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Remote Sensing of the Environment using Laser Radar Techniques

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Abstract. Environmental parameters can be measured remotely by using laser radar techniques. Atmospheric monitoring is based on differential molecular absorption observed in backscattering from aerosol particles. Three-dimensional mapping of pollutant distributions from industrial and geophysical sources can be performed for ranges up to a few kilometres. Induced fluorescence can be analysed spectrally, and multi-colour fluorescence images can be recorded by irradiation of vegetation or a water surface at distances of up to a few hundred meters.

1 Introduction

Laser techniques have had a strong impact on chemical sensing. Applications include the fields of analytical chemistry (Letokhov 1990, Radziemski et al. 1987), combustion diagnostics (Eckbreth 1987), medical diagnostics (Pettit and Waynant 1996, Svanberg 1989, Svanberg 1996a) and environmental monitoring (Measures 1988, Sigrist 1994, Svanberg 1991).

Laser radar monitoring of the environment is an application of time-resolved laser spectroscopy. Differential optical absorption as well as laser-induced fluorescence can be used for this type of remote sensing. Apart from providing range-resolved data, the use of an active illumination source provides a more accurate assessment than if just the ambient passive radiation is employed. However, by necessity a limited monitoring range is imposed by the use of an artificial source.

An overview of atmospheric pollution monitoring and vegetation status assessment using laser radar techniques will be given with illustrations from work at the Lund Institute of Technology. We will start with monitoring of industrial and urban air pollution and will continue with measurements of geophysical gas emissions. Applications of fluorescence lidar to vegetation and water are then discussed and, finally, an outlook for the future is given.

2 Monitoring of urban and industrial air pollutants

The differential absorption lidar (dial) technique (see e.g. Svanberg 1994 for a review) provides three-dimensional mapping of gas distributions in the atmosphere. Pulses from a tuneable laser are transmitted into the atmosphere

and photons, elastically back-scattered from aerosols and major constituents, are collected by an optical telescope giving rise to an electrical transient after detection in a photomultiplier tube. An example of a lidar curve for a range up to 4.5 km obtained with a vertically aimed lidar system (Wallinder et al. 1996) is given in Fig. 1. An excimer laser transmitter was used, providing pulses at 317 nm after stimulated Raman conversion of 248 nm KrF radiation. Since the laser beam is transmitted from a point displaced by about 0.3 m from the receiving telescope axis, the signal starts at a low value and reaches a maximum when the transmission and receiving fields of view overlap. Then a $1/R^2$ fall-off is observed, reflecting the normal illumination law. At a distance of about 2.1 km the increased backscatter from a dual-layered cloud can be seen. In the $\times 100$ magnification the optical attenuation by the cloud reducing the backscattered radiation from above the cloud can also be seen. While the relative distribution of aerosol particles can be displayed by a curve such as the one shown in Fig. 1, molecular concentration measurements require the recording of curves at two closely spaced laser wavelengths.

