogous to that of the central obstruction, we can evaluate the effect as a Strehl-ratio degradation. Comparing the pupil are with and without the presence of vanes, we get

$$s' \approx \left(1 - \frac{2Nt}{(1+o)\pi}\right)^2$$

Here, *s'* is the Strehl-ratio degradation ratio, *N* is the number of vanes, *t* is the vane thickness and *o* is the diameter of the central obstruction with both *t* and *o* expressed as fractions of the free aperture (Mahajan, 1998). Obviously, to get the effects of both light-collection obstruction and diffraction as small as possible, the intervening area of the spider vanes should be as small as possible. It is of importance to make this area as independent as possible of the position in the field of view. In practice, then, spider vanes in the form of pipes, or rods with circular cross sections are preferable as compared to blade-shaped spider vanes. In general, it is recommendable to restrict the relative aperture part obstructed by the spider vanes to less than 0.02, a target that can be realized in practice.

As demonstrated in Fig. 156, each vane gives rise to two diffraction spikes 180 degrees apart and perpendicular to the orientation of the vane. Thus, to minimise the number of diffraction spikes, the vanes should be arranged in parallel groups. As an example, a spider with 3 vanes will generate six spikes, while one with four vanes generates four spikes only. At any rate, for practical purposes, not only the number of spikes have to be considered but also the amount of energy spread out. From Fig. 156, it is, in addition, clear that the vanes do not have to be in line with each other.

In this context, also cables and pipes passing over the top-ring aperture have to be taken into account. All cables and pipes should be stacked onto the vanes in a way that as little as possible increases the obstruction effect of the spider vanes. A hands-on solution adopted for the ESO VLT is shown in Fig. 157.

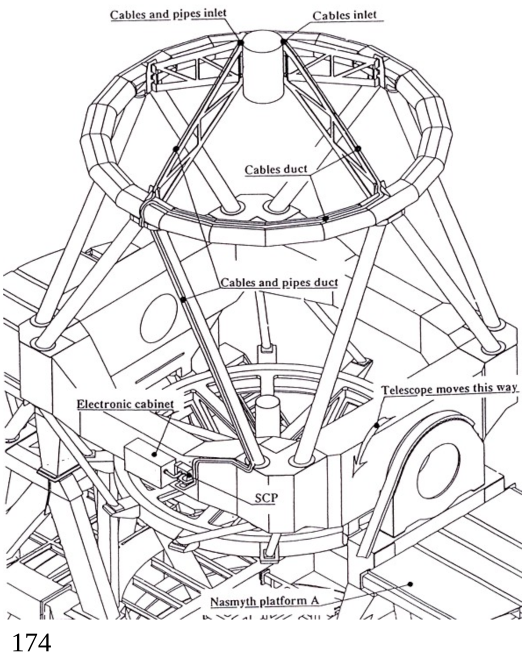


Figure 157. Cables and pipes stacked onto spider vanes, trusses and top-ring of the ESO VLT. (VLT technical report, 1994)

Spider stiffness

De-positioning of the secondary mirror with respect to the optical axis of the telescope can have very serious consequences in terms of image quality. Even a smaller tilt or de-centering of this mirror occurring during pointing or tracking can imply large aberrations and ruin the image quality of an exposure. The reasons for the tilts and de-centering effects are due to bending of and tensions in the mountings structures. It must be noted that the total weight of the secondary mirror together with its mounting can reach well above 100 kg for a 3 m class telescope, although measures should be adopted to keep this weight down to the extent possible.

Using simple in-plane spider vanes, it is not feasible to realise a spider structure stiff enough nor to guarantee obstruction homogeneity over the field of view. While a corresponding rod structure performs well in terms of obstruction homogeneity, it is normally not stiff enough to guarantee freedom from significant tilt and de-centering of the secondary mirror. The solution in practice is often to adopt a spider design with a triangular geometry. This is illustrated in Fig. 158.

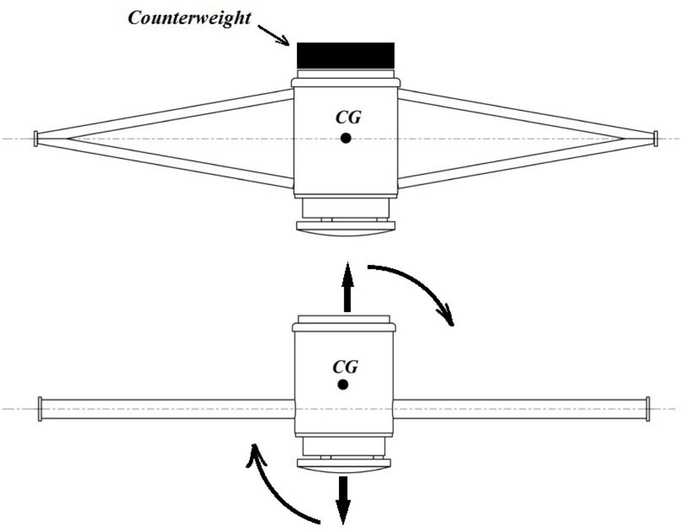


Figure 158. A triangular shaped spider structure with a counterweight maintaining the position of the centre of gravity (CG) offers high-rigidity support of the cell of the secondary mirror (Adopted from Bely, 2003).

Another important parameter for the design of spiders, especially for telescopes intended to work with some form of pre-focus adaptive optics or chopping ability, is torsion stiffness. While rotation of the secondary mirror around its optical axis is of limited importance, the low torsion frequency of the system can create serious problems in case of fast motions of the secondary-mirror unit. Such motions occur for adaptive-optics tip-tilt corrections as well as in corresponding chopping mode. To strengthen the torsion stiffness, the spider vanes should not cross the centre of gravity of the secondary-mirror M2 cell. Fig. 159 shows an example of a spider structure as discussed.

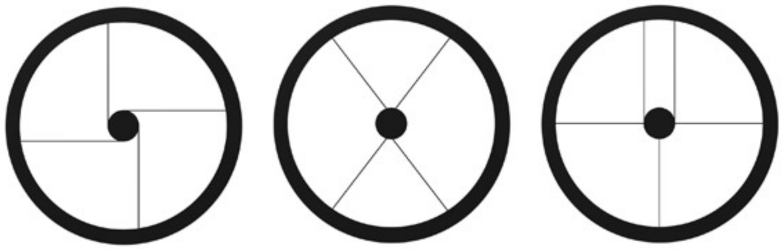


Figure 159. By offsetting the vane intersection points from the centre of gravity (left and centre) or adding a fifth vane (right) will significantly improve torsional stiffness. Note, however, that the left-hand version cannot be pre-

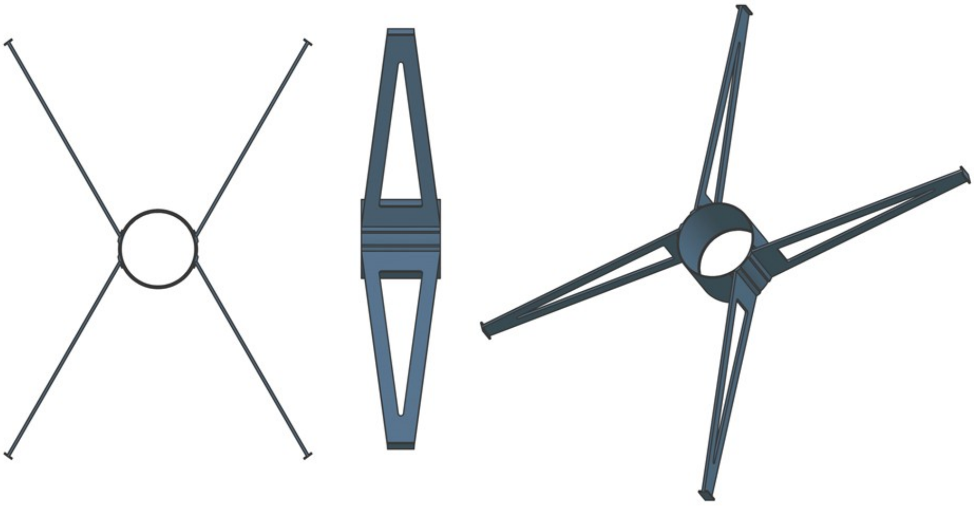


Figure 160. An example of a spider structure for a 3 m class telescope providing high stiffness.

Telescope tube

A structure supporting the primary and secondary mirrors of a telescope and surrounding the incoming light beam is, disregarding its detailed construction, called a telescope tube. In older telescopes as well as in many smaller new telescopes, the tube is a straight-forward cylinder with the primary and secondary mirrors at is extremes. However, for modern large telescopes, the cylinder-type tube can hardly be recommended. The reasons for this are several.

First, it is difficult to produce a light-weighted tube rigid enough to keep the alignment of the optical elements sufficiently accurate. Second, for a primary mirror enclosed in a tube, the practical thermal relaxation time will be significantly increased. For many telescopes, this effect has ruined the image quality otherwise reachable. In some of these telescopes, the tubes have been equipped with forced-ventilation devices to improve thermal relaxation. Often, still, the thermal time constant has been long and ventilation has been continued during observations, not seldom causing further decrease of image quality through internal air turbulence and shaking.

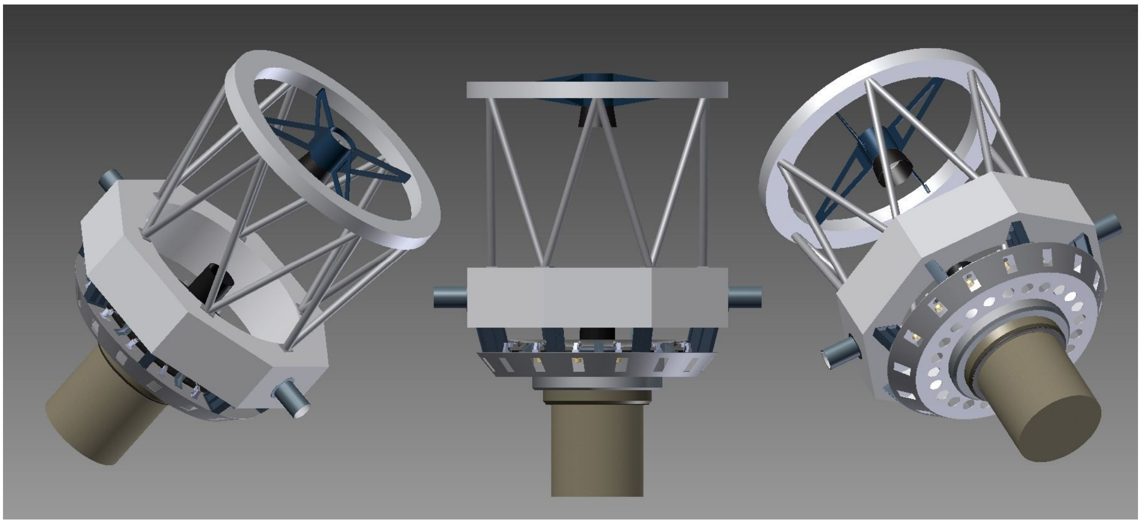


Figure 161. Different views of a modern 3m class Cassegrain telescope tube with rotator, adapter and instrumentation attached.

