Investigation of Antenna Radomes in Low Earth Orbits

Mathias Gren

Faculty of Engineering

Lund University

June 2023

A thesis submitted for the degree of

Master of Science in Engineering

Abstract

Introduction: This master's thesis focuses on exploring improved alternative material solutions for antenna radomes used to protect Beyond Gravity Sweden's satellite antennas in low Earth orbits.

Background: As the environment in low Earth orbit is harsh, surface materials on satellites experience high levels of atomic oxygen, ultra violet radiation, thermal-fluctuation, charged particles and micro meteoroids. Therefore, finding materials that can resist these harsh conditions while maintaining radio wave transparency for efficient communication and transfer of data is a complex challenge. Beyond Gravity's current satellite antenna radome is coated with a surface paint that has proven to be sensitive to mechanical touch, have long curing times, and expensive repairing procedures.

Aim(s): As a result of the expensive and vulnerable surface paint, my aim is to identify a cheaper, more efficient, and better material or coating to replace the current radome and/or coating.

Methods: To find alternative solutions I have researched radio wave transparent composite materials as well as thin metal-oxide films used in space and low Earth orbits, I have contacted space coating paint suppliers around Europe, and spoken with materials-experts at Beyond Gravity and Swedish universities.

Results: The results proved that the European space coating manufacturer *Enbio* could provide Beyond Gravity with a new paint coating that has the potential of meeting all Beyond Gravity's antenna radome requirements, while being more efficient and less costly than Beyond Gravity's current solution. The results along with the discussion also showcase the future work and testing that needs to be conducted before determining the coatings applicability to Beyond Gravity's antenna radomes.

Conclusion: In conclusion, Enbio's paint coating is less costly, more efficient and potentially better than Beyond Gravity's current surface paint coating. However, future testing and qualification is required to determine if Enbio's coatings meet up to Beyond Gravity's antenna radome requirements.

Acknowledgements

This thesis has been written at Lund University in collaboration with Beyond Gravity.

I would like to express my appreciation to my supervisor, Susanne Schilliger-Kildal, for her exceptional guidance, expertise, and support. Her feedback, constructive criticism, and dedication to my professional growth have played an important role in shaping this thesis project. I am truly grateful for her mentorship and the opportunity she has given me to expand my knowledge and skills within the space sector.

Additionally, I would like to extend my thanks to my supervisor at the Faculty of Engineering at Lund University, Martin Ek Rosén. His insights, thought-provoking questions, and suggestions have greatly enhanced the quality of this research project. I am thankful for his time and expertise in evaluating my work and providing me with constructive feedback.

Lund University

Lund, June 2023

Mathias Gren

Contents

1 List of Acronyms

2 Introduction

Beyond Gravity Sweden (BGS) manufactures advanced satellite antennas for space where the material properties and structures are important. Some antennas have radomes that protect the antennas, and are made of a composite material called *Ultem 2300* which is a Polyetherimide (PEI) with chopped glass fibers, see figure 1. This composite radome is later coated with a thin, conductive, Atomic Oxygen (AtOx) resistant paint called Black Paint (not actual name) manufactured by the company XCoating (not actual name).

Figure 1: Depiction of Beyond Gravity's Ultem 2300 radomes. Hollow cone-shaped radome with applied black surface coating. The aluminum chassis is shown as yellow in the image, is connected with the radome. To provide a grounded circuit, the black surface coating is also applied to the chassis to provide conductivity from radome to chassis.

Radomes, such as the one in figure 1 protect the antenna within from erosion, bad weather, debris, radiation, AtOx and in some cases, also serve as structural support for the antenna. The radome must still allow electromagnetic radio waves to transmit without distorting or attenuating the signal. On Earth, radomes are relatively easy technology as they are not exposed to AtOx and Ultra Violet Radiation (UV). In Low Earth Orbits (LEO), the radomes are subjected to mentioned hazards and are often combined with special coatings. In BGS's case, the coating serves as a protective layer against everything that the Ultem radome can not; UV, AtOx and Electro Static Discharge (ESD). The current coating that BGS is using is not optimal due to high costs, long curing times and sensitivity to mechanical touch. My goal in this master's thesis is to explore improved alternative solutions as radome-coatings for BGS antennas in LEO. This solution could be in the form of entirely new coatings, the same coating with improved recipe, or new composite material for the radome.

2.1 Background

Satellites and spacecrafts in LEO are exposed to particularly harsh environments. The altitude of a LEO extends from 160 km to 2000 km above Earths surface. For comparison, commercial airplanes fly at a tenth of the lowest LEO at approximately 14 km altitude, see figure 2.

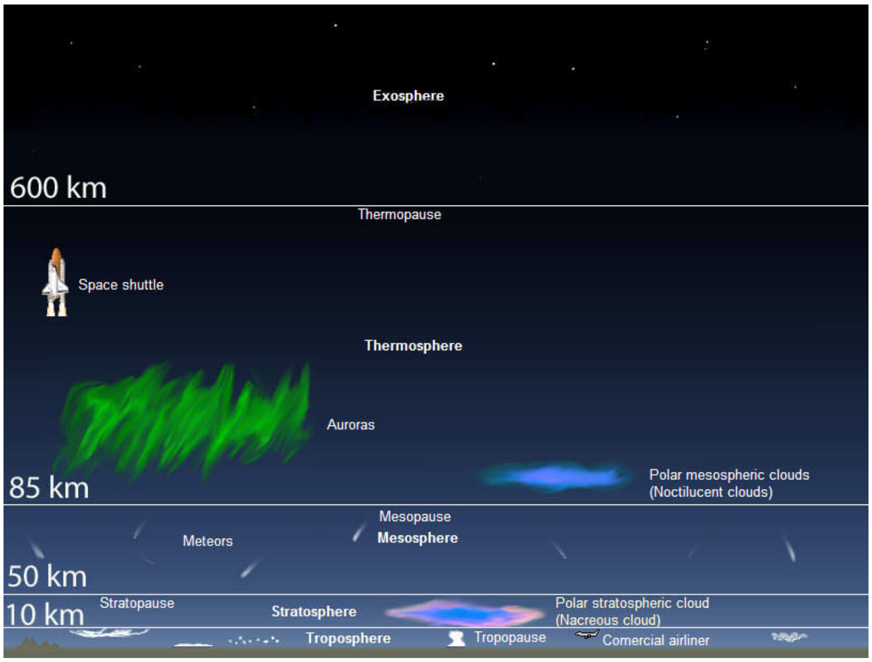

Figure 2: Low Earth Orbit depiction, made by ESA. [1]

Satellites in LEO travel at an approximate speed of 7.8 km/s, completing a full Earth orbit in 90 minutes [1]. At this altitude and speed the satellites experiences strong temperature fluctuations, high AtOx flux and high ionizing radiation. Antennas on satellites are one of the most exposed parts of the spacecraft and therefore need protecting. Some antennas use radomes that are placed around the antennas to protect the components from the harsh environment and/or for structural support. Besides being able to withstand the environment, the radome needs to be radio wave transparent and be able to ground electrons (conduct electricity). The thesis will focus on investigation and testing off suitable materials and/or coatings for radomes protecting antennas on satellites in low Earth orbits.

When designing antenna radomes for LEO it is important to consider which material properties are required in order to maximize the End of Life (EOL) time. Throughout the radomes lifetime it experiences three main stages: production and preparation, launch, and orbit. During production the radome is under ordinary temperature and pressures. When the radome along with the satellite is launched into LEO the entire spacecraft experiences intense G-forces. The components and structures of the spacecraft require high tensile strengths in order to avoid deformation and catastrophe. Once the satellite is in orbit, the most vulnerable parts are those on the surface, exposed towards space. The LEO is where the satellite will spend the most time, and is also where it experiences the harshest environments.

Oxygen gas (O_2) exists naturally in our atmosphere. The ozone layer absorbs approximately 98% of incoming UV-radiation and it lays at altitudes of 15 km to 30 km above Earths surface. AtOx forms from high solar energy UV-beams ($\lambda < 250$ nm) dissociating the oxygen gas molecule into two oxygen radicals. At altitudes of 180-650 km where satellites orbit, the concentration of AtOx peaks, see table 1.

Species	LEO	MISSE-7	MEO	GPS
Atomic oxygen flux (cm^{-1} s – 1)	10^{13}	3×10^{20}	10^{6}	negl.
Solar UV	1 sun	3200 ESH	1 sun	1 sun
Trapped protons >100 keV(cm^{-2} day^{-1})	5×10^{8}		6×10^{9}	2×10^{12}
Trapped electrons >40 keV(cm^{-2} day^{-1})	9×10^{9}		5×10^{11}	3×10^{12}

Table 1: Table showing the different particle concentrations at different altitudes. Notice that the highest concentrations of AtOx can be found in LEO and Materials International Space Station Experiment (MISSE-7) orbits, it's worth noting that MISSE-7 orbit is within LEO, Medium Earth Orbit (MEO) and Global Positioning System (GPS). Reproduced from reference [5]

These oxygen radicals are highly reactive and can oxidize everything from polymers, composites, metals and silicon and can etch away up to a couple millimeters in depth of the material. This results in rough, damaged surfaces which ruins the components on the surface of the spacecraft. Polymers and composites are sensitive to the oxygen radicals and the resulting degradation can interfere with the optical properties by increasing scattering and reflectivity, ultimately decreasing transmission to and from the antennas. The dissociation energy of chemical bonds in polymer materials are 3.9 eV and 3.2 eV for C-C bonds and C-N bonds respectively. The reactive AtOx energy ranges from 4.5-5.0 eV which is enough to deteriorate carbon based polymers, by breaking the chemical bonds of the polymer chains. The oxidized polymers form large amounts of volatile components: CO_2, CO, H_2O, and NO. These volatile components can interfere with other equipment on the spacecraft, see figure 3. [5]