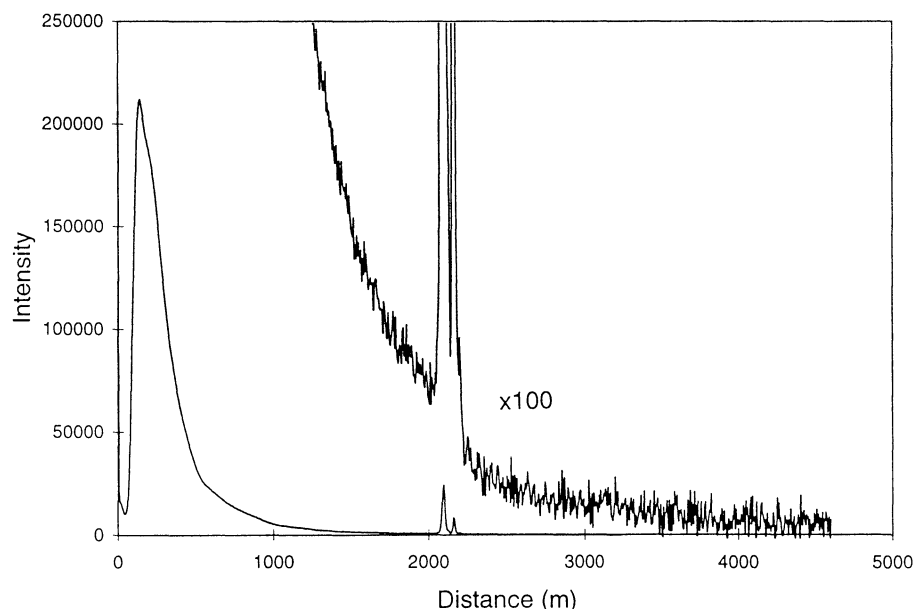


Fig.1. Lidar signal obtained in vertical sounding using an excimer lidar. Initially the signal displays a gradual increase as the transmitted beam and the telescope fields of view start to overlap. Then a fall-off, basically with a $1/R^2$ dependence, follows. An increased back-scatter from thin clouds at a height of about 2 km is observed.

One is chosen corresponding to a strong absorption of the gas under study while the other one, off-resonance, is used for reference purposes. By dividing the "on"-resonance curve by the "off"-resonance curve the influence of aerosols is eliminated and the range resolved gas concentration is calculated from the slope of the divided "dial" curve.

An urban measurement scenario is shown in Fig. 2, illustrating our mobile laser radar system during urban pollution monitoring in the city of Prague. The laser beam is transmitted and backscattered radiation is received from the roof-top rotatable dome. The construction of the lidar system is described in Edner et al. (1987). A measurement along a street in Prague is shown in Fig. 3 (Engst et al. 1995). A laser wavelength pair around 226 nm is chosen to yield a vertical mapping of NO as the laser beam is scanned under computer control. The two concentration maxima, spaced by about 100 m, correspond to two street crossings.

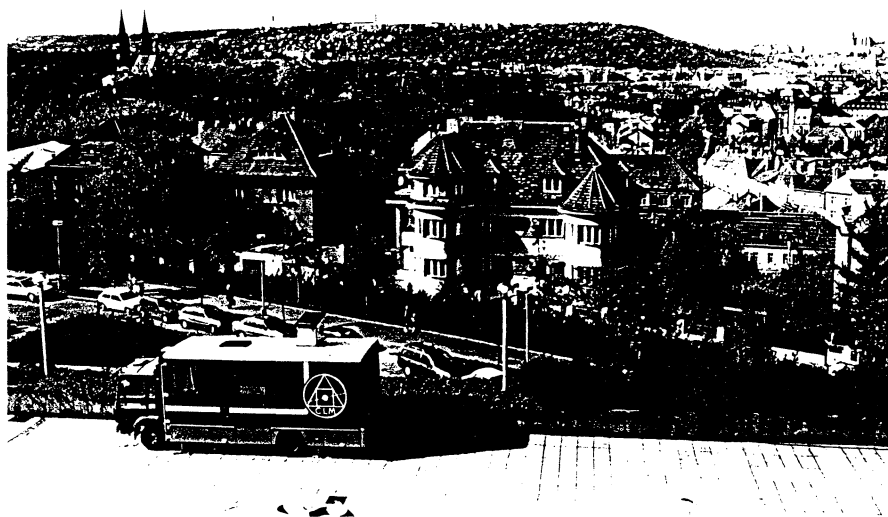


Fig. 2. Photograph of the Swedish lidar system during measurements in Prague, the Czech Republic.

The Swedish mobile lidar system has recently been fully reconstructed and modernised. While still using the same dye laser transmitter, waiting for replacement by an optical parametric oscillator system, all electronics, computers and software have been replaced (Andersson et al. 1996). In particular, graphical software routines written in the industrial standard, LabVIEW are used and an improved concentration precision and uncertainly



Fig. 3. Results from measurements of NO along a street in Prague, showing increased concentrations at two subsequent street crossings. Concentration values are given in $\mu\text{g}/\text{m}^3$. (Adapted from Engst et al. 1995).

assessment is obtained by statistical treatment of the lidar signals. While reliable concentration values are the most interesting ones in urban monitoring, industrial measurements more focus on flux determinations. Then the wind velocity component, perpendicular to the vertical lidar scan through the plume and/or diffuse emissions is needed apart from the concentration values. A video camera plume monitoring technique, incorporating temporal cross-correlation of the plume features has been implemented and geometric angles and distances are inferred by lidar shots. The wind data are obtained simultaneously with the concentration mapping, allowing near real-time flux monitoring. A first example, from a campaign at the Nymölla paper plant, is given in Fig. 4. Here SO_2 is measured using a wavelength pair close to 300 nm, and a flux of 140 kg/h was determined in very good agreement with in-stack monitoring values provided by the plant.