Third, in general, a closed tube above the primary mirror tends to create and maintain air streaming with detrimental effects for image quality. Fourth, a closed tube structure has a large cross section against wind forces. Even in the case of modest wind speed, this can cause serious effects of shaking.

Most modern medium-sized and large telescopes have tubes with a V-shape truss structure. To avoid undesired moments, these trusses intersect in a common plane in the centre section of the telescope. It should be noted that the primary-mirror cell, with its considerable weight, is attached to the centre section with rigid connector elements. However, as the weight of the primary-mirror cell is much higher than that of the top ring with the secondary-mirror assembly, the centre of gravity of the telescope tube is rather close to the surface of the primary mirror. Accordingly, there is no need for a V truss structure between the primary-mirror cell and the centre section. It is added that it is essential to combine a design of the primary-mirror cell leaving the surface of the mirror open to natural free air flushing with a reasonable distance between the mirror cell and the centre section.

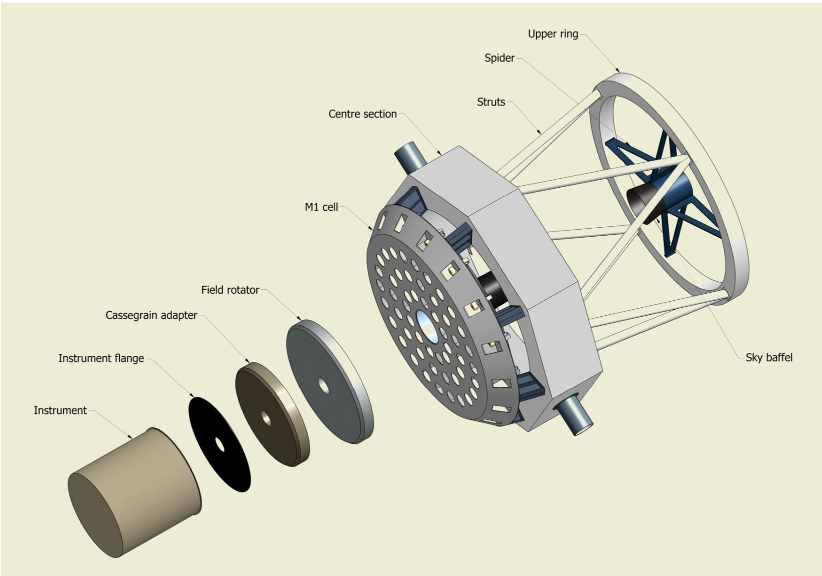


Figure 162. Indicative layout of a modern Cassegrain telescope tube.

The secondary mirror spider connects to a ring on the top-end of trusses that is called the top ring When the tube is in vertical direction, the primary and secondary mirrors shift along the axis. There is no pointing error introduced. When the tube points at the horizon, the trusses do not support the mirror weight and their average lengths remain unchanged. The side trusses deform downwards, so that the primary mirror moves laterally in gravitational direction. No mirror tilt is produced. The lateral displacements of both the primary and the secondary mirrors can be adjusted to be the same by altering the cross section area of their support structure members. In this way, neither pointing error nor coma is produced by the tube.

For a Serrurier strut design, if the weight of the mirror is ***W***, the cross sectional of a truss member is ***A***, the distance between the mid-part and the mirror is ***L***, and the width of the mid-part is ***D***, then the lateral displacement of the mirror when the tube is in horizontal position is

$$\delta = \frac{\left((D/2)^2 + L^2\right)W}{2AED}$$

Here, ***E*** is the Young modulus of the truss material (Cheng, 2009). The axial deformation of such a truss is roughly proportional to the square of its length, so that the beam cross section for the secondary mirror support is generally large while that for the primary is very small. A large cross sectional area results in a weight and thermal time constant increase.

Centre section

The centre section of a telescope has some essential functions. First, it connects the cell of the primary mirror, via the tube or Serrurier structure, to the top ring with the secondary-mirror assembly. Second, it holds the elevation axis, thereby providing connection to the telescope mount and movement in elevation. Third, via the elevation axis, it offers the optical path to the Nasmyth focus or foci. Fourth, it provides space and basis for some ancillary components, such as covers for the primary mirror and counter weight arrangements.

At the same time, the centre section must not, at any elevation, obstruct the telescope main beam. Further, the centre section has to combine a light-weight structure with high stiffness. For a 3 m class telescope, this can be achieved with a metal-sheet construction. Further, the centre section has to provide generous space for cables and pipes, via the elevation axis or otherwise. Fig. 163 shows a simple centre-section concept.

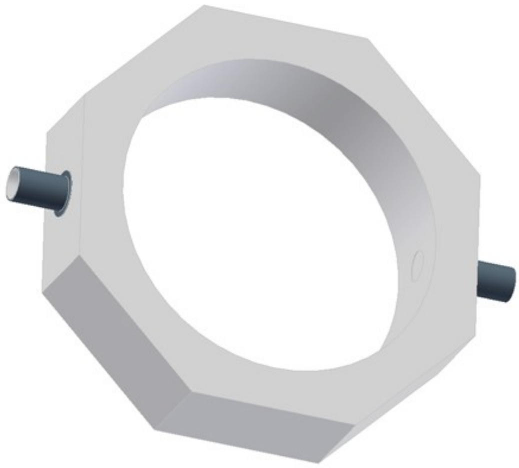


Figure 163. A simple centre-section design

Primary-mirror cover

When the telescope is not used for observations, the primary mirror and the opto-mechanical components behind it have to be protected. This protection has to be effective concerning dust but also regarding rain, snow and ice that may enter through the observing slit or otherwise. In addition, protection of the primary mirror should be available against all sorts of tools accidentally falling towards it as well as for people that might approach it.

Figure 164. A primary-mirror cover of tulip type.

Accordingly, a primary-mirror cover is required. It has to be reasonably dust and water proof but also be able to resist impacts and objects with weight up to around 100 kg. At the same time, the cover itself and its control functions must not be sources of contamination, dust and liquids. Further, when opened, the mirror cover must not, in any position, limit the clear telescope aperture. It has to be light weight, easy and safe to operate. The motors and control systems of the mirror cover must be turned off during observations in order not to act as an extra source of heat and air turbulence. Fig. 164 shows a tulip-type primary-mirror cover.

Mount

Of all the sub-systems being part of a telescope, the mount is, normally, the largest and heaviest. Below, we will, as has been done above, in the general discussion assume a telescope with altitude-azimuth mount while we will, in addition, provide some dedicated comments regarding both this and other types of telescope mounts. The latter comments concern equatorial mounts, transit mounts, and fixed mounts.

The telescope mount has to provide a stable platform based on the telescope pier via an azimuth bearing. In azimuth, the mount has to move smoothly, especially with respect to tracking motion but also in the case of acceleration, slewing and deceleration, the latter three operations at high speed without introduction of oscillations. It has to be able to point highly accurately in azimuth and provide a firm support of the elevation axis and its bearings and drives. Further, the mount has to be designed to allow convenient access to all parts of the telescope part moving in elevation, for mounting and dismounting of a range of instruments and other equipment. In addition, it should be provided with adequate service access points for electricity connectors, pipes and network cables. The service access points and the corresponding attachments must not interfere with the motions of any part of the telescope.

Equatorial mount

Equatorial mounts were, over many decades, the predominant types of mounts, not least for larger telescopes. The equatorial or right-ascension axis is parallel to the axis of rotation of the Earth. The other axis, the declination axis, can be rotated around the equatorial axis and, in any orientation, fixed to it. Thus, rotating only one axis at constant speed, all distant celestial objects can be tracked. This tracking can be powered by a simple clock mechanism, even a pendulum arrangement. For nearby objects, as near-Earth objects, the Moon, planets and their moons, asteroids and comets, target-specific differential tracking has to be added.

An equatorial mount offers a number of advantages. First, it requires rotation around one axis only. Second, the speed of this rotation is, for most objects, constant. Third, the straightforward mode of tracking allows relatively simple telescope mechanics. Fourth, the field of view of the telescope does not rotate. Fifth, no computer control is necessary, an advantage that today is negligible.

Equatorial mounts have been designed in a large number of manners, optimised for different situations, conditions and requirements. Constantly though, telescopes with equatorial mounts have had rather large and heavy structures. Thus, they distort in the gravitational field and require enclosures of large dimensions. Not least does the axis of rotation bend under its heavy load in a manner dependent on the position observed. The heavy telescope and enclosure structures require heavy-duty drives. Thermal inertia, structural deformations, telescope and enclosure air turbulence and costs are all rather high. For these reasons, equatorial mounts are today chosen only for smaller telescopes. See Fig. 165 for some examples of telescopes with equatorial mounts.

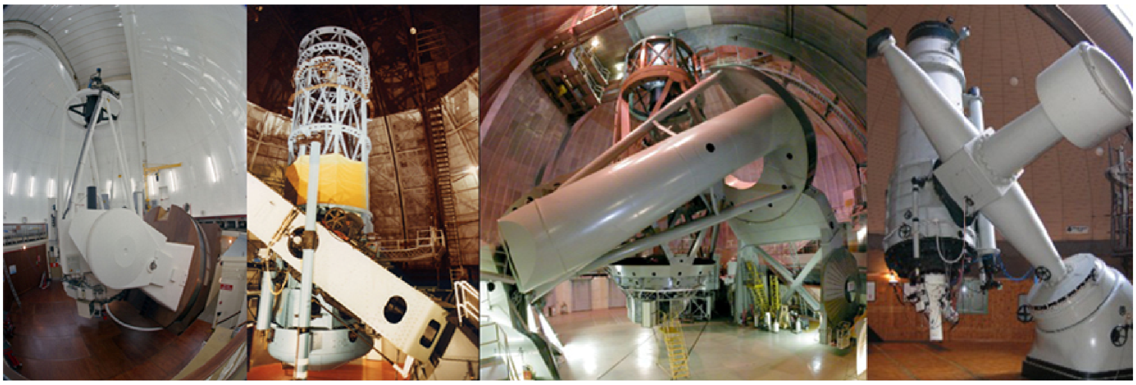


Figure 165. Different types of equatorial mounts. From left to right, INT with Fork shape, Hooker telescope with English yoke, Hale telescope with Horseshoe and Galileo telescope (at the Asiago Astrophysical Observatory) with English cross-axis mount.

Altitude-Azimuth mount

Some of the earliest large-size telescopes were provided with altitude-azimuth mounts, notably Herschel's 1.2 m telescope from 1789. Later, especially from the end of the nineteenth century, they were more or less fully replaced by equatorial mounts. However, more recently, altitude-azimuth mounts have come back strongly. In principle, altitude-azimuth mounts are simple arrangements with one axis, the azimuth axis, perpendicular to the horizontal plane, another, the elevation axis, parallel to it. In practice, normally, the azimuth axis is a vertical fork rotating around a horizontal bearing. One can imagine the equatorial mount as an altitude-azimuth mount based on a wedge with a wedge angle equal to the local latitude. This is illustrated in Fig. 166.