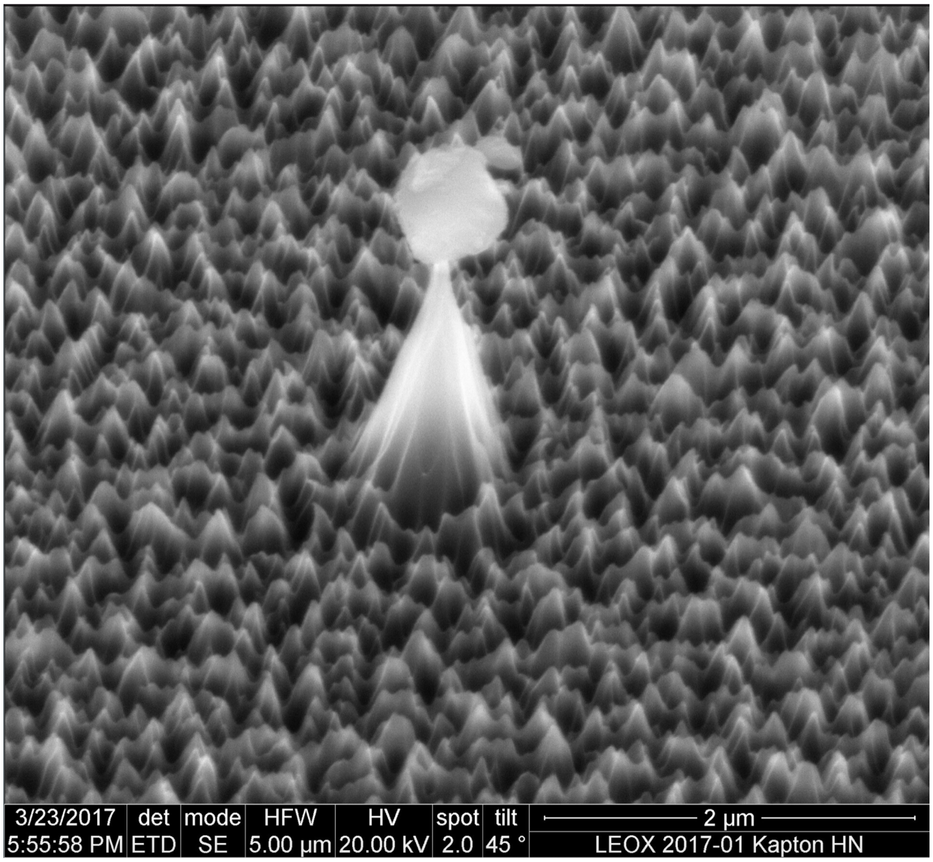

Figure 3: Scanning Electron Microscope (SEM) image of a piece of Kapton done by European Space Agency (ESA). Center pillar is a metallic particle meant to preserve the polymer around it. The surrounding polymer has been eroded away using ESA's LEOX machine that generates high concentrations of AtOx to simulate LEO environments. Reproduced from reference [11]

Satellites surface components are exposed to high amounts of radiation in LEO. Static electricity is easily built up on rubber, plastics and composites and especially in space were radiation is high. The built up static electrical charge can result in ESD that puts the spacecraft's internal electronics at risk of damage. Therefore, it is important to have radomes around antennas that can conduct the built up static electricity away from the surface of the radomes and keep the internal electronics intact. [7] Radiation induced damage mechanisms include: ions and protons from solar flare activities, and UV-beams. These high energetic particles come to an abrupt stop in the materials, where there kinetic energy is dissipated, thus damaging the material. To avoid absorption of high energy particles and UV-beams, materials should be resistant to UV and have a high refractive index. [2]

In LEO satellites move incredibly fast and complete an orbit around Earth in 90 minutes. This means that the satellite and its surface components are constantly cycling in and out of the sun's solar radiation and Earth's shadow, and experience extreme thermal fluctuations. Consequently, the components are qualified to cycle from temperatures as low as -180 °C to as high as 180 °C. The materials need to be stable under these temperatures and not undergo phase-transformation or uncontrolled thermal expansion compensation.

2.2 Objective

The radome along with the surface paint meets all environmental requirements and has been used for many years at BGS and their customers. However, the surface coating Black Paint is sensitive to mechanical touch which results in accidents where the coating comes off to occur frequently, costing the company time, money and trust. Furthermore, the lead time and cost of Black Paint has continued to increase and Beyond Gravity Sweden are in need of an alternative solution. Black Paint's function is to protect the radome from AtOx, UV and to avoid electrostatic build up. The paint conducts the charge to the grounded ring chassis at the bottom of the radome see figure 4. The objective of the master's thesis is to find a alternative material or coating solution to Beyond Gravity Sweden's radomes.

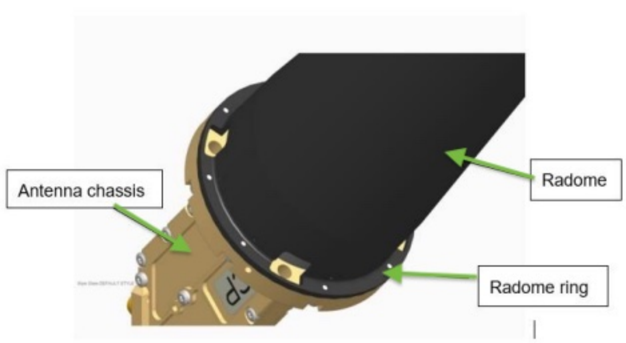

Figure 4: Enlarged image of figure 1 with the different sections marked. Notice how the dark Black Paint is painted onto the chassis, this is to conduct the charged surface to the grounded chassis.

2.3 Constraints

As the field of Material Science is vast, there are potentially many undiscovered materials and composites suitable for this application. After doing research I have chosen to focus on three main potential solutions: metal-oxide coatings, soluble viscous coatings (such as Black Paint), and additive manufacturing of composite materials. The later alternative was investigated by the Research Institute of Sweden (RISE) on behalf of BGS with the same topic as this thesis. The task proved to be complex and RISE did not find an alternative radome composite that met all the requirements and could substitute the current radome and paint coating. There are likely additional solutions to solve BGS problem, but this thesis will focus on the three mentioned. In the Theory section 3, I will provide a summary of the potential materials. By analyzing feedback from material suppliers in the various industries, I will evaluate the feasibility of further studies in the Results section 4. Lastly, I will discuss the appropriateness of the applicable material options and suppliers in the Discussion section 5.

3 Theory

In this section, I will present the technology and space solutions of BGS that ensure the reliability and durability of their complex antennas in space. Additionally, I will describe various potential material alternatives that could potentially replace BGS's current solution. Finally, I will describe multiple verification methods used to determine the material properties suitable for space coating paints, expanding on a previous qualification carried out by BGS.

3.1 Beyond Gravity's Antennas

Different satellite antennas have different areas of applications and therefore operate in different frequency bands from L- to Ka-band, see figure 5. One antenna application is Telemetry, Tracking and Command (TTC) which gives information of the satellites status, location and uplinked given commands. This includes communication to Earth, between satellites and other spacecrafts. [15] Other applications include data links, mobile communications and Global Navigation Satellite System (GNSS).

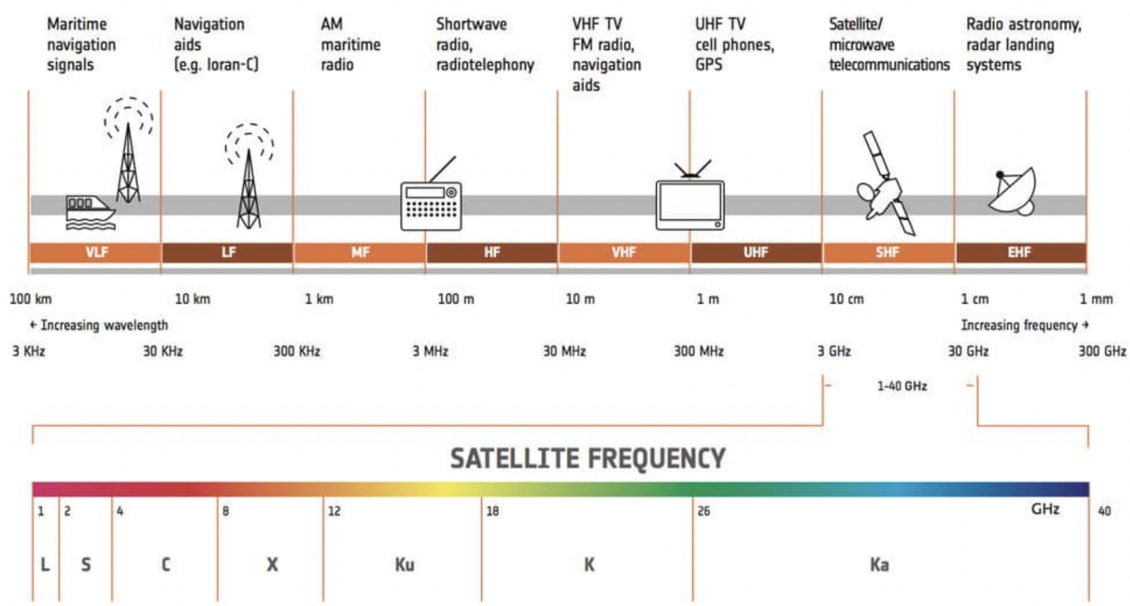

Figure 5: Frequency spectrum for different technological applications, with greater detail over the satellite frequency bands stretching from L-band to Ka-band frequency's. [14]

Beyond Gravity Sweden manufacture many types of satellite antennas for its customers, see some examples of these in figure 6. Different customers have different requirements on their antenna-orders based on the specific space mission and application. Most of the antennas in figure 6 are made of anodised aluminum and do not require a protective radome around them, they can survive on their own. The S- and X-band helices, however, need a structural supportive radome to handle the forces during launch. In space, the radome has to be resistant against the harsh environment, including AtOx , UV-radiation, debris and more. The Beyond Gravity S- and X-band helices are encapsulated by a Ultem 2300 radome painted with Black Paint to be able to withstand the LEO environments, see figure 7.