3 Measurements of gases of geophysical origin

While pollutants of antropogenic origin are abundant there are also substantial emissions to the atmosphere from geophysical sources relating to geothermal energy, ore deposits and volcanic activities. Among several gases Hg and SO_2 could be specially mentioned. Measurement scenarios in a geophysical

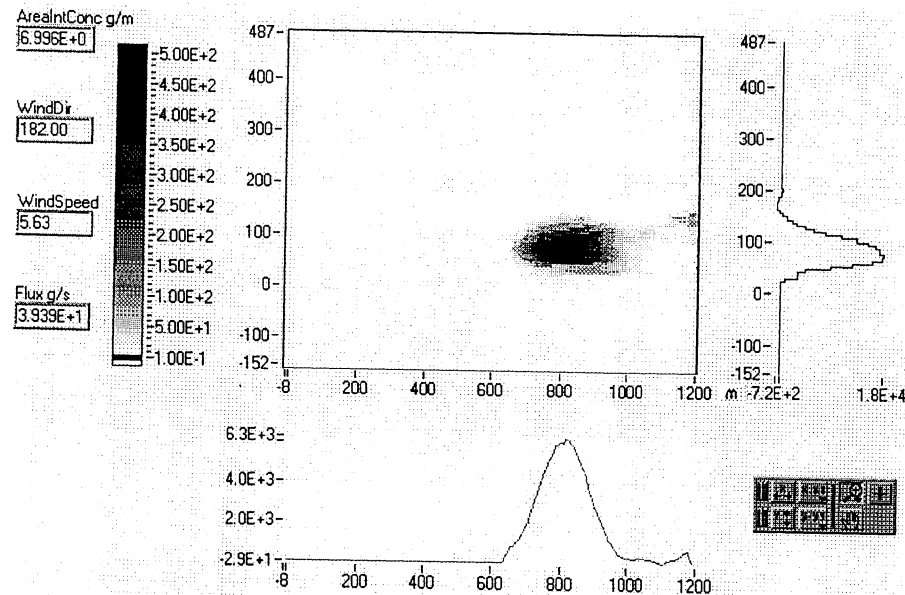


Fig. 4. Sulphur dioxide emission from a Swedish paper mill. The measurements were performed with the upgraded Swedish lidar system, employing LabVIEW software and automatic wind measurements by video cross correlation. (From Weibring et al. 1996a)

environment are shown in Fig. 5 (Svanberg 1991).

Emissions of atomic mercury follow geothermal steam extraction and mercury could be considered as a tracer gas for geothermal energy. Since free atoms rather than mercury compounds are emitted, a spectroscopic sensitivity increase of more than a factor of 10^3 is obtained allowing the optical measurement of concentrations down to the order of the Atlantic background value 1 ng/m^3 . Lidar techniques for the mapping of Hg using the absorption line close to 254 nm are described in Edner et al. (1989), where measurements of industrial emissions from a chlor-alkali plant are also reported. Fig. 6 shows the results of a vertical lidar scan lee-ward of a cooling tower at the largest geothermal power plant in Europe, Larderello (Tuscany) (Edner et al. 1992a). Results from point monitors employing atomic-absorption measurements on mercury collected as amalgam on gold foils are included in the figure and show good agreement with the dial data. Measurements at the mercury mine at Almaden, Spain (Ferrara et al. 1996), following studies at