A large advantage of the altitude-azimuth mount is that the fork arms deflect symmetrically. The weight of the elevation axis and the structure rotating around it is directly transferred to the azimuth axis. Neither the azimuth axis nor the elevation axis vary in direction with respect

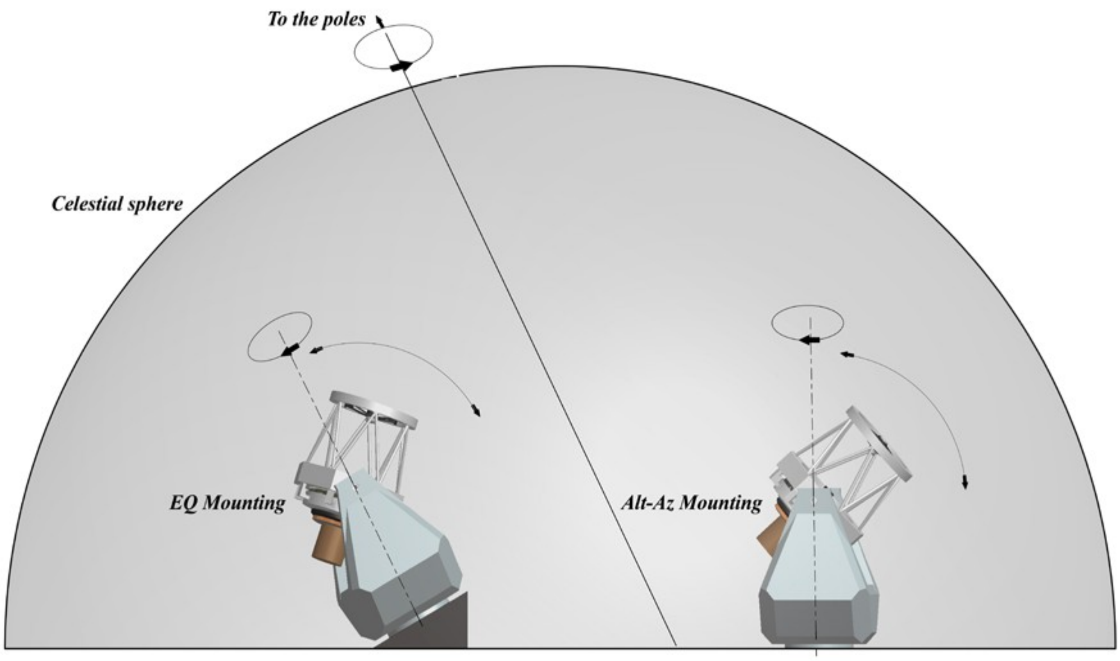


Figure 166. An equatorial mount imagined as an altitude-azimuth mount atop a wedge with a wedge angle equal to the site latitude.

to gravity. The altitude-azimuth mount is sturdy and straightforward. Compared to the equatorial mount, it implies significant reductions in weight and cost.

For the same primary-mirror diameter and focal ratio and the same telescope f ratio, an altitude -azimuth mount gives a more compact telescope than does an equatorial mount. Thus, there is a reduction of cost not only for the telescope but also for the enclosure. In addition, the amount of enclosed air is smaller in the altitude-azimuth case. In addition, for telescopes with altitude-azimuth mounts, the design is independent of site latitude. A disadvantage of the altitude-azimuth mount is the so called blind spot around local zenith. This is discussed below.

Blind spot

Altitude-azimuth mounts work with a horizontal-elevation coordinate system for pointing and tracking celestial objects. In this coordinate system, both axes move in time-dependent manners, as discussed below. A telescope with an altitude-azimuth mount can point and track over all the sky available except for a small area around the zenith, the so called blind spot, that remains inaccessible for observations. When an object is tracked, the relative speed of the telescope in altitude and azimuth varies. The speed in azimuth increases with decreasing zenith distance. Close to the zenith, it is very high. Here, for the corresponding tracking and acceleration, there is a clear limit causing the blind spot.

We get

$$z(t) = \arccos(\sin\varphi \sin\delta + \cos\varphi \cos\delta \cos t)$$

$$A(t) = \arctan[\sin t / (\sin\varphi \cos t - \cos\varphi \tan\delta)]$$

with

$$t = \textit{Local Sidereal Time - object Right Ascension}$$

Here, z is the zenith distance, t is the hour angle, φ is the site latitude, δ is the declination of the object observed and A is the azimuth.

Thus, the corresponding rate of change of velocities during tracking of an object can be expressed as (Borkowski, 1986).

$$\dot{z} = \cos\varphi \sin A \quad \textit{and} \quad \dot{A} = \frac{\sin\varphi - \sin\delta \cos z}{\sin^2 z}$$

These relations show that the absolute velocity in elevation is never faster than that of the local hour angle. In contrast, the velocity in azimuth increases steeply with decreasing z. It reaches arbitrarily high values when z approaches zero, that is when the objects moves towards the zenith point.

The transitional velocity in azimuth for an object passing the local meridian is (Borkowski, 1986)

$$\dot{A} = \cos\delta / \sin(\varphi - \delta)$$

The corresponding accelerations of the altitude and azimuth axes during tracking are

$$\ddot{z} = \cos\varphi \cos A\left(\sin\varphi + \frac{\cos\varphi\cos A}{\tan z}\right)$$

$$\ddot{A} = -\frac{\cos\varphi \sin A}{\sin^2 z}\left(\sin z \cos z \sin\varphi + \cos\varphi \cos A\left(1+\cos^2 z\right)\right)$$

From the last equation, it can be seen that the acceleration in azimuth changes sign at transit of the meridian, and that it reaches high and very high values when the object observed approaches zenith.

A telescope with an altitude-azimuth mount tracking a star will keep pace with it until a point, east of the meridian, where $\dot{A}$ reaches its maximum allowable azimuth velocity. Using the actual azimuth velocity of the star at the meridian, the tracking limitation is reached for stars with declination in the range (Borkowski, 1986)

$$\varphi - \arctan\frac{\cos\varphi}{|V| - \sin\varphi} \langle \delta \langle \varphi + \arctan\frac{\cos\varphi}{|V| + \sin\varphi}$$

Here, V is the maximum azimuth tracking velocity.

This relation provides the northern and southern boundaries of the blind spot. The actual blind spot at the zenith is, in practice, also influenced by the maximum azimuth acceleration and the slewing velocity.

To obtain a more exact shape and size of the blind spot, we must consider the three parameters tracking velocity, tracking acceleration and slewing velocity. In addition, the elevation drive and field rotation contribute to the size of the blind spot. In the telescope design, optimum tracking velocity and acceleration can be determined through analyses of the corresponding relations.

It should be emphasised that, in practice, the blind spot is more of an academically interesting fact than a real problem. In general, the size of the blind spot is not very big. Typically, it covers around one square degree. First, only very rarely will real observational objects pass this spot. Second, if they happen to do, an easy remedy is to halt observations for the short while it takes them to pass the blind spot.

Field rotator

At any focus of a telescope with an altitude-azimuth mount, when a celestial object is tracked, the orientation of the field observed will change with time. The field angle, or the parallactic angle and its rate of change are given by (Borkowski, 1986)

$$p(t) = \arctan[-\sin t/(\sin\delta\cos t - \cos\delta\cos t - \cos\delta\tan\varphi)]$$

$$\dot{p} = -\frac{\cos\varphi\cos A}{\sin z}$$

$$(t = LST - object\ \ RA)$$

Here, $\boldsymbol{p}$ is the parallactic angle or field angle, $\boldsymbol{t}$ is the hour angle, $\boldsymbol{\delta}$ is the declination of the object, φ is the site latitude, $\boldsymbol{A}$ is the azimuth and $\boldsymbol{z}$ is the zenith distance.

Obviously, to achieve a stationary field of view with high image quality, accurate compensation of the field rotation is a requirement. Such compensation can be obtained in two different ways. We refer to optical and mechanical field de-rotators.

Optical field de-rotation is accomplished through successive reflections. These reflections can be provided by an ensemble of three flat mirrors. This is called a K-mirror. Another option is to use three internal reflections in a prism, called a Dove prism. The latter solution is illustrated in Fig. 167.

Optical field rotation has often been preferred due to its relative simplicity. However, this is true for smaller fields of view only. With increasing field dimensions, the dimensions and mass of both the K-mirror ensemble and the Dove prism become rather large and less manageable. Other limiting effects are caused by polarization of light and adjustment problems. Further problems are mirror movements and colour effects in the case of the K-mirror and the Dove prism, respectively.

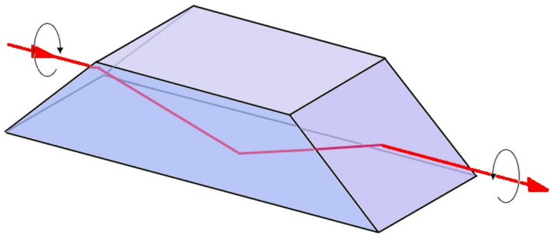


Figure 167. Field de-rotation with a Dove prism.

As a consequence of the limitations due for optical de-rotators, often mechanical field de-rotators are preferred. This is especially the case when the field of view is large. Mechanical field de-rotators are mechanical arrangements that rotate either the entire instrument or, in some cases, alternatively, only the detector(s) along the optical axis. This is done with respect to telescope position and object coordinates. For an instrument attached in Cassegrain focus, mechanical field de-rotation is a relatively straightforward procedure while it is much less so for an instrument installed on a Nasmyth platform.

Fixed-altitude mount

A large part of the cost for a modern telescope is due to the requirements on pointing and tracking in two axes. Significant savings can be achieved through suppression of one of these movements. Corresponding designs have been implemented for two very large telescopes, the Hobby-Eberly Telescope (HET) and the Southern African Large Telescope (SALT). Both these telescopes can rotate only in azimuth.

The first large fixed-elevation telescope to be designed and constructed was HET. It has an asymmetric segmented spherical primary mirror with a diameter of around 11.0 m by 9.8 m. However, at any given time, the usable aperture is 9.2 m only. Not only is the HET fixed in elevation, not even in azimuth does it track but point only. Once pointing has been achieved, the instrument at the focus tracks the object of observation. This way, exposure times of up to two hours can be obtained.

The elevation axis of the primary mirror is fixed at 55 degrees. Observing targets are pointed via rotation in azimuth and movement of the secondary mirror. This way, around 75 % of the sky can be covered. While this mode of operation violates fundamental optical principles for provision of high image quality, it allows construction at a very low cost. HET was completed at a cost of less than 20 % of that normally due for a fully rotatable telescope with the same aperture (9.2 m). The price to be paid is a modest image quality. Still, HET has produced large amount of frontier results, not least for exoplanets, supernovae and galaxies. HET was completed in 1997 at McDonald Observatory in Texas, USA.

SALT can be regarded as an improved version of HET. That has allowed use of the telescope not only for spectroscopy and polarimetry but also for imaging purposes. SALT has produced images with FWHM of around one arcsecond. It was completed in 2005 at the South African Astronomical Observatory close to the town of Sutherland in South Africa. At a cost of around the double of that of HET, SALT is still a rather low-cost telescope. Some details of SALT are illustrated in Fig. 168.