Figure 6: Different types of antennas available at Beyond Gravity with different frequency bands and applications.

Figure 7: The left image is Beyond Gravity's S-band antenna with protective radome encapsulation. To the right is Beyond Gravity's X-band antenna with protective radome. The S- and X-band antennas have different design and therefore different radome design.

3.2 Radome Material Ultem 2300

As previously mentioned the antenna radome is radio wave transparent and provides structural support protection by encapsulating the helix antenna. The radomes are located on the outer most part of the space craft, exposing them directly to LEO environments. As the component is exposed to harsh and volatile environment, the processing method and material specifications are very important. Examples of material specifications include: Glass transition temperature > 190 °C, low outgassing, radiation resistance > 2500 Mrad, tensile strength > 160 MPa, etc. A complimentary surface coating to the radome is often necessary to fulfil the requirements.

The material used by Beyond Gravity for its antenna radomes is Ultem 2300. Ultem 2300 is a Glass Fiber Reinforced Plastic (GFRP), or more specifically a thermoplastic PEI reinforced with 30% glass fibers, processed with milling. The glass fibers contributes with high strength and stiffness for tolerating satellite launches, and the PEI is resistant to thermal fluctuations of -190 to 190 °C, chemicals and radiation. Furthermore, the cone shaped plastic has a thickness of less than 1 mm and can easily be processed into the desired shape. The two main material requirements that Ultem 2300 does not meet, are AtOx resistance and prevention against electrostatic discharge, which can be resolved with coatings. Beyond Gravity use an electrostatic silicone based paint herein called Black Paint, that is applied on the surface of the radome. There are potentially other alternatives to the Ultem 2300 and Black Paint system such as: Improving the processing and ingredients of the current paint, using new paints, deposition of thin metal-oxide films on the Ultem surface, or incorporating all material requirements by engineering a new composite material as a bulk radome. [8]

3.3 Paint Coatings

This section discusses the theory behind paint coatings relevant to this master's thesis project. Paint coatings are viscous substances that coat the surfaces of components and structures. The coatings are cured to form a stable layer on the outer most part of a component. Different paints have different colors, ingredients, functions, viscosities, and curing temperatures. Currently, BGS uses Black Paint as a coating for their satellite antenna radomes.

3.3.1 Black Paint

XCoating is a company that focuses on space paint coatings and their main clients are various companies around Europe such as ESA and Beyond Gravity. Beyond Gravity has for many years used this supplier for various coating solutions, including the product Black Paint for their antenna radomes. Over the years the lead time of the paint has increased, as well as the price.

Black Paint is a matt, flat-black anti-static silicone coating developed for aerospace applications. The coating provides excellent thermal protection with good thermo-optical properties and very high resistance to AtOx and UV irradiation. The coating also provides a very good thermal stability at low temperatures (-180 °C) and prevention of ESD due to its anti-static properties. The paint has low outgassing values, which is important to avoid evaporation (in low pressure environments) and later, condensation on other satellite components. The resistance of the paint is tuned so that the paint is slightly conductive and can transport away charged particles, and the typical film thickness is 30-50 μm, see table 2. The main issues that BGS experiences with Black Paint are: sensitivity to mechanical touch, complicated paint repair, long lead times, and high price tag. The biggest problem being Black Paint's poor adhesion, commonly being scratched off by BGS technicians or customers, requiring a complicated and expensive repair, to fix the scratched paint. Additionally, to avoid cracking and degradation, the paint has a long curing time of 4 weeks before ageing tests such as thermal vacuum cycling should be performed. [6]

Property	Unit	Requierment	Comment
Handling	NA	Not sensitive to mechanical touch.	
Reach Material	NA	None	Must be compliant with Reach standards.
Glass transition temperature (Tg)	°C	>190	Important limit as we can't risk the materials to soften.
Outgassing	%	CVCM < 0.1 RML < 1	
Temperature range	°C	-180 < T < 180	
Radiation resistance	Mrad	>2500	
Lifetime in space		Up to 20 years	
Resistance to Solar exposure (UV resistant)	NA	Requirements fulfilled after Solar exposure (applicable for complete lifetime)	
Solar absorptivity divided by the IR emissivity (α_{sol} / ε_{ir})		<=1.06 (applicable for complete lifetime)	
ATOX fluence	[atom O/cm^2]	Resist a total lifetime fluence of maximum $1{\cdot}10^{22}$	
Dielectric constant	NA	<~4	
Surface resistance / Sheet resistance	MΩ/Square	1 ≤ Rs ≤ 1000	
Volume resistivity, ρ	MΩm	t*1 <ρ< t*1000 For uniform conducting radome material with thickness t [m]	
Ultimate limit stress	MPa	>160	
Coefficient of thermal expansion, CTE	$\times 10^{-6}$ m/m°C	10-30	
Glue ability		Possible to glue towards radome aluminum ring if applicable	

Table 2: Desired material properties of XCoating's Black Paint based on Beyond Gravity's current solution, used as requirements and/or guidelines for which material properties are needed on alternative solutions in order to survive LEO and be beneficial for Beyond Gravity.

3.3.2 Enbio Coatings

Enbio is an Irish space technology company focusing on aerospace materials and coatings for spacecrafts. Enbio has previous records of partnerships with the European Space Agency and their products are of high quality and precision. For Beyond Gravity's applications, Enbio's coatings SolarWhite and SolarBlack is of particular interest.

SolarWhite is a specially formulated inorganic coating that reflects heat and light (thermo-optical reflector coating) and is intended for use in space. It has been approved by the ESA for deployment on the Solar Orbiter mission for use on the Stood-Off Radiator Assembly (SORA) and certain components on the I-Boom.

Currently, SolarWhite is undergoing evaluation by ESA for potential use on NeoSat (Advanced Research in Telecommunications Systems (ARTES) next generation satellite platform). When applied, SolarWhite utilizes SolarBlack (described in the next paragraph) as a tie-layer for metal substrates, and it is applied using a pressurized spray process followed by a thermal cure. Some notable features of SolarWhite include its ability to be applied at room temperature, its inorganic composition, its cleanability with solvents like Isopropyl Alcohol (IPA) and Acetone, its compliance with Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulations, its resilience during Assembly, Integration, and Testing (AIT) activities, and its near-complete diffusion of UV/Visible/Near-Infra Red (IR) light range. SolarWhite absorptivity and emissivity values are very stable at high and low temperatures, as well as high radiation exposure. The paint is also conductive and can easily be applied to complex geometries. See table 3 for a summary over the material properties. [9]

Typical Property	Value
Thickness	150 μm
Density / Weight	1.9 g/cm^3 or 285 g/m^2
Typical Absorption (α_s) on Al 2024 T3	0.18
Typical Emissivity (ε_h) on Al 2024 T3	0.89
Adhesion (ECSS-Q-ST-70-13C)	Compatible (no change in optical properties)
Tested thermal range	-180°C to 180°C (under vacuum)
Outgassing (ECSS-Q-ST-70-20C)	CVCM: 0.01 (%) TML: 0.30 (%) RML: 0.03 (%)
Volume Resistivity	200 MΩ/cm
RF Antenna compliance	No effect on RF properties

Table 3: Table of SolarWhite material properties. Other properties such as Atomic Oxygen resistance, radiation resistance, and sheet resistivity depend on substrate and test method, mentioned more under in section Result 4.1. [9]

SolarBlack is a thermo-optical coating with a broad range of applications in thermal control and anti-reflective use cases. It has undergone qualification for deployment on the European Space Agency Solar Orbiter mission and is a mission-critical coating for numerous key components, including the titanium heat-shield and titanium high-gain antenna. The CoBlast process used to apply SolarBlack involves compressed air in a low pressure, dry, room temperature environment, with selective area treatment via line-of-sight. SolarBlack is also REACH compliant, robust to AIT activities, and can be applied to thin foils (18 μm) as well as thick plates exceeding 1 mm. Furthermore, SolarBlack boasts excellent edge-retention, with 25 μm curves having been tested, and it exhibits near-complete diffusion in the UV/Visible/Near IR light range. See table 4 for a summery of the material properties. [10]

Property	Value
Thickness	2-5 µm
Density / Weight	3.2 g/cm^3 or 16 g/m^2
Typical Absorption (α_s) on Ti6Al4V	0.96
Typical Emissivity (ε) on Ti6Al4V	0.78
Adhesion (ECSS-Q-ST-70-13C)	Compatible (no change in optical properties)
Tested thermal range	-191°C to 700°C (under vacuum)
Outgassing (ECSS-Q-ST-70-20C)	CVCM: 0.001 (%) RML: 0.03 (%)
Surface Resistivity	< 1 kΩ/sq

Table 4: Table of SolarBlack material properties. Other properties such as Atomic Oxygen resistance, radiation resistance, and sheet resistivity depend on substrate and test method, mentioned more under the Result section 5.2. Reproduced form reference [10]

3.4 Metal-Oxide Coatings

In the study Development and Testing of Coatings for Orbital Space Radiation Environments by Pellicori, they investigate the possibility of extending the EOL of exterior space equipment in LEO, more specifically solar cells on satellites. The article suggests physical vapor deposition techniques of protective metal-oxide coatings. Some of the suggested deposition techniques are: Ion-assisted Deposition Electron Beam (E-beam IAD), Plasma Ion-Assisted Deposition (PIAD), and Pulsed Direct Current Magnetron Sputtering (PDCMS).