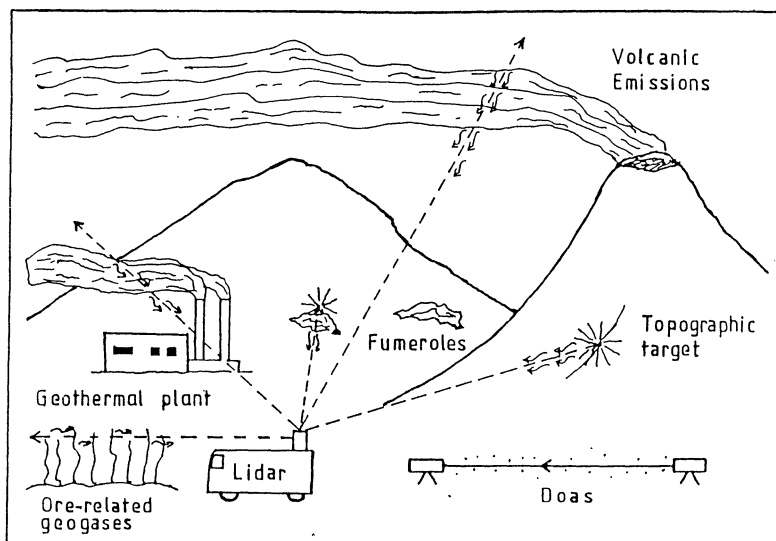


Fig. 5. Measurement scenarios for optical monitoring of gases of geophysical origin (From Svanberg 1991).

the smaller, abandoned mine at Abbadia S. Salvatore (Italy) (Edner et al. 1993), revealed atmospheric mercury fluxes of about 1 kg/hour. A mapping of the diffuse mercury plume from the Almaden area is shown in Fig. 7 (Ferrara et al. 1996).

Very large emissions of SO_2 occur from active volcanoes. We have performed two measurement campaigns on board the Italian research vessel *Urania* to monitor the emissions from Etna, Stromboli and Vulcano (Edner et al. 1994a, Svanberg et al. 1996b, Weibring et al. 1996b). By firing the laser beam vertically while passing under the volcanic plume it was possible to measure the integrated concentration, and also the flux by combining with wind data. A photograph showing the *Urania* with the lidar on its aft deck and with the island of Vulcano in the background is presented in Fig. 8. Lidar data were compared with differential optical absorption (doas) results obtained by a spectral analysis of the overhead sky radiation (passive monitoring). Measurement results for Mt. Etna obtained during the most recent cruise are shown in Fig. 9. The uncorrected doas data are almost a factor of 3 higher than the lidar results (35 tonnes/h). The reason for the large discrepancy is scattering within the plume, strongly affecting the passive doas data. The scattering will now be modelled to allow the correct evaluation also from the more simple passive measurements, which can also be performed with COSPEC correlation spectroscopy.

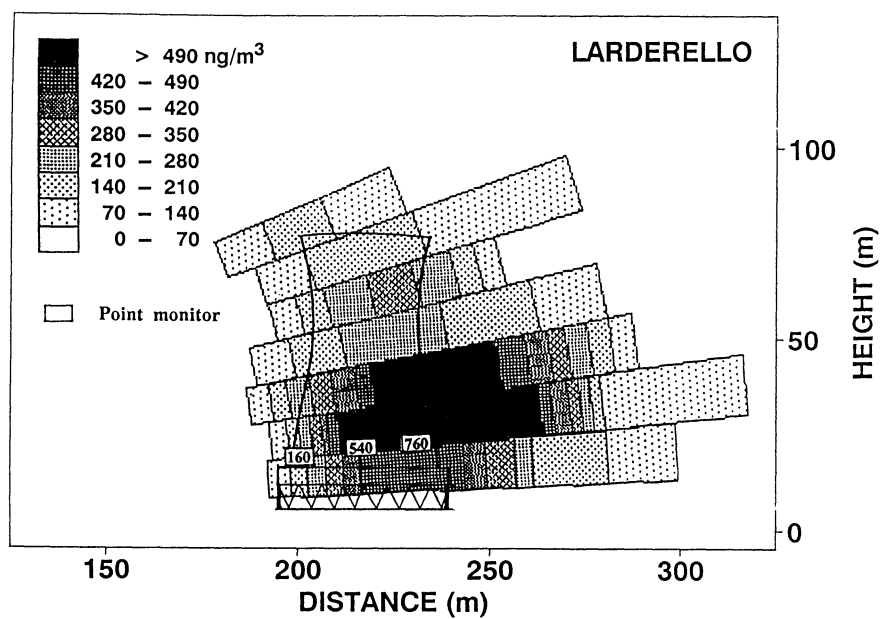


Fig. 6. Lidar monitoring of mercury concentrations around a cooling tower at the geothermal power plant at Larderello, Italy (From Edner et al. 1992a).