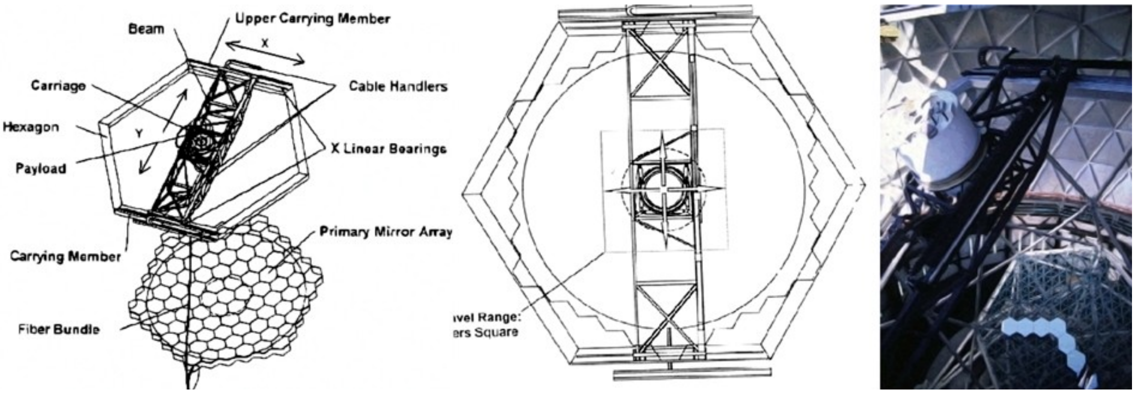


Figure 168. SALT details. Its tracker can move in both X and Y directions by 3.25 m in total, while the payload itself can tilt by 8.5 degrees off the Z axis in the two directions perpendicular to X and Y (pictures from SAAO, 2011 and SALT observatory, 2011).

Fixed-primary-mirror mount

Even more radical than fixation of the elevation axis is total fixation of the primary mirror. In this case, there is neither an azimuth axis nor an elevation axis. The primary is fixed towards the zenith. Such a telescope, a zenith telescope, can observe a small area around the zenith only. While the Earth’s rotation moves a thin belt of the sky over the local zenith, the image in the sensor is moved electronically, following the sky motion. Still, the total part of the sky available for observations is tiny. However, relative to its aperture, a zenith telescope can be constructed at even lower cost than a fixed-altitude telescope.

A prominent example of a zenith telescope is the Large Zenith Telescope (LZT). It has an aperture of 6.0 m and a primary mirror the surface of which is a constantly spinning pan filled with liquid mercury. LZT is a University of British Columbia telescope and is located 70 km east of Vancouver, Canada.

Some details of altitude-azimuth mounts

Currently, for medium-sized and larger telescopes, altitude-azimuth mounts are the rule. Thus, it seems adequate to discuss some of the more important parts of the corresponding mounts. These include the main body, the drives, the bearings, cable warps and twists, brakes, end stops and locking devices.

Fork of an altitude-azimuth mount

The main body of an altitude-azimuth mount is the dominant part of that mount. It has to carry the weight of the elevation axis and the part of the telescope rotating around it, including instrumentation, equipment for this rotation as well as possible Nasmyth stations and their equipment and instrumentation. At the same time, it must not deform and, thereby, introduce errors in pointing and tracking. Thus, the mount main body has to have a stiff structure. Nevertheless, it should have a weight as low as possible. In smaller, mid-sized and even larger telescopes, a steel-plate structure is adequate, while for the largest telescopes a truss structure is a more natural solution. The two structural alternatives are shown in figs. 169 and 170.

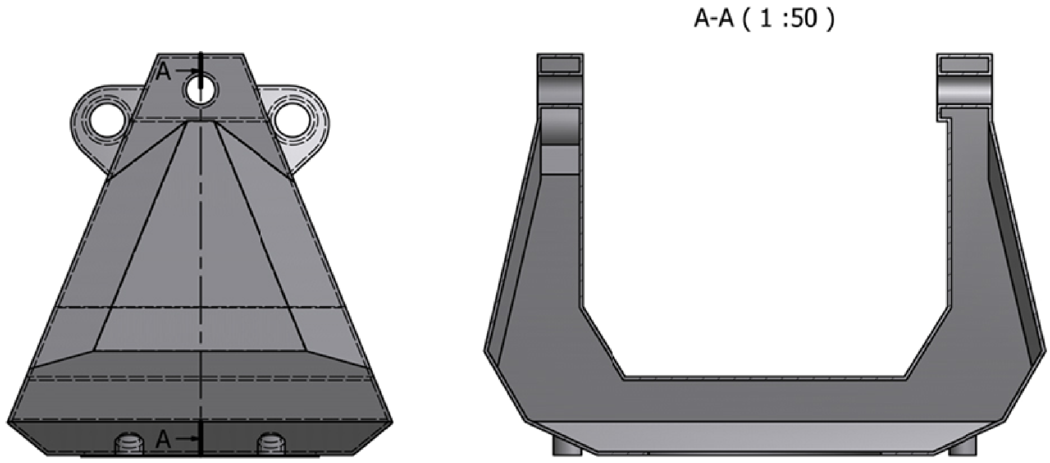


Figure 169. Fork of an altitude-azimuth mount for smaller, mid-sized and larger telescopes. A combination of stiffness and reduced weight is provided with a steel-plate structure.

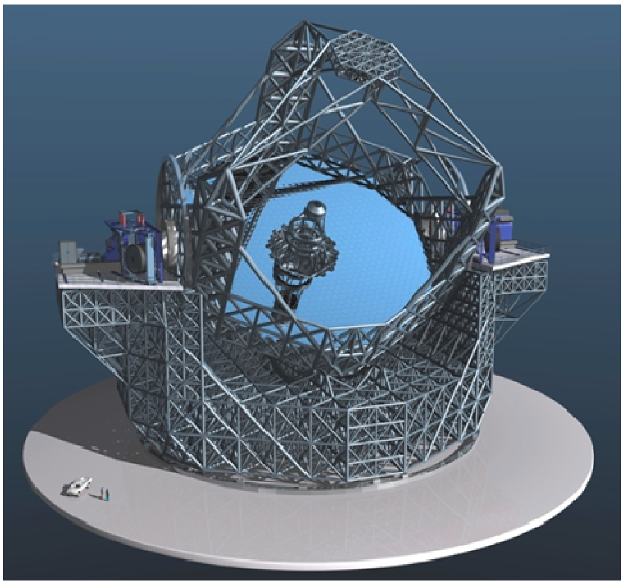


Figure 170- EELT mounting. (EELT project, ESO)

Drives

Drives, motors and gears, are essential parts of telescopes. There are two main types of motors, regular DC motors and motors with direct drives. When a regular type of motor is used, power is via its shaft transferred to a gear system attached to the moving system. For a direct-drive motor, the shaft is the moving part, and, thus, gears and other connectors do not exist.

Adoption of a direct-drive motor gives a simple total drive system that is easy to control. It is, on the other hand, an expensive solution. With normal motors and gears, the total cost is lower. Unfortunately and unavoidably, it comes with backlash problems. One method to overcome the backlash dilemma is to adopt a dual motor system.

While these considerations are rather general, the case of Nasmyth platforms require further considerations. In this case, the light beam has to pass through the elevation axis. Thus, if a direct-drive motor is chosen, the light beam will pass a zone with enhanced temperature. This is a serious matter for the image quality.

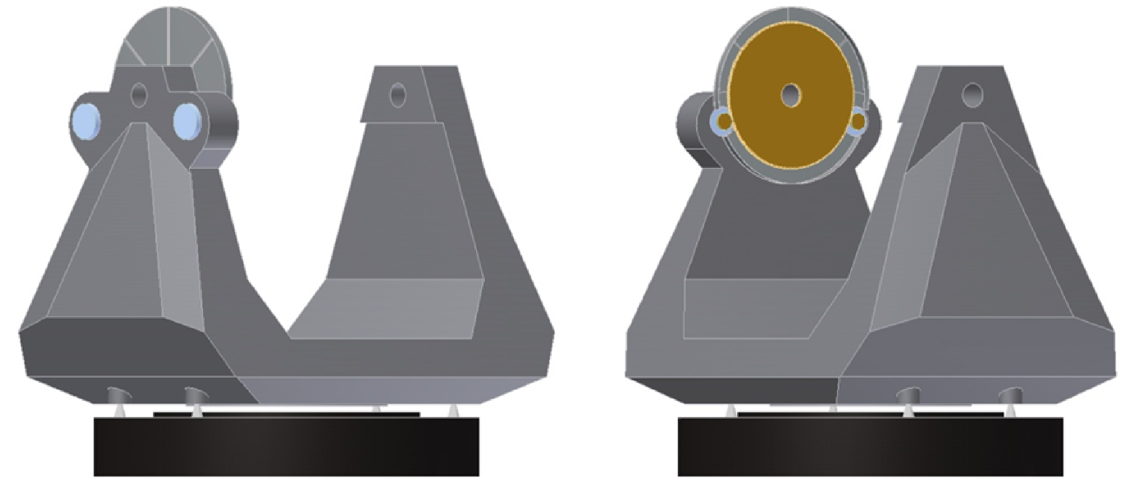


Figure 171. Motors and gears for the elevation axis in an altitude-azimuth mount.

Bearings

In regular altitude-azimuth telescopes, bearings are required for three, four or five axes. These are the azimuth axis, the elevation axis and the axes of the field rotator in the Cassegrain focus and the Nasmyth focus or foci. In all cases, they should be located in a manner to support minimum flexure of the structures supported. Important considerations for the choice of bearings are stiffness, precision and friction.

With larger telescopes, two types of bearings are predominant. They are rolling-element, ball, bearings and hydrostatic bearings. Rolling-element bearings can be made rather stiff, with high precision and low friction. Hydrostatic bearings, however, are, if properly designed, fabricated and installed, extremely stiff, have very high precision and are practically free from detrimental effects of friction. In addition, they have very high load capacity. However, hydrostatic bearings are, compared to rolling-element bearings, more sophisticated installations with higher cost.

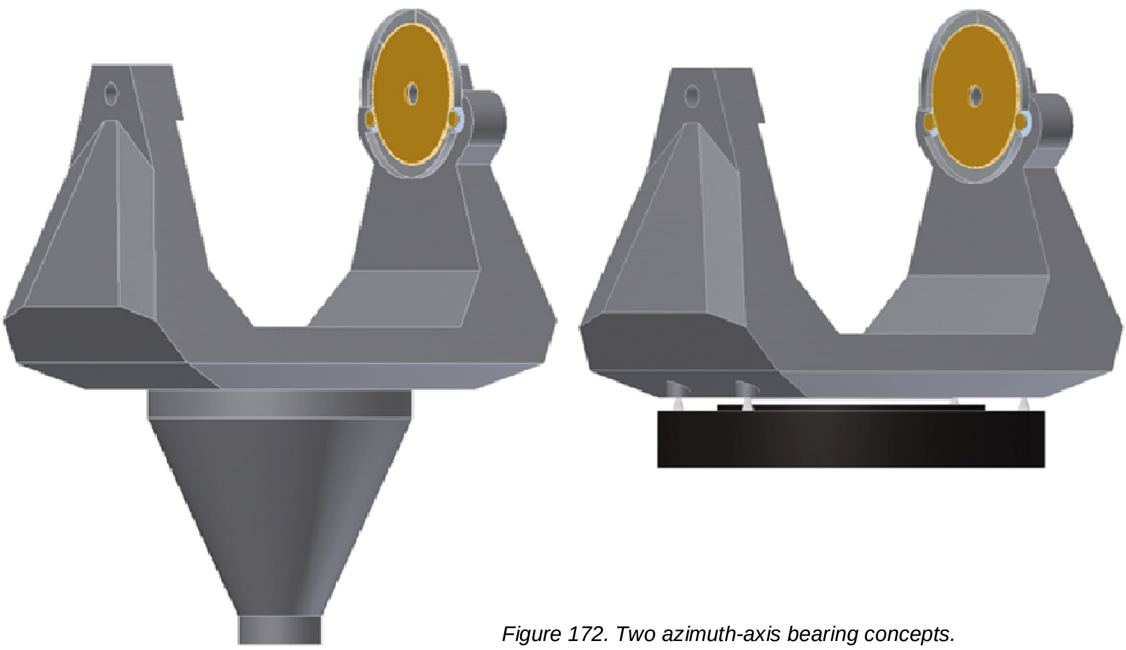


Figure 172. Two azimuth-axis bearing concepts.