The article investigates proton irradiation on different metal-oxide combinations, deposited with various high energy deposition techniques. The deposition methods produced high packing densities and achieved low extinction coefficients (low absorption) when compared to low-energy deposition techniques. PDCMS and PIAD are low temperature methods and are compliant with temperature sensitive materials such as polymers. All metal-oxide coatings proved excellent refraction index and absorption stability to irradiation. Ta_2O_5 had the highest index of refraction followed by $LaTiO_3$, HfO_2, and ZrO_2. The low index materials such as silica (SiO_2) were stable to irradiation when deposited with PDCMS and PIAD.

The four high-index materials where combined with the two low-index materials to make test samples of Ultra Violet-Reflective/Anti-Reflective (UVR/AR) coatings. These materials were deposited with two low-temperature methods (PIAD and PDCMS) and one high-temperature method (E-beam IAD). In addition to the previous proton irradiation test, these substrates were subjected to: AtOx-exposure, humidity (Earth-like conditions), and tape-pull for mechanical adhesion. Each substrate was tested respectively for transmittance and PDCMS deposition of Ta_2O_5 and SiO_2 experienced the least loss. [3]

3.4.1 PDCMS Deposition of Ta_2O_5/SiO_2

The best selection of radiation resistant coatings and high-energy process was concluded to be Ta_2O_5/SiO_2 deposited with PDCMS. This process is as previously mentioned a low-temperature process which is suitable for deposition on temperature sensitive polymers, suggesting compatibility with BGS Ultem 2300 radomes. Furthermore, the process is easily repeatable, reliable, stable and optimal for commercial large production use.

In the study form Pellicori, the deposition of Ta_2O_5 and SiO_2 with PDCMS was conducted on four different polymer substrates (A,B,C,D). The deposition process was adjusted to achieve maximum adhesion to the polymers. The coatings adhesion to the polymers proved to be excellent after performing a series of mechanical and humidity tests. The substrates with and without the UVR/AR coatings where exposed to high concentrations of AtOx ($4.94x10^{21}$ atoms/cm^2) at the NASA Glenn Research Center (NGRC). In this experiment transmission losses where measured for wave lengths between 300-500 nm, this is an indication of how well preserved the surface was, thus indicating how protective the coating was against the AtOx degradation. Table 5 shows the transmission change in % before and after the substrates were subjected to atomic oxygen. The transmission of bare polymers A, B, C and D were significant while the coated polymers showed minimal transmission loss after high concentrations of AtOx.

Average T(%) Between 300 and 500 nm[a]	
Coating/Substrate	% Change
Bare polymer A	24.2%
Bare polymer B	8.7%
Bare polymer C	22.3%
Bare polymer D	21.4%
Bare-fused silica	0.4%
UVR/polymer A	−1.8%
UVR/polymer B	−0.5%
UVR/polymer C	−3.2%
UVR/polymer D	1.4%
UVR/fused silica	0.0%

Table 5: Average transmittance (300 nm - 500 nm) change in % after substrates had been subjected to AtOx at the NGRC. Negative % change indicates an increase in transmittance, something that can appear from the speedometer systemic error of ± 0.5%. Reproduced from reference [3]

In figure 8, the transmittance of polymer D with the UVR/AR coating is schematically shown, before and after subjected to AtOx.

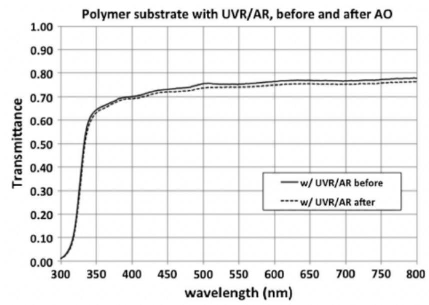

Figure 8: Polymer D with metal-oxide coating subjected to AtOx. Transmittance measure before and after introduced AtOx. [3]

To test the tantala silica UVR/AR coatings deposited with PDCMS, the metal-oxide was deposited on solar cells that were flown on the MISSE-7 in LEO exposing the solar cells to similar environments as BGS antenna radomes. The solar cells were facing the zenith direction and were exposed to solar rays for over 18 months. After 4200 (Equivalent Sun Hours (ESH)), the MISSE-7 Solar UV did not show any significant damage. Analysis of the results indicates a worst case scenario of 0.5% loss of UV induced damage, it amounts for a 5% loss after 10 years. Comparing this loss to that of the one mentioned in the Aerospace report (referred to in article), it is a 3-5x longer EOL improvement. [3]

3.4.2 PDCMS Deposition of AZO, Aluminum−Doped Zinc Oxide

An alternative transparent conductive coating that the article investigated is Aluminum-Doped Zinc Oxide (AZO) which they compare with the industries standard material Indium Tin Oxide (ITO). Both ITO and AZO are transparent, conductive coatings, but only AZO is resistant to AtOx. Pellicori and his colleagues have been developing and optimizing the PDCMS deposition process of AZO for several years, and they have concluded AZO to be a stable material with low absorption in the blue/UV spectral region. They deposited a 30-40 nm thick film and measured the resistance to approximately 100 kOhms/square which is a factor 10 too small for the requirement to avoid ESD. By adjusting the film thickness the resistance and transmittance can be tuned. The AZO on fused silica sample was subjected to the same radiation tests as previously mentioned, and the index of refraction as well as the extinction coefficient did not change significantly. Furthermore, the AZO samples were exposed to AtOx. The transmittance improved in all samples, implicating oxidation of films and satisfying AZO as a protective coating for polymers against AtOx, see table 6. [3]

Average T(%) between 300 and 500 nm[a]	
Coating/Substrate	% Change
AZO/polymer A	−1.2%
AZO/polymer B	−17.9%
AZO/polymer C	−1.4%
AZO/polymer D	−10.6%
AZO/fused silica	−3.8%

Table 6: Average transmittance (300 nm - 500 nm) change in % after AZO substrates had been subjected to AtOx at the NGRC. Negative % change indicates an increase in transmittance, something that can appear from the speedometer systemic error of ± 0.5%. Reproduced from reference [3]

3.4.3 Deposition Technique (PDCMS)

The deposition method that the article concluded to be the best when depositing Ta_2O_5 and AZO is pulsed direct current magnetron sputtering (PDCMS). The technique can be used at ambient temperature which is very important when dealing with polymer or composite substrates that are temperature-sensitive. [3] PDCMS is a sputtering technique were plasma ions collide with the target material (Ta_2O_5), knocking atoms out. The atoms are aimed at a substrate (Ultem Radome) where they are deposited. As the name suggests, PDCMS uses a pulsed direct current as its energy supply. Short pulses provide more control on the deposition and minimizes impurities. The technique is also low cost and easy to use for large substrate processes. [4]

3.5 New Composite Radome Materials

BGS uses a PEI with chopped glass fibers (Ultem 2300) as a material for their antenna radomes. This material is susceptible to AtOx-degradation and is not conductive. Therefore, an additional surface paint coating is needed to protect the radome from these conditions. This section, explores the possibilities of incorporating all material requirements for LEO in one composite material, eliminating the need of an external coating.

3.5.1 Cyanate Ester Matrix with Glass Fiber Reinforcement

During a conversation with a Materials Engineer from Beyond Gravity's Zurich office, he suggested that several intriguing conductive, AtOx-resistant materials that have been commonly utilized in various non-radome components within LEO. The most relevant material being a prepreg (preimpregnated fibers with a partially cured polymer-matrix) Cyanate Ester with Glass Reinforcements made by the company Toray Advanced Composites. It is potentially a very good candidate for substituting the Ultem radome all together. The material is regulated under "international traffic and arms regulated material" and has flown numerous times in space. The composite material has been used several times within Beyond Gravity and has functioned in various exposed LEO satellite components.

The Cyanate ester's material parameters look excellent and has proven to be AtOx /UV resistant, mechanically durable, high radiation resistance, low moisture absorption, low outgassing, resistance to micro cracking, even when subjected to thermal cycling and high levels of radiation exposure, low dielectric and low loss values which makes it outstanding for radome and antenna applications. From the data sheet the Tg is 174 °C, which might be slightly too low (< 190 °C), but the documentation states that higher Tg's can be achieved with post curing. The data sheet does not indicate sheet resistance, which is an important parameter to prevent ESD but still ensure low Radio Frequency (RF)-losses.

There are potentially more cyanate ester prepreg materials on Toray's website that could be even better candidates for our purpose. However, the Zurich office communicated that they have this specific material in-house. Which could mean that overall costs for test and logistics could be kept to a minimum as we could rely on internal materials instead of dealing with external parties.

3.5.2 Additive Manufacturing of Composite Materials (RISE Study)

The aerospace and space industry demands materials that have a unique combination of material properties such as high strength, stiffness, lightweight, resistance to environmental degradation, and prevention of ESD. The use of composite materials in aerospace applications has increased significantly in recent years due to their superior mechanical and physical properties. However, some composite materials such as Ultem require coatings to protect against environmental factors such as AtOx and UV-radiation. This additional coating layer adds complexity to the design, increasing the cost and time of production, testing and operation. Therefore, developing a composite material that incorporates all the required properties without the need for additional coatings is of significant interest to the industry. RISE investigated the possibility of developing a new composite material for radome parts for BGS antennas, which could survive and perform in LEO-environments without the need for additional coatings, using additive manufacturing technology. Additive manufacturing, also known as 3D printing, allows one to combine different composite materials and additives in a layered structure to incorporate multiple qualities simultaneously.