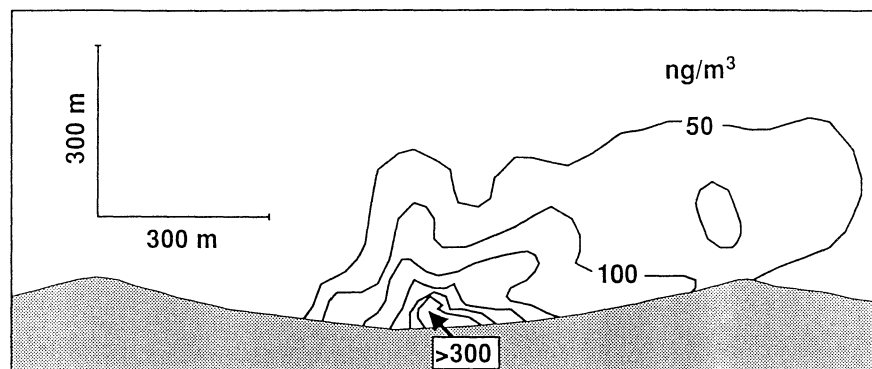


Fig. 7. Distribution of atomic mercury in the valley downwind from Almadén, Spain (From Ferrara et al. 1996).



Fig. 8. Photograph of the research vessel Urania with the Swedish lidar system, off Lipari with the island of Vulcano in the background.

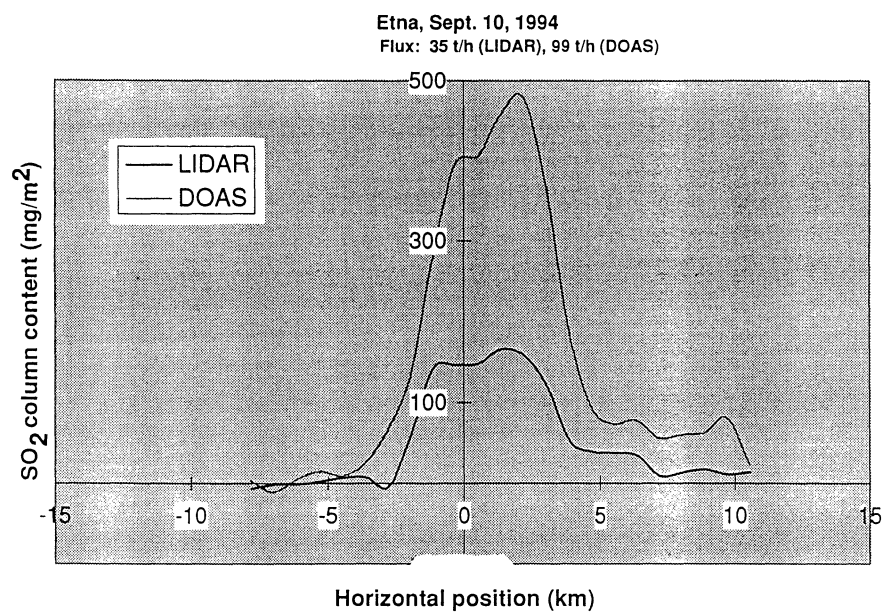


Fig. 9. Sulphur dioxide data from traverses with a ship-borne remote-sensing system under the volcanic plume of Mt. Etna, Italy. The integrated over-head SO₂ load as inferred from dial and doas monitoring are presented (From Weibring et al. 1996b).