As azimuth bearings, both rolling-element and hydrostatic bearings are adequate. As noted above, though, high-quality hydrostatic bearings outperform rolling-element bearings. The same is, at least in principle, the case for elevation bearings. In the latter case, however, one should make a distinction between telescopes with and without Nasmyth focus or foci. In the first case, the elevation bearing can be made relatively small. Thus, the friction moment is small and rolling-element bearings can perform fully adequately. In the second case, the case for a hydrostatic bearing is stronger.

Cable wraps and cable twists

Many power and signal cables as well as various pipes have to be connected between instruments, telescope, control units and other facilities. These lines must pass through one, two or more moving interfaces between instruments and telescope, the two axially rotating parts of the telescope, and between the mount and the pier. To provide safe transits through these interfaces, it is common to form a large-radius loop with a slack take-up arrangement. This type of solution is referred to as cable wrap. If space allows, another option is to arrange the lines, cables and pipes, along the axis of rotation and twisted around it. This is normally called a cable twist. Both cable warps and cable twists represent considerable weight and friction. Thus, they have to be provided with motorised assistance.

Brakes

As essential parts of the safety system, brakes have to be applied whenever azimuth, elevation and instrument rotation is off. This safety measure is a guarantee against accidental activation of the drives and when the telescope or parts of it are temporarily out of balance, for example during instrument change. When initiated, the brakes must not exert over-all force on the body to be safeguarded. Further, they must have an auto-alignment capability.

There are various types of brakes, many well suited for use with telescopes. Such types are electrical, hydraulic and pneumatic brakes. An important feature is fail-safeness. The brakes must be able to stop the part to be influenced at maximum speed without any risk of destructing it.

In addition to the set of brakes for use in regular telescope operation, the telescope has to be provided with an emergency braking system. This system is composed of some different mechanisms with different locations and actions. Safety brakes have to be more powerful than regular brakes. They have to be able to stop the telescope instantly, even at the risk of some damage.

End stops

Moving in elevation, the telescope will, via a software system, be prevented to point below a defined lower elevation, often of the order of 15 degrees above the horizon. Similarly, in azimuth, a software system protects cables and pipes. However, if such a prevention system, for some reason, does not work, some sort of mechanical stop mechanism has to protect the telescope from passing the elevation limit defined or from damaging cables and pipes. Such a mechanism is a force-absorbing system, a spring or a metal plate with a deceleration not endangering optical elements and instrumentation.

Locking devices

During maintenance, removal of mirrors and other telescope parts as well as during exchange of instrumentation, the telescope will be unbalanced, sometimes heavily so. Thus, it must be possible to lock both the azimuth and altitude axes in a safe manner. The mechanisms to be provided can be mechanical connectors activated automatically or by hand.

Suggestions for a 3m telescope

As a result of this study, the specification of a modern 3m-class ground-based telescope for optical-visual and adjacent wavelengths, can be as follows:

Telescope

Parameter	***Value***	***Remarks***
Telescope aperture	3000 mm	
Working wavelength	325 – 2500 nm	
Field of view	30 arcmin	
Telescope focal ratio	f/11	
Telescope plate scale	6.25 arcsec/mm	For high-resolution
Detector pixel size	15x15 µm	
Optical concept	Cassegrain	
Optical arrangement	Ritchey–Chrétien	
Mounting	Altitude-Azimuth	

Primary mirror

Parameter	***Value***	***Remarks***
Diameter	3000 mm	
Focal ratio	f/1.5	
Aspect ratio	20	
Shape	Meniscus	
Conical constant	-1.0066	
Central-hole diameter	600	
Material	Zerodur	

Secondary mirror

Parameter	***Value***	***Remarks***
Diameter	508 mm	
Curvature radius	1584 mm	
Conical constant	-1.7993	
Material	Zerodur	Not critical

Optical configuration

Parameter	***Value***	***Remarks***
Back-focal distance	1200 mm	
Distance between mirrors	3816 mm	
M1-M2 maximum allowed de-centering	100 μm	
M1-M2 maximum allowed tilt	35 arcsec	

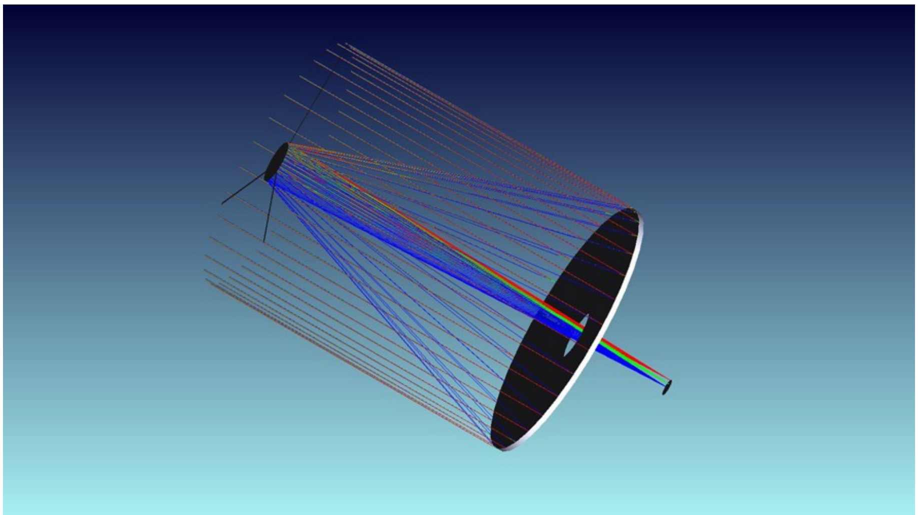


Figure 173. Overall ray tracing for a typical Cassegrain telescope with a normal obstructing surface at the entrance pupil (spider). Different colours indicate different parts of the field of view. Primary mirror aspect ratio exaggerated in figure.

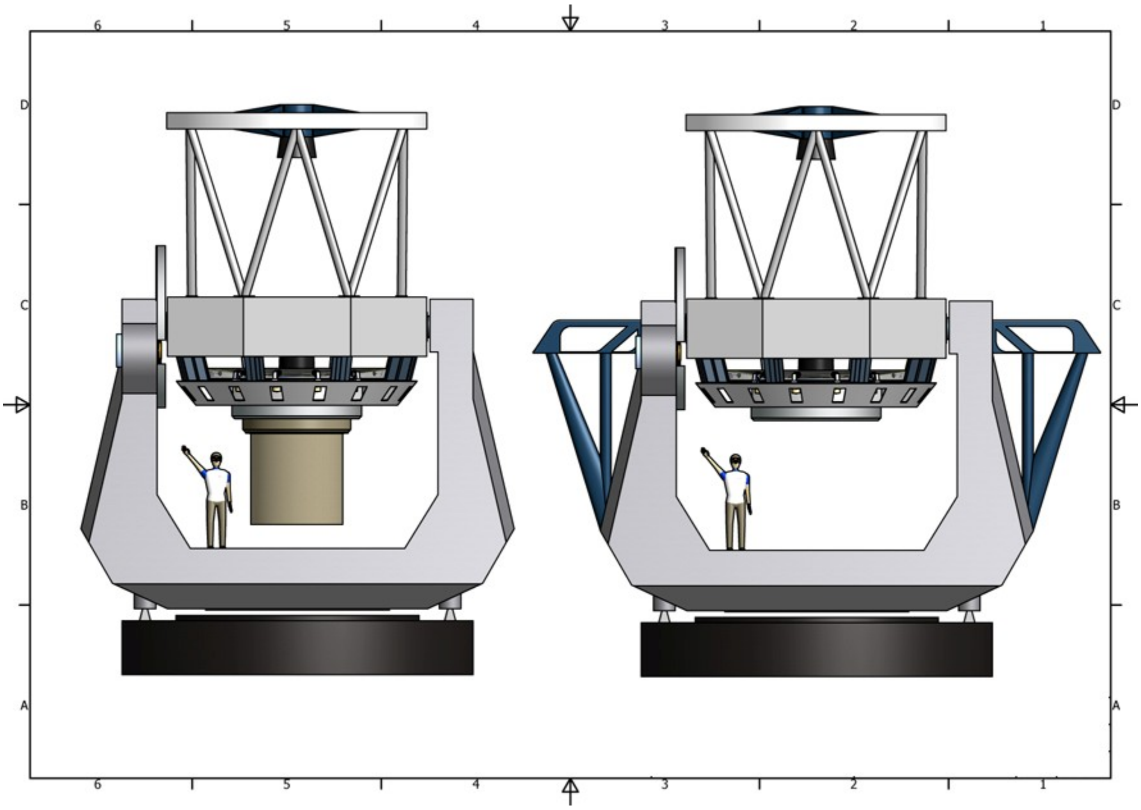


Figure 174. A Cassegrain-only concept (left) compared to a Cassegrain-plus-Nasmyth concept (right).