One approach to developing such a material is the incorporation of Carbon Nano Tubes (CNT) into the Ultem composite matrix. CNT have exceptional electrical conductivity and can be uniformly dispersed throughout the material matrix, preventing ESD. Furthermore, CNT can enhance other properties such as mechanical strength, stiffness, and thermal conductivity, making them an attractive option for the aerospace industry in general.

Another crucial aspect of developing a composite material for satellite applications is its resistance to AtOx. AtOx is highly reactive and can cause significant degradation to unprotected surfaces in LEO as mentioned in section 2.1. Glass fibers are effective materials for providing AtOx resistance in composite materials. Incorporating glass fibers into the composite matrix can improve the material's AtOx resistance while also providing the required strength and stiffness. The use of glass fibers has been shown to reduce the material's weight while maintaining mechanical strength and durability.

In summary, developing a composite material that incorporates all the material requirements for space applications is complex. However, the incorporation of conductive materials such as CNT, glass fibers, and carbon fibers into the composite matrix can provide the required properties such as prevention of ESD, AtOx resistance, strength, stiffness, and lightweight. The development of such a material can simplify the design, reduce weight and cost, and provide excellent performance in harsh LEO-environments, making it an attractive option for BGS. [27]

3.6 Verification and Testing of Material Requirements

In this section I will talk about the verification procedure of working with new materials for LEO. This includes verification testing of composite materials and paint coatings, such as Ultem and Black Paint. Beyond Gravity verify most of its components in-house. Some tests require external partners' equipment and laboratories, such as high concentrations of AtOx and UV. AtOx -testing for Beyond Gravity has previously been done at European Space Research and Technology Centre (ESTEC), and ESA. ESA's low Earth orbit machine, LEOX, generates atomic oxygen traveling 7.8 km/s to test LEO components for erosion resistance, see figure 9. [12]

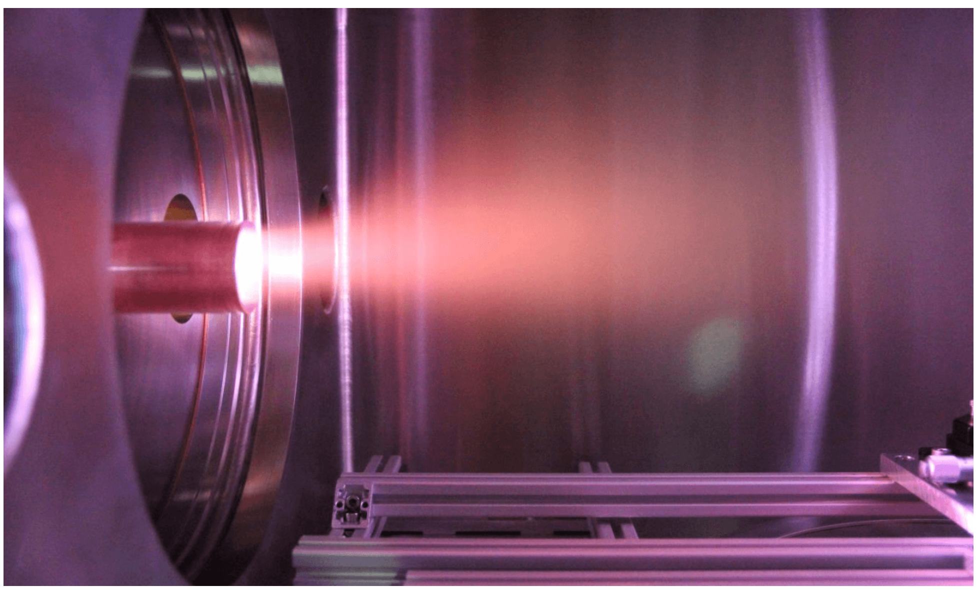

Figure 9: Image of atomic oxygen-beam traveling at 7.8 km/s generated by ESA's LEOX machine at ESTEC to test erosion resistance on LEO components and structures. [12]

3.6.1 Most Recent Qualification Tests done to Black Paint

Black Paint is similar to Enbio's paints, previous qualifications that have been performed to Black Paint are therefore relevant and can possibly be copied in the future when performing qualification testing on Solar White and Solar Black. Beyond Gravity's commonly used Black Paint by XCoating was recently updated with a new primer, and therefore required a new delta qualification. Black Paint was applied to a variety of different test samples including: aluminum alloy 6082 passivated with SurTec 650, aluminum alloy 6082, aluminum foil, Isola 620i, and Ultem 2300, all which had a thickness in the range of 1-2 mm. It is worth noting that samples painted with Black Paint required 28 days of curing time before any tests could be performed. The qualification test flow chart of Black Paint can be seen in figure 10 demonstrating the flow of testing. [23]

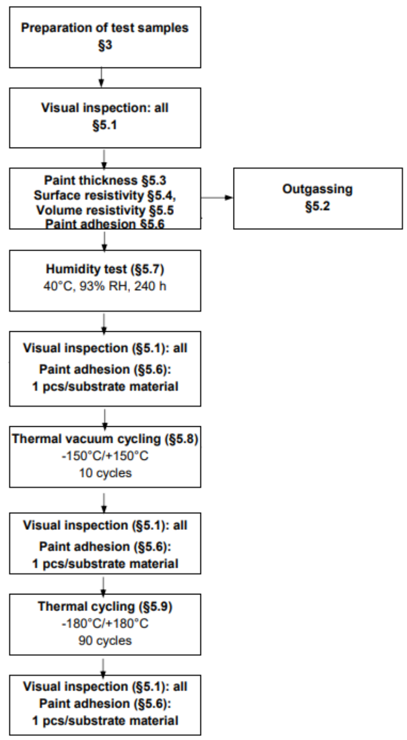

Figure 10: Qualification flow chart of Black Paint, demonstrating in which order the various steps were performed. Outgassing tests were performed externally in Spain. The flow chart serves as a good starting point for future paint qualifications. Reproduced from reference [23]

Visual Inspections Visual inspections are often carried out by analysing a sample with the naked eye under a bright white light, or under a microscope. The usual magnification range when using a microscope is 1-15x. The aim of visual inspections is to identify any flaws, cracks, blisters or contaminations of the sample. The samples are inspected prior and after any thermal cycling or thermal vacuum cycling and throughout the verification testing phase.

Outgassing In the flow chart seen in figure 10, outgassing was the only test performed externally from BGS. The test samples were prepared by Beyond Gravity and sent to National Institute of Aerospace Technology (INTA) in Spain. Outgassing is particularly important when dealing with non-metal materials in LEO, as the released gas could condense on other sensitive satellite electronics such as lenses. In short, an outgassing test is performed by exposing a part at around 125 °C and near vacuum, a cooling collector plate then collects the condensed material. The weight of the collector plates is measured before and after, and if the Total Mass Loss (TML) $< 1\%$, and the Collected Volatile Condensible Materials (CVCM) $< 0.1\%$, the materials pass. [13] Beyond Gravity performs the outgassing tests according to the European Cooperation for Space Standardization (ECSS) standard ECSS-Q-70-02, Thermal vacuum outgassing tests for the screening of space materials. [24] [28]

Surface & Volume Resistivity Surface resistivity was measured using a resistivity probe similar to the one depicted in figure 11. The surface resistivity should be measured on all samples. However, the surface resistivity can not be measured on a radome, due to the geometry of a radome. Therefore it is important to have separate flat-plate samples, exposed to the same environment and procedures as the radomes. The surface resistance should be measured prior to and after any thermal vacuum cycling or thermal cycling. According to previous Black Paint qualifications [28], the resistance is measured according to American Society for Testing and Materials (ASTM) [ASTM D 257, Standard Test Methods for DC Resistance or Conductance of Insulating Materials], and the test succession criteria is that the surface resistance is $< 10^9$ Ω/sq.

Figure 11: Image of probe used to measure surface and volume resistivity. The probe is placed on the sample using a 100 V bias to measure surface resistivity and 10 V bias for volume resistivity.

Paint Adhesion Similar to surface and volume resistivity tests, cross cut tape adhesion tests can not be performed on samples with cone shaped geometry. Therefore, the tests were performed on flat samples similar to the ones depicted in figure 12. According to previous Black Paint qualifications [28], adhesion was tested with cross-cut tests according to International Organization for Standardization (ISO) [EN ISO 2409, Paint and varnishes – Cross-cut test] with tape *M No.92*, and the test success criteria: Classification 2 or better according to table 1 in [EN ISO 2409, Paint and varnishes – Cross-cut test].

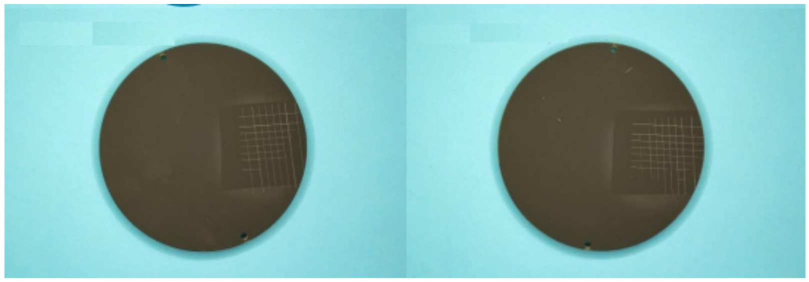

Figure 12: Flat samples of Ultem 2300 with coated Black Paint exposed to adhesion tests. Photographs of paint adhesion cross-cut test results from a previous qualification report of a new primer for Black Paint. [23]

Humidity test A humidity test was included in the qualification program. In this specific program the samples were exposed to conditions of 40 °C and 93% Relative Humidity (RH) for a period of 240 hours.