4 Fluorescence monitoring of water and vegetation

When a pulse of ultraviolet radiation from a lidar system is impinging on a target, fluorescence is induced. The fluorescence can be collected by the lidar receiving telescope and be spectrally dispersed and detected on a CCD detector preceded by an image intensifier, which is gated in synchronism with the arrival of the laser-induced signal. In this way the whole fluorescence spectrum can be detected for every laser shot. Scenarios for water and vegetation monitoring are shown in Fig. 10 (Svanberg 1994). Measurements from a vehicle can be used in preparation for airborne monitoring. In Fig. 10a, water monitoring is illustrated (Edner et al. 1992b). The spectrum features a broad blue-green distribution from DOM (Dissolved Organic Matter) or Gelbstoff. A weak signal due to chlorophyll in algae is seen in the red spectral region. Oil on the water surface would result in a very strong blue fluorescence emission (Reuter 1991). Vegetation monitoring (Svanberg 1995) (Fig. 10b) yields prominent chlorophyll peaks at 690 nm and 735 nm, the relative intensity of which depends on the chlorophyll concentration (Lichtenthaler and Rinderle 1988). In addition, blue-green fluorescence is obtained relating to cell structures and the leaf surface layer. The spectrum can carry information on stress conditions. For efficient excitation of chlorophyll and less stringent eye safety requirements, a wavelength just below 400 nm should be chosen. This can be done by using the Nd:YAG laser third harmonic at 355 nm and then shifting the radiation to 397 nm by stimulated Stokes Raman scattering in deuterium. Examples of single-shot and multishot spectra from different trees are given in Fig. 11 (Andersson et al. 1994).

Multi-spectral fluorescence imaging can be performed by expanding the laser beam to cover a certain area that is then imaged onto a two-dimensional ccd detector with simultaneous recording of the image in several suitably chosen spectral bands (Edner et al. 1994b). The area cannot, however, be increased in an unrestricted way since the induced fluorescence has to compete with the ambient light in day-light monitoring. Then the laser radiation can instead be spread out in a streak using cylinder-lens optics, and the fluorescence along the lines can be captured. When the line is swept over e.g. a tree from the root to the top, image lines can be detected sequentially and a full image can be built up in the computer. Such imaging is shown in Fig. 12 where a spruce tree was illuminated at a distance of 60 m (Johansson et al. 1996). From individual colour registrations ratio images can be formed as shown in the figure. In this way spectral anomalies may be enhanced while still eliminating influences by topography and uneven illumination.

5 Discussion

Optical remote-sensing techniques using lasers for the monitoring of the environment illustrate how methods, primarily developed for more fundamental

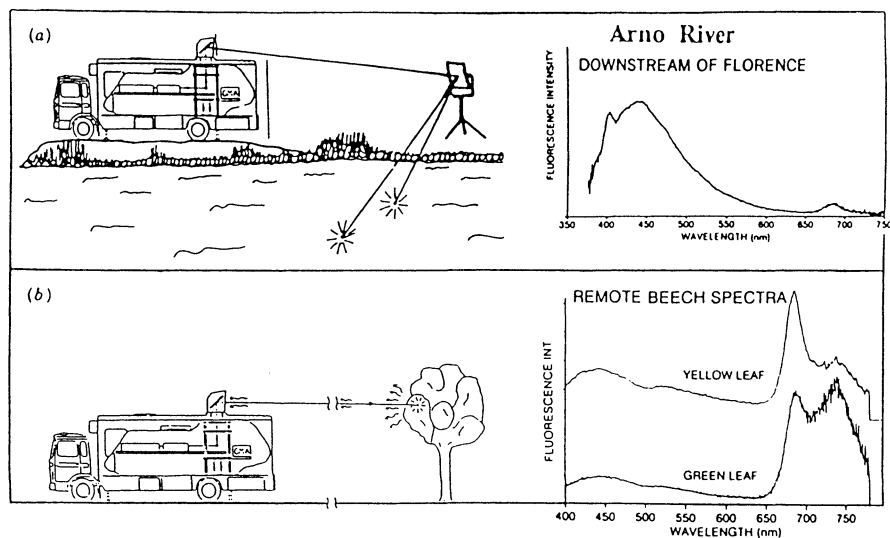


Fig. 10. Overview of hydrospheric and vegetation monitoring using remote laser-induced fluorescence. Typical fluorescence spectra are included (From Svanberg 1994).