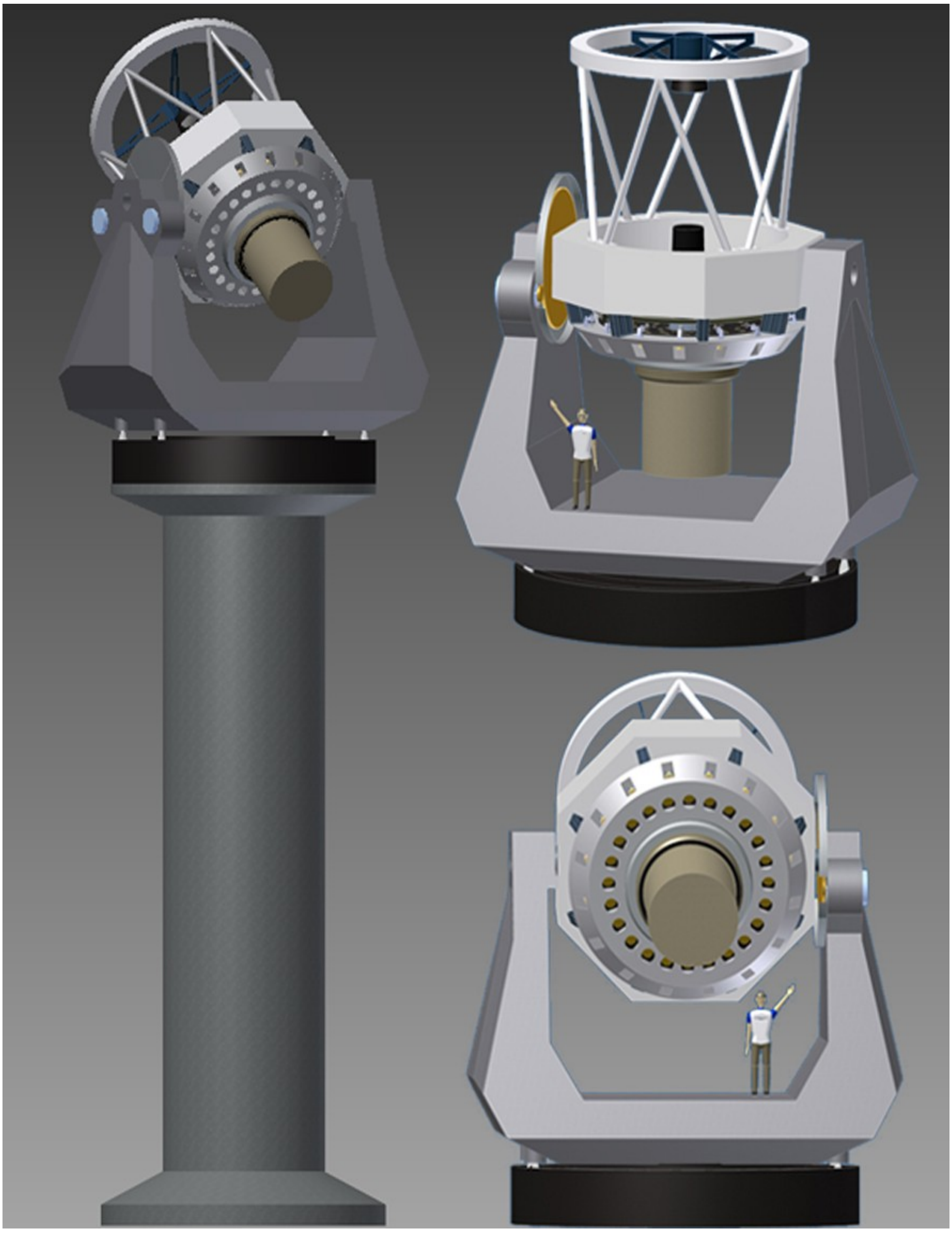


Figure 175. Different aspects of a 3m-class telescope with Cassegrain focus only.

Telescope active optics and mirror-support system

Parameter	***Value***	***Notice***
Number of M1 support rings	3	Needs FEM calculation
Number of M1 axial supports	52	Needs FEM calculation
Actuator type	Air cushion	Other types possible
Number of M1 axial hard points	3	Maybe modified depends on design strategy
Axial fix-point type	Hydraulic	Design-strategy dependent
Number of the M1 lateral supports	16	Needs FEM calculation
Lateral support type	Levers	Other types possible
Number of the M1 lateral fix-points	3	Design-strategy dependent
Lateral fix-point type	Hydraulic	Other types possible
Secondary-mirror motion	5 DOF	
Secondary-mirror motion mechanism	Hexapod	Other types possible

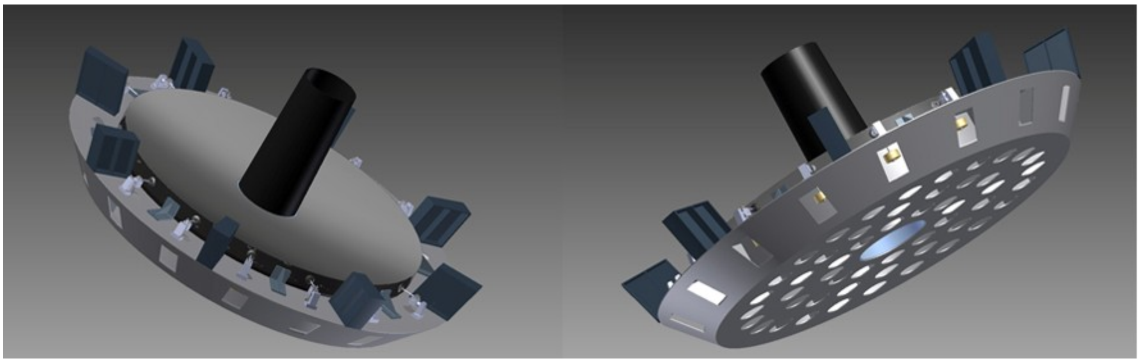


Figure 176. Primary mirror, its cell, baffle, and related components. Holes in mirror-cell backside are for axial supports.

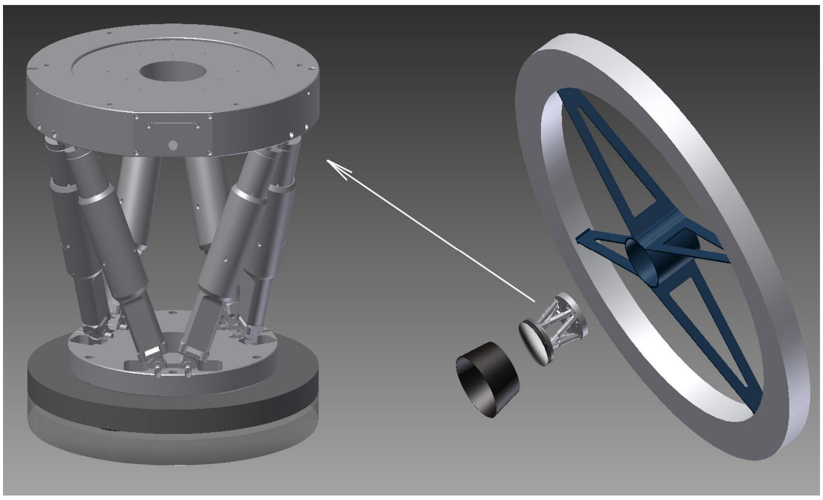


Figure 177. A hexapod is suggested as a mechanism for the secondary mirror alignment and motions.

Enclosure

Parameter	*Value*	*Remarks*
Architecture	Cylindrical	
Dome and hatches	Semi-spherical dome with sliding hatch	
Type	Co-rotating with control room under false floor and observing floor	
Pillar structure	Depends on site topography and ground-layer turbulence.	Needs site micro-thermal data (see Fig. 8) and site air-flow modelling
Air flushing windows	Up to 300 degree opening around observing floor	Free, incoming air flow must reach M1 surface

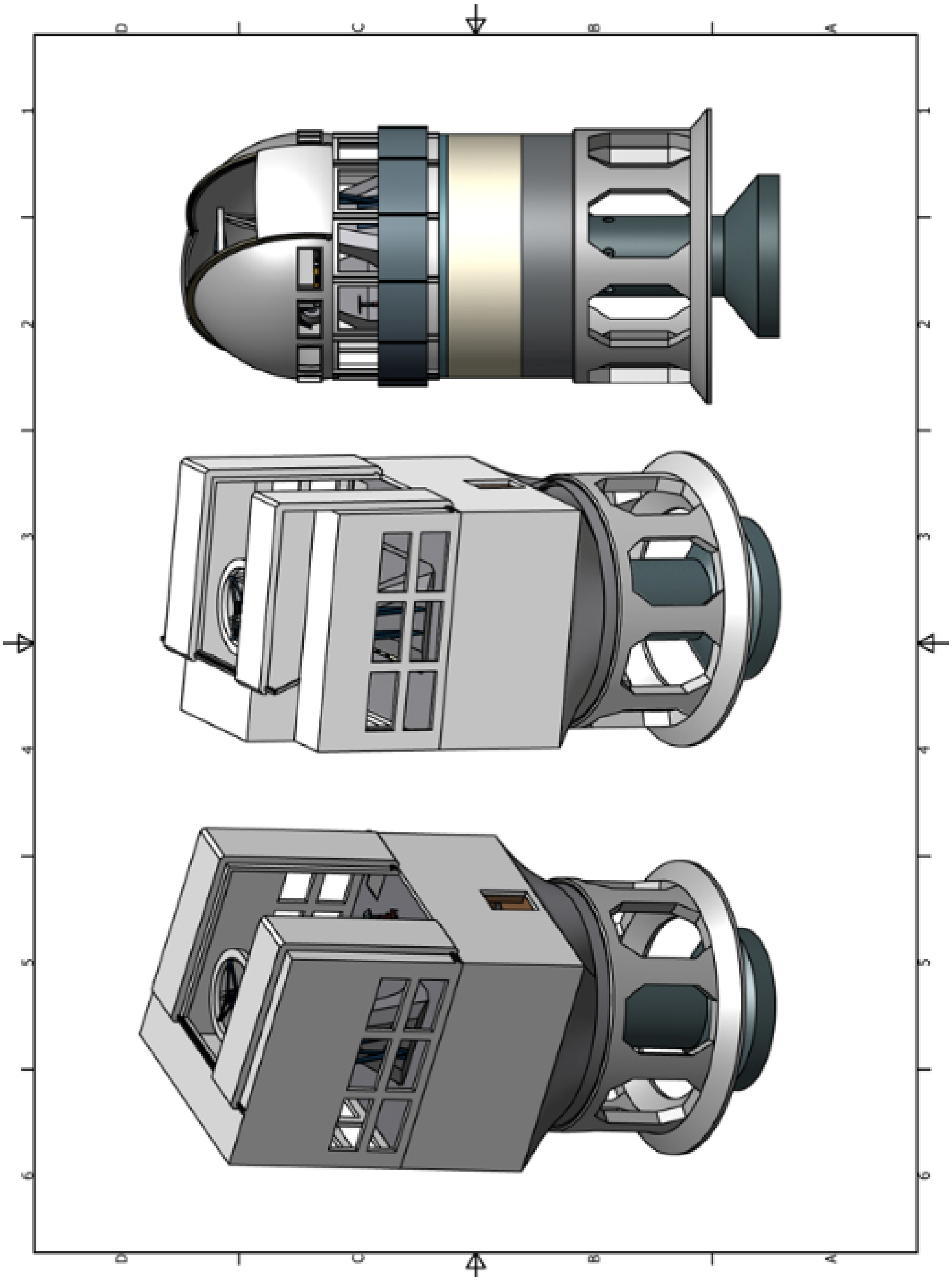


Figure 178. Different types of architecture for the enclosure of a 3m-class telescope.