Thermal Vacuum Cycling and Thermal Cycling Thermal Vacuum Cycling (TVC) and Thermal Cycling (TC) are important tests when dealing with materials for space. Beyond Gravity have several TVC that can reach different temperatures and fit different substrates and samples, see figure 13.

Figure 13: Image of one of Beyond Gravity's Thermal Vacuum Cycling chambers. This specific one has working area for test specimen: 600mm x 600mm x 600mm. Process pressure: 0.1 mPa. Pumping capacity at 1 mPa: 6000 l/s. Temperature range: -165°C - 180°C. [26]

Depending on the specific thermal cycling and TVC machine, test chambers can vary temperature from −180°C to 180°C. The samples undergo up to 100 cycles, ramping up with approximately 10 °C/min and holding each temperature for at least 15 min at a time, taking about a week to complete. It is important that the chambers reach the given temperature to ensure the sampled material is durable/does not part take in phase change. Therefore, high precision and careful calibration is necessary. See table 7 and 8 for TVC and Thermal Cycling specifications to the qualification of Black Paint in flow chart 10. According to previous

Black Paint qualifications [28], TVC is performed at a pressure of 1x10^{-3} Pa or less, and according to the ECSS standard ECSS-Q-70-04 Thermal cycling test for the screening of space materials and processes.

Parameter:	Specification:
Maximum temperature: # [°C]	150
Minimum temperature: # [°C]	-150
Number of cycles: #	10
Dwell time: # [h]	0.5
Temperature change rate, dT/dt: # [°C/min]	Max: 10
Temperature tolerance: Max temperature: # [°C]	-0 / +10
Temperature tolerance: Min temperature: # [°C]	-10 / +0
Final pressure: below # [Pa]	1.3*10^{-3}
Pressure tolerance:	±80%

Table 7: Specifications for thermal vacuum cycling qualification testing of XCoatings Black Paint. [23]

Parameter:	Specification:
Maximum temperature: # [°C]	180
Minimum temperature: # [°C]	-180
Number of cycles: #	90
Dwell time: # [min]	Min: 10
Temperature change rate, dT/dt: # [°C/min]	Max: 10
Temperature tolerance: Max temperature: # [°C]	-0 / +10
Temperature tolerance: Min temperature: # [°C]	-10 / +0
Pressure	Ambient
Atmosphere	Nitrogen

Table 8: Specifications for thermal cycling qualification testing of XCoatings Black Paint. [23]

3.6.2 Further Mandatory Qualification Tests for Black Paint

In the previous qualification process mentioned in section 3.6.1, some of the required tests were not conducted since they had been previously carried out. It was determined that the new primer used in section 3.6.1, would not affect certain parameters being tested. In this section, the additional mandatory tests previously performed on Black Paint will be discussed.

RF Loss and Reflectance Testing is vital and needs to be conducted at an early stage when trying out a new paint, to make sure the antenna can receive and transmit undisturbed signals. One way of testing the RF losses and reflectance of a painted Ultem sample would be to place the sample in a wave guide and measure the reflection coefficient, S11, with a network analyzer. To test the losses, the sample is put on the inner side of a shorted plate and compared to measurements with a shorted plate without sample. To test the reflectance, or return loss, the sample is placed in the open waveguide and compared to measurements of the open waveguide, see figure 14.

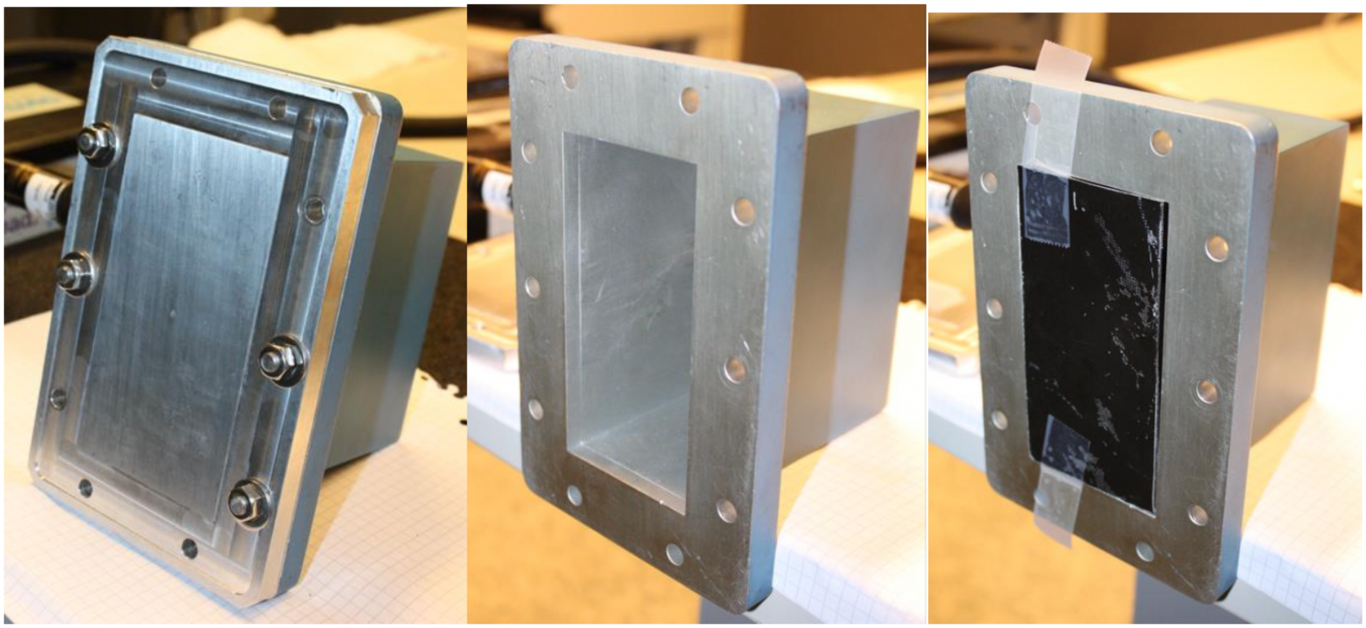

Figure 14: Left: Waveguide with short circuit. A sample could be placed on the inside. Centre: Waveguide with open end. Reference for the reflection measurement. Right: Waveguide with sample in the opening. [27]

Dynamic Mechanical Testing (DMA) is a common method when studying the viscoelastic behavior of polymers or composites. Temperature and applied stress is varied while measuring the strain of the sample. At Beyond Gravity Gothenburg, there exists a unique machine that can combine DMA with Thermal Mechanical Analysis (TMA). A sample is placed in an oven, and the temperature is fluctuated from around -180 °Cto 300 °C. The machine can measure the Coefficient of Thermal Expansion (CTE), the glass Glass Transition Temperature (Tg) and the Elastic Modulus (Young's-Modulus) (E-modulus). DMA was not tested in figure 10 because the new primer mentioned in 3.6.1 was not believed to have an impact on the painted radomes CTE, Tg, and E-modulus. According to previous Black Paint qualifications [28], measurements are carried out with a Perkin-Elmer DMA7e, using three point bending steel holder and rectangular sample symmetry for measuring Tg and mechanical properties, and quartz holder to measure CTE. [25]

Atomic Oxygen Resistance is important when dealing with materials in LEO, and has been mentioned several times throughout this report. In section 2.1 I discuss where AtOx exists, how it is formed and how it affects satellites in LEO. In the beginning of this section, 3.6, I mention how AtOx-testing require specific laboratories and refer to a specific ESA machine that BGS previously has worked with, see figure 9. When it comes to AtOx-resistance testing for paints, BGS and ESA bombarded Black Paint with oxygen atoms with a fluence of $1.8x10^{20}$ to $1.9x10^{20}$ atoms/cm^2 in 2005. The AtOx-tests on Black Paint were successful, as Black Paint showed low degradation from AtOx, according to the results, see list 3.6.2. [29]

- $\Delta\alpha_s = -0.01 \pm 0.01$ (Solar Absorptance Variation)
- $\Delta\epsilon_{IR} = +0.01 \pm 0.01$ (Solar Emission Variation)
- $\Delta e = -0.16 \pm 0.1$ μm (AtOx Etching Depth)

UV-Radiation Resistance is critical for materials in LEO because of the high concentration of UV-rays, as previously mentioned in section 2.1. UV-rays have a short wavelengths and carry enough energy to dissociate molecules, etch components surfaces and even damage components. Rough, etched surfaces can lead to the materials absorbing more heat and radiation, damaging the components. In 2005, BGS sent Black Paint to be tested against UV at French Aerospace Lab (ONERA), that has a system of space environment simulation named *SEMIRAMIS*. The description of the system and irradiation conditions are given in the ONERA report referenced [RTS 2/09067 DESP (December 2004)]. The results were successful and after 3298 ESH the solar absorptance variation was $\Delta\alpha_s = +0.003 \pm 0.010$. [29]

Solar Absorptivity and IR-emissivity should be measured before adhesion and TVC with and without potential primers. Materials solar absorptivity (α_{sol}) and IR-emissivity (ϵ_{IR}) is important in LEO when analyzing how much radiation and heat a material will absorb, contra how much it will emit, and the value is given in the ratio: $\alpha_{sol}/\epsilon_{IR}$. For a passive surface exposed to the sun, with no generated power, the temperature is decided by the $\alpha_{sol}/\epsilon_{IR}$ ratio. A lower ratio equals a lower temperature, and vice versa. Black Paint showed a $\alpha_{sol}/\epsilon_{IR}$ ratio = 1.06 from 0.95/0.90 for the black paint, see table 2. In general, non-metallic materials have a lower ratio than Black Paint, while pure metals have higher ratios, thus reaching higher temperatures. The critical $\alpha_{sol}/\epsilon_{IR}$ ratio depends on the specific product and its requirements. According to previous Black Paint qualifications [28], measurements were carried out at the Swedish National Testing and Research Institute, and the measurements were performed according to ASTM, E 408 (Standard test method for total normal emmitance of surfaces using inspection-meter techniques) and ASTM E 903 (Test method for solar absorptance, reflectance, and transmittance of materials using integrating spheres).