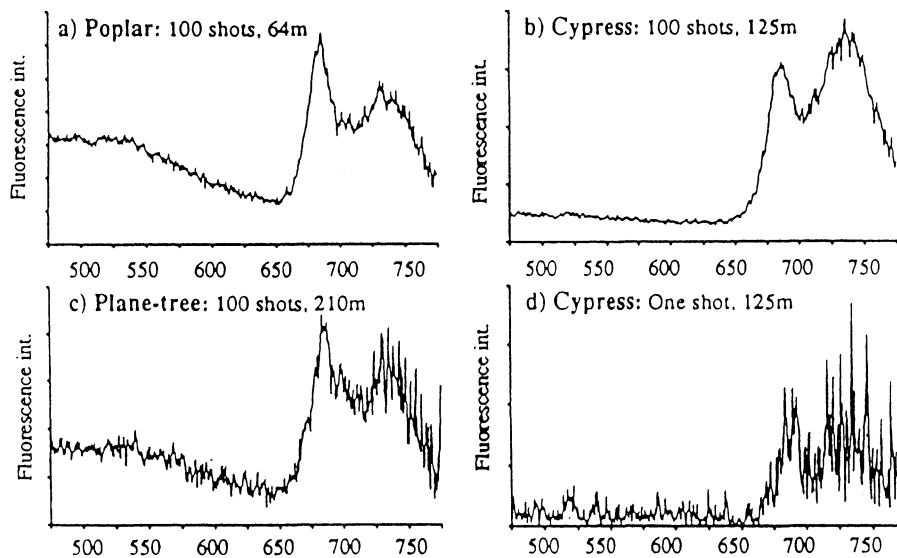


Fig. 11. Examples of point monitoring of vegetation fluorescence for different species and different distances (From Andersson et al. 1994).

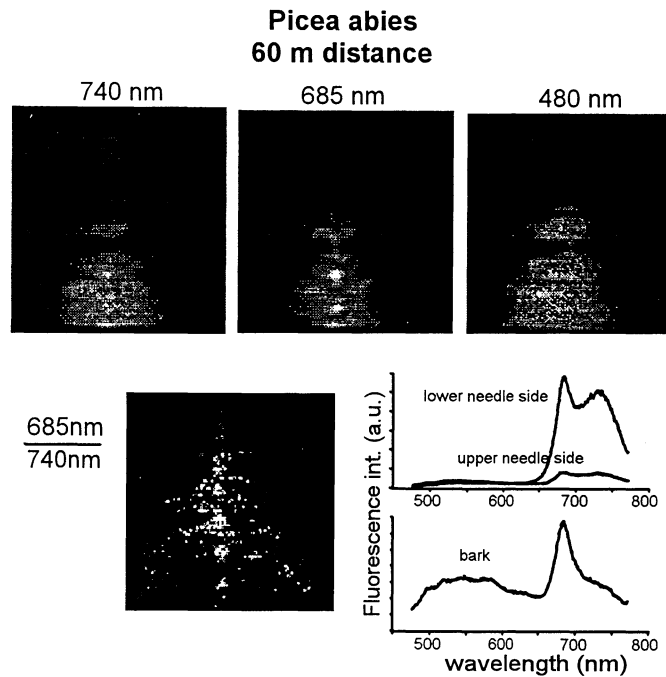


Fig. 12. Fluorescence images of a spruce tree at a distance of 60 m. An image obtained by dividing images recorded at 735 and 690 nm, respectively, is also shown. Typical fluorescence spectra (point monitoring) from spruce are included (From Johansson et al. 1996).

laboratory spectroscopy can be brought to practical applications. Frequently, the most advanced techniques are required for front-line atomic physics research, and new methods and instruments can then be taken over in the applied field. Important applications can then provide additional motivation for fundamental research.

Laser monitoring of the environment is developing quickly and is likely to be used more routinely in the near future. This is because realistic and reliable laser sources based on all-solid-state technology are now becoming readily available, and very powerful and cost-effective computers can now handle large amounts of data in near real time. Decreasing size and weight also allows practical installation arrangements for laser-based sensors. Space-based lidar systems have thus been developed and have been successfully tested.

Acknowledgements

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