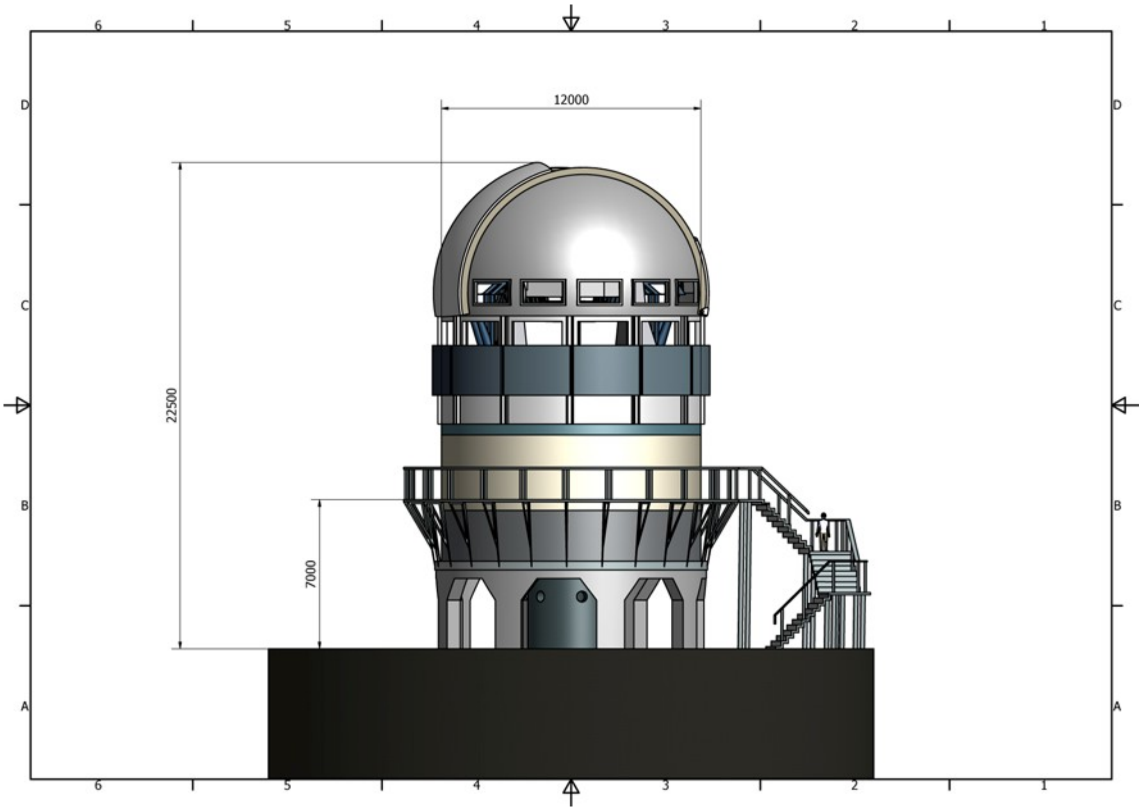


Figure 179. Dimensions of a typical 3-m telescope enclosure. The height of pillars and corresponding total height have to match the site ground-layer turbulence.

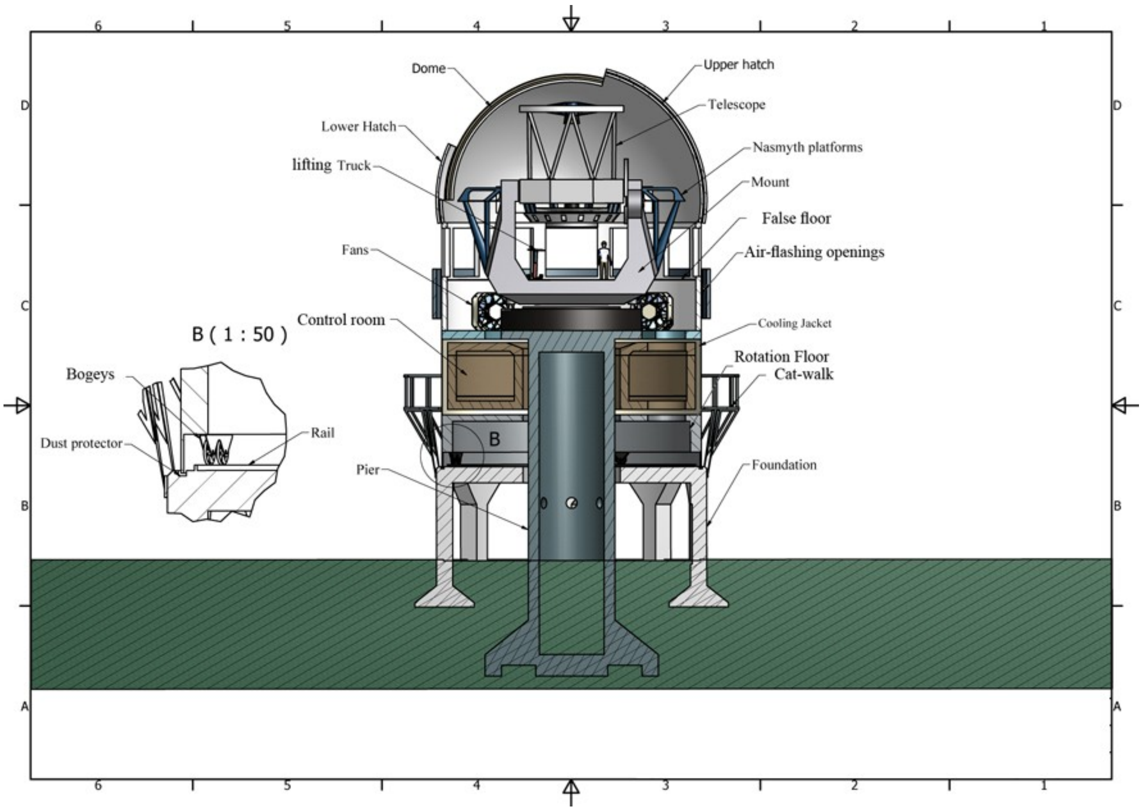


Figure 180. A typical co-rotating enclosure.

Appendices

Appendix 1. Active optics control schemes

Open-loop and closed-loop operation of active optics

In a telescope with active optics, the pattern and level of forces that may be applied to the primary mirror for surface correction vary with the mode of operation of the control system. The architecture of any control system depends on the system bandwidth and on the predictability of the disturbances to be corrected. Open-loop control can be sufficient when the predictability is high. For telescopes of high opto-mechanical quality, this is often due for effects due to gravity and temperature variations. Thus, in this case, open-loop control can be made using a "look-up table" of corrections.

In a look-up table serving an open-loop control system, correction forces are tabled as functions of sky positions. An adequate usefulness of open-loop active optics requires that the mechanical telescope system is free from major effects of friction and, thus, effects of hysteresis. While effects of hysteresis are always limiting performance, these limitations are especially serious in the case of open-loop operation of active optics.

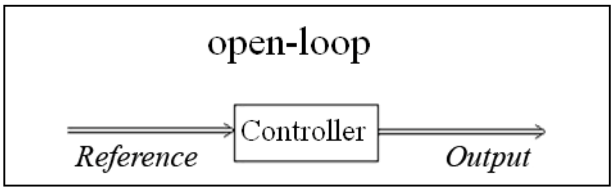


Figure 181. A simple open-loop control diagram.

Whenever the requirements for successful open-loop operation are not fully secured, closed-loop feed-back operation is preferable. The feed-back signal of a closed-loop system is the wavefront error obtained for a reference star as defined by a wavefront sensor. Data from this sensor are processed by a wavefront analyser, or a dedicated computer, that generates commands for individual primary-mirror actuators. As opposed to the open-loop control system, the closed-loop system requires stability of the forces only for limited time periods. It is noted that exposure times for reference stars always have to be sufficiently long to avoid spurious input data due to effects of atmospheric turbulence.

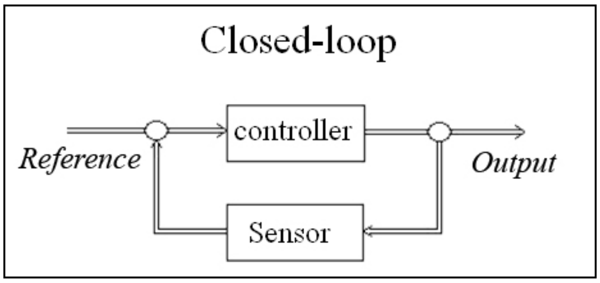


Figure 182. A simple closed-loop control diagram.

Active optics in practice

In practice, in modern telescopes, both open-loop and closed-loop control systems are available and optional for the observers. As long as the opto-mechanical stability of the telescope is sufficiently high, there are several advantages of open-loop operation. It avoids preparation of lists of reference stars fitted to the target objects. It eliminates time loss for observations of the reference stars. It makes observing routines easier and more straight-forward.

The corrections resulting from active-optics systems are often realized through actions via both the primary and the secondary mirrors. The primary-mirror corrections are corrections of surface shape. The corresponding control loop has often a bandwidth of around 0.1 Hz. For mirror diameters below six metres, even a bandwidth of 0.01 Hz suffices, as effects of wind are in practice only those due to wind pressure. For larger mirrors, due to be deformed by wind gusting, adoption of bandwidths as large as and larger than 1 Hz can assure elimination of these latter effects.

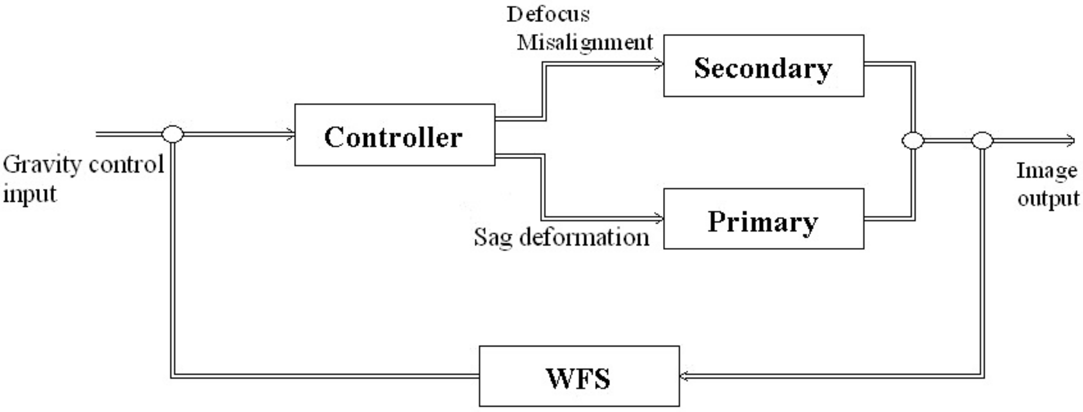


Figure 183. In a telescope with active optics, the controller sends commands to the primary and secondary mirror according to the type of aberration.

Corrections applied to the secondary mirror, or the secondary-mirror unit, are different. They are intended to correct for deformations of the telescope structure. Included are effects of defocusing and misalignment. The corresponding corrections can be provided via a system with five degrees of freedom. Corrections are then applied in the form of translations along three axes and rotations around two axes.

Control schemes for active-optics systems are sometimes described in terms of interaction matrices and their pseudo-inverses, referred to as reconstruction matrices. Another approach is that of a sparse-matrix method, in which the wavefront is decomposed into a basis set of actuator influence functions. The influence function of each actuator is assumed to have a boundary condition at some distance from the actuator. This means that each actuator is supposed to influence only a predefined neighbourhood (Noethe, 2001).

Appendix 2. Wavefront sensors

Types of wavefront sensors

Wavefront sensing, in real or pseudo-real time, is a necessity for active and adaptive optics. In general, there are four different groups of sensors useful for the purpose. There is the true wavefront sensor, the slope sensor, the curvature sensor and the phasing sensor. The true wavefront sensor measures wavefront errors, the slope sensor wavefront gradients, the curvature sensor wavefront curvature and edge slopes, and the phasing sensor piston errors between adjacent mirror segments in segmented-mirror telescopes. Wavefront sensors can provide information either in the pupil plane or in the image plane. The basic function of wavefront sensors is to detect wavefront errors with required sensitivity and spatial resolution, all within an adequte time range. The spatial resolution should match the number of actuators used in the system.