Ultimate Stress Limit or tensile strength is the maximum strength a material can withstand while being elongated or pulled, and can be measured with a tensile test. In a tensile test, one end of a specimen is remained stationary while the opposite end is clamped and pulled, and the applied pulling force is measured.

The specimen is elongated until the specimen fractures, and the ultimate stress limit can be calculated of a stress-strain curve. Satellites are launched into LEO at high speeds, and are subjected to strong vibrations and acceleration forces. Once in LEO, satellites are subjected to intense temperature fluctuations, radiation, and micrometeorites that can cause mechanical stress and deformation on components such as antenna radomes. Therefore, the radome along with the coating, must be able to withstand these stresses and forces, and the minimum tensile strength for BGS antenna radomes is $> 160\ MPa$. [22]

Resistance Between Top Layer and Metal Substrate is necessary to ensure that charged particles are transferred from radome to antenna chassis, see figure 4. As previously discussed in 2.1, there are high concentrations of radiation in LEO, and surface components get charged up. Electrical conductivity between radome and chassis is necessary in order to ground the electric charge. The resistance-measurement should be performed before and after TVC-exposure, and the test success criteria is $R < 10\ M\Omega$ according to previous Black Paint qualifications. [28]

4 Results

In this section, I will showcase the results of this master's thesis. The primary importance of the results revolves around the studies conducted by Enbio, as their products demonstrates the highest potential for meeting the specific requirements of BGS antenna radomes in LEO.

4.1 Enbio Coatings

The following presented results are based on studies done by Enbio prior to my thesis project.

Enbio was the first and only company to reply with saying they might be able to work with us. After a couple of meetings and technical discussions, it was concluded that their products SolarWhite and SolarBlack showed great potential in functioning as a substitute to the current Black Paint solution. During our technical discussions I asked for additional specific material properties that were not stated in Enbio-tables 3 and 4 and they were given separately. However, Enbio could **not** provide values for all material properties, these are listed below 4.1:

- Coefficient of Thermal Expansion, CTE
- Glass Transition Temperature, Tg
- Solar Emissivity Variation (from AtOx-tests), $\Delta\epsilon_{IR}$
- Solar Absorption Variation (from AtOx-tests), $\Delta\alpha_s$
- UV-Radiation Resistance, Exposure During Complete Satellite Lifetime
- Atomic Oxygen Resistance, Total Lifetime Fluence of $1.0x10^{20}$ $atoms/cm^2$
- Radiation Resistance, Mrad, (Although Enbio refers to similar test, figure 15)

Enbio provided us with material values for SolarWhite and SolarBlack that had previously been collected, see tables 3 and 4.

The following table demonstrates a side by side comparison of Black Paint's material properties found in table 2, with SolarWhite and SolarBlack, see table 9.

Property	Unit	Black Paint Requierments	SolarWhite	SolarBlack	Comment
Handling	NA	No specific requirement, Black Paint is sensitive to mechanical touch.	Not sensitive to mechanical touch, according to Enbio	Not sensitive to mechanical touch, according to Enbio	According to Enbio the lacquers are very durable and can be applied to complex geometries. BGS will carry out additional adhesion tests.
REACH Material	NA	REACH compliant	REACH compliant	REACH compliant	Both SolarWhite and SolarBlack are REACH compliant which is good.
Glass transition temperature (Tg)	°C	>190	No tested	Not tested	BGS to carry out tests. However, the lacquers are deemed too have high Tg due to previous missions in high temperature environments such as ESA's SolarOrbiter mission to the Sun.
Outgassing	%	CVCM < 0.1 RML < 1	CVCM: 0.01 RML: 0.03	CVCM: 0.001 RML: 0.03	Good outgassing properties. BGS to carry out additional tests.
Temperature range	°C	-180 < T < 180	-180 < T < 180 (under vacuum)	-180 < T < 700 (under vacuum)	Very stable, suggesting high Tg-temperature points. BGS to carry out additional tests.
Radiation resistance	Mrad	> 2500	Not tested	Not tested	Enbio performed similar test to SolarWhite, but result was presented in different units. BGS to carry out additional tests.
Lifetime in space	NA	Up to 20 years	Not tested	Not tested	BGS to carry out additional tests.
Resistance to solar exposure (UV resistant)	NA	Requirements fulfilled after solar exposure (applicable for complete lifetime)	Almost totally diffuse in UV/Vis/NIR range	Almost totally diffuse in UV/Vis/NIR range	BGS to carry out tests. However, lacquers are deemed too be UV resistant due to previous missions such as on ESA's SolarOrbiter.
Solar absorptivity emissivity ratio, α/ε	NA	≤ 1.06 (applicable for complete lifetime)	0.20	1.23	SolarWhite's ratio is good, SolarBlack is too high and could absorb too much heat. BGS to carry out additional tests.
AtOx fluence	atoms/cm^2	Resist a total lifetime fluence of maximum 1x10^{22}	Silica based lacquer, and most likely resistant	Previous Enbio customer performed tests and determined SolarBlack to be resistant	BGS to carry out additional tests.
Dielectric constant	NA	<~4	Not tested	Not tested	BGS to carry out tests.
Surface resistance (To ensure ESD)	Ω/sq	$1x10^6 \leq R \leq 1x10^9$	$1x10^8$	$< 1x10^3$	SolarWhite is within range, SolarBlack has too low surface resistivity and is therefore too conductive. BGS to carry out additional tests.
Volume resistivity, ρ	MΩm	t*1 < ρ < t*1000 For uniform conducting radome material with thickness t [m]	Not tested	Not tested	Depends on the thickness of the sample, Enbio has performed other tests. BGS to carry out additional tests.
Ultimate limit stress	MPa	> 160	Not tested, but has previously been launched to space with ESA	Not tested, but has previously been launched to space with ESA	Space launches require materials with high stress tolerances and SolarWhite and SolarBlack have previously withstood launches, thus suggesting high stress limit. BGS to carry out tests.
Coefficient of thermal expansion, CTE	x10^{-6}m/m°C	10-30	Not tested	Not tested	BGS to carry out tests. However, the lacquers are deemed too have good CTE due to previous missions in high temperature environments such as ESA's SolarOrbiter mission to the Sun.
Glue ability	NA	Possible to glue to radome aluminum ring if applicable	Applicable to aluminum	Applicable to aluminum	BGS to carry out additional tests.
RF antenna compliance	NA	No effect on RF properties	No effect on RF properties, according to Enbio	Testing by Nokia Labs: No RF losses	Enbio recommends BGS to perform additional tests.

Table 9: Side by side material property comparison of XCoatings Black Paint's with Enbio's SolarWhite and SolarBlack. Black Paint's material properties also act as minimum requirements for surface lacquers on BGS antenna radomes. Red highlighted boxes represent material properties that do not meet the desired requirements, for example Black Paint is sensitive to mechanical touch. Most important material properties include AtOx-resistance, RF-antenna compliance, and surface resistivity. However, each property is important to consider in order for the coating to be efficient in LEO. To conclude, BGS is interested in testing all material properties again, discussed further in section 5.2 and 7.

The following sheet resistivity values were given by Charlie Stallard (R&D manager at Enbio) from previous sheet resistivity (ρ) measurements on SolarWhite:

- $2.9x10^7 < \rho < 4.4x10^9\ \Omega/sq$ (Enbio measurements across a range of potentials)
- $\rho = 5.0x10^8\ \Omega/sq$ (Airbus measurements)
- $\rho = 2.5x10^8\ \Omega/sq$ (The National Centre for Space Studies (CNES) measurements)

In order to test the performance of the coating, p/e irradiation was performed with the aim of delivering the modelled dose. This was done by irradiating coated samples with different particle energy levels. The penetration depth into the material is dependent on material properties such as density. In figure 15 the grey line is the accumulated dose delivery into the material (sum of all energies).

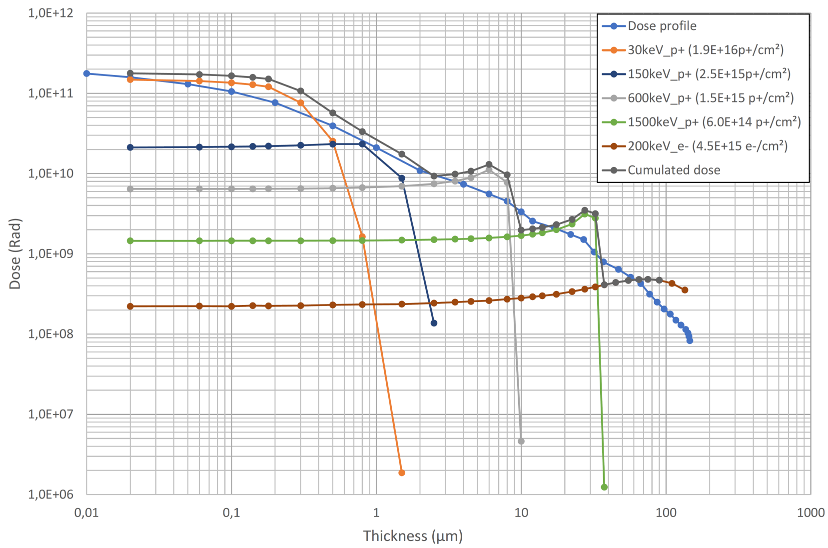

Figure 15: Calculated/modelled proton/electron dose made by Enbio prior to order. The SolarWhite coating exposed during a 18 year Geosynchronous Equatorial Orbit (GEO) telecommunication satellite platform, which also includes a 210 day electronic orbit raising phase. During this orbit raising phase there is a higher dose of proton irradiation. Blue: Modelled dose. Brown: Electron dose. Orange, Violet, Green: Proton dose at various energies, Gray: accumulated dose delivery into the material (sum of all energies) Y-axis is the dose delivery to SolarWhite, and the x-axis is the thickness of the SolarWhite paint. Reproduced from reference [16]

The following irradiation sequences were performed on SolarWhite:

- Accelerated storage ageing (70 % RH and 56 °C for 7 days)
- Followed by TVC (100 cycles between -180 and + 180 °C)
- Followed by p/e irradiation (conditions to match 18 year GEO orbit and 210 days orbit raising phase)
- Followed by UV-radiation (ESH to match 18 year GEO)

After this life cycle sequence the solar absorptance (α_s) increased from 0.15 to 0.39, $\Delta\alpha_s = 0.24$ which was deemed by the primes working with Enbio on the qualification as the most durable of solar reflector coatings tested to date. Thermal emittance (ϵ_{IR}) remained unchanged. [17]

Moreover, have both coatings been flown on the ESA SolarOrbiter which is the most complex laboratory ever sent to the sun. The SolarOrbiter has taken the closest images of the sun as well as the first close-up images of the sun's polar regions.