The wavefront sensors most commonly used are based on slope measurement in the concept of geometric optics or interference. Geometric optics assumes lightrays to be orthogonal to the local wavefront and the direction of a ray can be found by focusing a sub-pupil beam. Two much-discussed geometric-optics wavefront sensors are the Shack-Hartmann and pyramid prism sensors. Pyramid prism sensors are based on four-fold schlieren techniques.

Common sensors based on effects of interference are those based on transverse grating shearing and phase contrast. In both cases, information is provided on local wavefront slopes. From these local slopes, the total wavefront shape is derived.

Shack-Hartmann wavefront sensor

In a Shack-Hartmann wavefront sensor, a lenslet array divides the pupil into sub-apertures. For a plane wavefront, images of a reference star are formed in the lenslet foci. If the wavefront is disturbed, the images of the reference star are shifted away from the corresponding foci. The

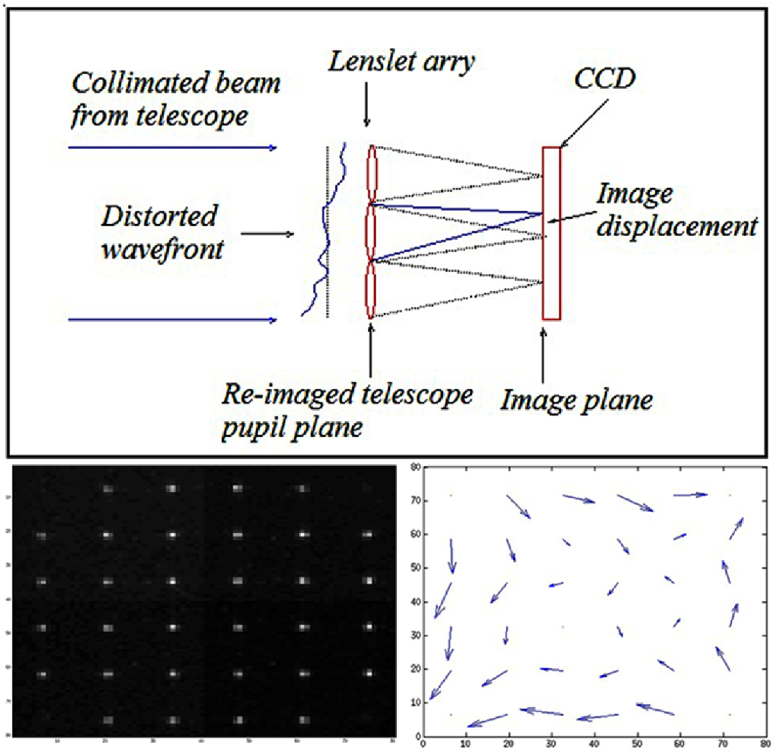


Figure 184. A Shack-Hartmann wavefront sensor concept diagram (top), telescope pupil image from a point source produced by lenslet (left) and their corresponding displacement vectors on the CCD surface.

displacements are proportional to the local wavefront slopes (Fig. 4). A Shack-Hartmann sensor has its own reference wavefront generated by a reference light source. This plane incoming wavefront provides precise focal positions of the lenslet array.

To derive wavefront errors, the entire pupil has to be sampled. Derivation of sub-aperture image positions is made either by quad-cell or centre-of-gravity approaches. The concepts of both methods are shown in Fig. 5. Slope in the wavefront, $\boldsymbol{W}_y$, causes the incoming photons to be displaced on the CCD surface by:

$$\Delta y = Z \bullet \boldsymbol{W}_y$$

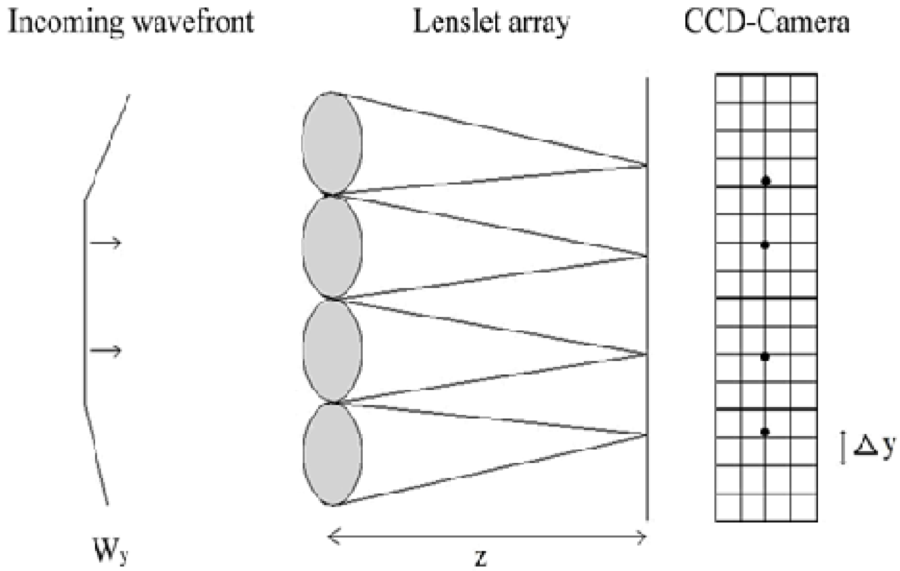


Figure 185. Determination of local slope of a wavefront in a Shack-Hartmann sensor.

It is possible to derive the whole wavefront from the slopes in two dimensions of all point-spread functions produced by the array of lenses. In practice, each point-spread function has been given a designated workspace on the detector, i. e. a given pixel area. This restrains the maximum slope that can be measured.

The Shack-Hartmann wavefront sensor is widely adopted in practice. It provides adequate precision and is relatively easy to use. As the Shack-Hartmann sensors measure only wavefront slope, not phase, care has to be taken when this device is used for telescopes with segmented primary mirrors, as the wavefront in a segmented-mirror aperture does not necessarily display continuity.

The Shack-Hartmann wavefront sensor can be applied also when the reference light source is extended. In this case, instead of simply finding the image positions from the lenslet array, the cross-correlation functions between the lenslet images are used for determination of the wavefront slope changes. One of the lenslet images is taken as a reference, to which the other lenslet images are compared. The peak position of the cross-correlations of all sub-images with the reference image give the wavefront slopes relative to the reference sub-aperture.

Appendix 3. A brief history of INO and INO340

The Iranian National Observatory (INO) 340 (INO340) is a national project for development of a front-line observatory in Iran. The first detailed project concerns design and construction of a 3-metre class telescope for optical-visual and adjacent wavelengths. This telescope, INO340, will have a primary mirror with diameter 340 cm. The INO project is one of the prime-priority undertakings of the Iranian national research programme as defined by a selected domestic team of scientists in 1997.

The site selection project for INO340 was launched at the Institute for Advanced Studies in Basic Sciences (IASBS) in Zanjan in 2000. Y. Sobuti (as IASBS's president) and S. Nasiri (as project manager and scientist) were the project leaders. They studied climate and geological condition parameters and accessibility for 31 regions and summits in all of the country. In 2003, the site-selection team selected four sites as candidates for continued site evaluation. The candidate sites were Birjand in the east, Kerman in the south, and Kashan and Qom in the centre of Iran. In 2005, the Birjand and Kerman sites were rejected from the list of site candidates. The prime reason for this rejection was the inferiority of image quality as compared to the Kashan and Qom site candidates. Subsequently, site-selection teams continued image-quality measurements in the Kashan and Qom regions.

The INO institute, as an independence science institute, was formed in 2005 for. Its main purposes were formulated as follows.

1. Covering and leading formal INO project activities and contracts.
2. Recruiting and administrating staff required for the INO project.
3. Covering INO scientific and technical activities after installation of INO340.
4. Preparing a co-operation platform between Iranian astronomers and project technical staff and international scientific societies and institutes as well as individual scientists.
5. Being an interface between the project and state authorities with responsibility for project activities and budget.

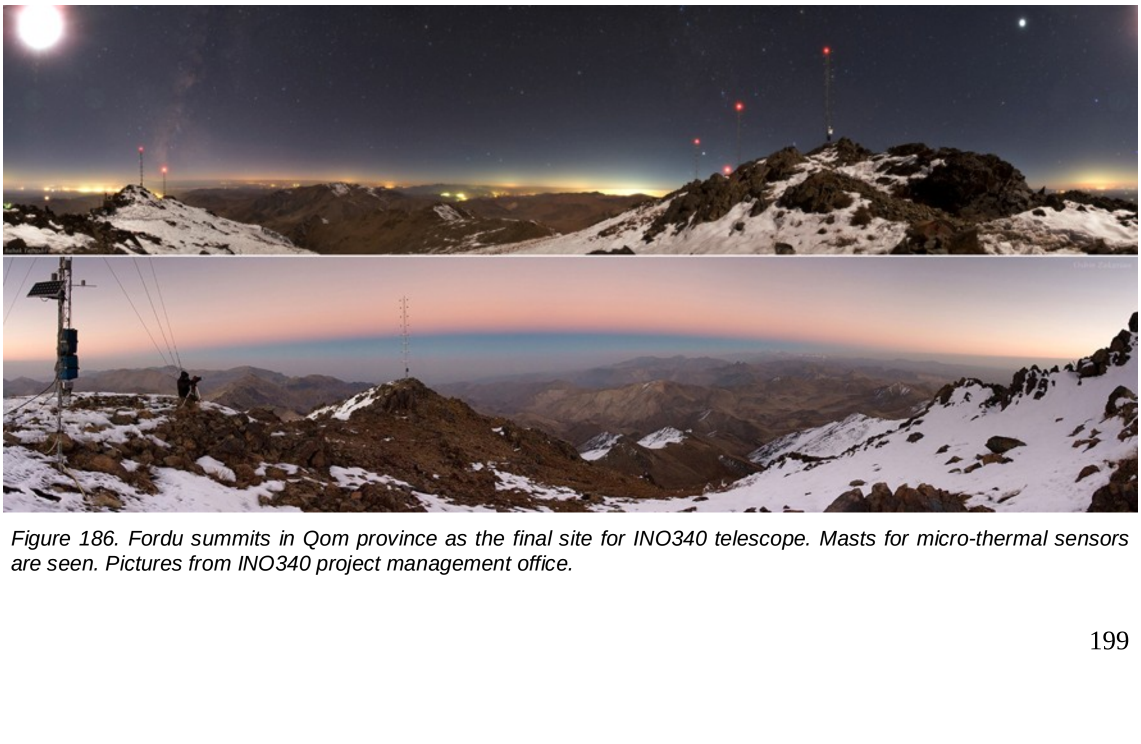


Figure 186. Fordu summits in Qom province as the final site for INO340 telescope. Masts for micro-thermal sensors are seen. Pictures from INO340 project management office.

The INO institute joined to the Institute for Studies in Theoretical Physics and Mathematics (IPM) in 2006. Subsequently, the INO project is under the administration of IPM. In 2009, the Fordu summits, around the city of Qom, were selected as the final site of INO. In 2010, the design of INO340 was commenced.

Figure 187. INO logo.

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