4.2 Tantalum Peroxide as Metal-Oxide Coating

4.2.1 International Suppliers of Deposition Method

After doing research on the web for companies selling and offering pulsed DC magnetron sputtering techniques I found the Chinese company CY Scientific Instrument providing various deposition techniques, including PDCMS. They quoted 37612 USD for one Direct Current (DC) magnetron sputterer machine. This would acquire BGS the machine, BGS and I would then need to test the technique, buy the material (Tantalum peroxide) and deposit it on the radomes. First when deposition is successful, mechanical, thermal, AtOx and additional tests described in section 3.6 can be performed. After internal discussions with the Chinese supplier CY, I projected the following timeline, see table 10.

Task	Estimated Duration
Ordering and sending of ULTEM-samples to China.	2 Months
Acquiring of target material tantalum peroxide and testing feasibility of the deposition method at Chinese supplier CY's sites.	2 Months
In the scenario of successful testing and deposition - Ordering and delivery of deposition machine.	2 Months
Learning deposition method and machine, and depositing Tantalum peroxide on ULTEM radomes.	3 Months
Mechanical, thermal, AtOx, and additional tests.	3 Months
Unpredicted interferences/delays.	1 Month
Total duration before results.	**13 Months**

Table 10: Estimated time-duration of testing, ordering and acquiring CY's metal-oxide deposition machine's compatibility with tantalum peroxide deposited on BGS Ultem radomes.

4.2.2 Deposition of Tantalum Peroxide in Sweden

After contacting various institutions I found two potential cooperators, the Royal Institute of Technology (KTH) and Linkoping University (LiU). My supervisor at Lund University, Martin Ek, and I had a discussion on possible deposition techniques at LiU with Per Eklund, professor in thin film physics at LiU. Professor Eklund investigated my inquiry and suggested a LiU related start-up that provided magnetron sputtering techniques. The start-up had a particulate set of target materials including: Ti, Al, and Si with metal alloy oxides. The company also offered to order specific target materials Zr and Ta, but at an additional cost of 1900 USD and 6000 USD respectively, and an approximate lead time of 6-8 weeks.

4.3 Prepreg Cyanate Ester as Substitute for Ultem Radome

During our inquiry, Toray Advanced Composites (TAC) stated that they were willing to collaborate on research regarding the performance of their materials in a low orbit environment. Their cyanate esters are their best offering for resistance against aggressive environments, although they have limited resistance to atomic oxygen and radiation. Toray Advanced Composites does not have any data on the atomic oxygen resistance of their cyanate esters. They have extensive flight history with their TAC-materials, specifically composites RS-3, EX1515, EX-1522, and RS-36, being different cyanate esters. While they do not produce or supply atomic oxygen resistant coatings, their end-users have proprietary solutions that work with their materials. Toray Advanced Composites suggests consulting a laboratory to predict the radiation environment for a space program and advises on whether testing would be needed.

In terms of ESD, the sheet resistance of their material depends on the fiber reinforcement. If it is quartz or glass, it will have a very low sheet resistance. Toray Advanced Composites recommends painting the radomes with slightly conductive paints that contain carbon filaments or particles to achieve electrostatic discharge on Earth. Furthermore, the company does not process prepreg into parts but states that their customer base does. Toray Advanced Composites offers materials for structural aircraft radomes with E-glass or quartz reinforcement, and their cyanate esters meet outgassing requirements for space applications. Additionally, TAC suggest that the choice of radome material, also depends on the components structural design.

5 Discussion

In this section, I will analyze the outcomes presented in Section 4, with a particular focus on the results obtained from Enbio, which demonstrated the most promising findings. Furthermore, I will discuss the reasons for not pursuing further research on the other solutions and what can be done in the future.

5.1 XCoating's Black Paint

As Black Paint already is operational at BGS, I explored ways on how to improve the paint in terms of, lead time, cost, and mechanical sensitivity. My initial vision was to contact the supplier of Black Paint, XCoating, and ask them about the possibility of improving their recipe of Black Paint in order to achieve a better adhesion coefficient. After conversations with Material Scientists at XCoating we came to the conclusion that it is not possible to improve the mechanical strength of XCoating's Black Paint. Changing the Black Paint formula or adding an additional additive layer will change the composition and configuration of the original ESA-standard, qualified paint. Thus requiring costly, up to date qualifications that XCoating is disinclined to do.

As a result of my discussions with XCoating, I spoke internally with Material Scientists at Beyond Gravity's Zurich office. Beyond Gravity Zurich have a workshop where they manually apply coating paints, some of which are from XCoating's. My idea was to try to reduce lead times and costs by applying the paint internally at the company, consequently avoiding sending radomes to the external supplier. However, it was concluded that none of the paints applied in Zurich contain silicone. The reason being that silicone-based paints can be very volatile and spread to other parts of the production facility. The volatile components can deposit and act as a lubricant or release agents, which can negatively affect bonding processes within the facility. Therefore, all silicone paints are strictly forbidden in the production facility in Zurich. Consequently, sending a silicone based Black Paint to our Zurich offices was out of the question, and my investigation on improving Black Paint logistics was discontinued.

5.2 Enbio

The results in 4.1 and theory sections 3.3.2 indicate that Enbio's SolarWhite shows great potential to substitute the current Black Paint as a surface paint on BGS antenna radomes. SolarBlack is also of interest to BGS, but likely not for antenna radomes. There are many similarities when comparing SolarWhite and SolarBlack material parameters with Black Paint in table 9, and this is also the reason for my progression with the Enbio paints. Furthermore, the price point of buying and applying SolarWhite and SolarBlack is significantly less in comparison with Black Paint. Additionally, Black Paint has a curing time of 4 weeks before ageing tests should be performed, and according to Enbio the drying and curing time for SolarWhite is approximately 24 hours, which would save BGS valuable time. [19]

SolarWhite and SolarBlack show excellent resistance to thermal fluctuation in high and low temperatures, low outgassing values, great mechanical resistance and adhesion properties, no interference with RF-properties, applicability to aluminum, and are REACH-compliant. Additionally, SolarWhite also shows great solar absorption and emission ratio, and anti-static surface resistivity properties. Moreover, although no data has been shared on AtOx-resistance, UV- and radiation-resistance, CTE, or Tg, the paints are thought to be stable in LEO, which will be further discussed.

Table 9 and list 4.1 present the material properties that have not undergone testing to the BGS-standard, resulting in several unknown properties for SolarWhite and SolarBlack, as outlined in list 4.1. However, considering Enbio's previous flight history and cooperation with ESA, as well as discussions with Enbio, the unknown material properties listed in 4.1 have a high likelihood of being within BGS-surface paint requirements. Nevertheless, BGS will perform multiple tests as well as visual inspections to analyze the new radome-configuration's material properties, and response to mechanical, electrical and thermal tests.

RF-Properties According to SolarWhite's material property table 3, the coating is RF-antenna compliant and have no effect on RF-properties. Enbio communicated the Previous testing by Nokia Bell Labs indicated no RF-losses, but no testing parameters were shared. As there is limited information available on the testing methodology used, BGS intends to carry out further RF-tests to ensure that the SolarWhite and SolarBlack do not cause any disruption to the RF-properties. Moreover, there is no data available on the dielectric constant, and capacitance tests should be conducted to ensure that the new radome configurations have a dielectric constant of less than 4, as specified in the desired material properties table 2.

Atomic Oxygen Resistance Enbio communicated that a previous customer (Nokia Labs) had done AtOx-tests to SolarBlack and deemed the paint to be resistant, however the results were trade secreted and could not be shared. SolarWhite is also deemed to be AtOx-resistant as SolarWhite is a silicate based material. Nevertheless, BGS will still conduct additional AtOx-tests to test specific material properties before and after AtOx-exposure, for example: solar emissivity variation $\Delta\epsilon_{IR}$ and solar absorption variation, $\Delta\alpha_s$. As there are limited facilities with high concentration AtOx-environments, BGS will likely need to collaborate with an external organisation such as ESTEC to test these parameters. Considering that both paints have been flown on the ESA SolarOrbiter, it is safe to assume that ESA has tested the paints against AtOx before. Provided that the results of the previous AtOx-tests are shared, it is possible that further costly testing may not be necessary.

UV- and Radiation-Resistance Thermo-optical properties of SolarWhite remained unchanged for all proton/electron irradiation previously tested by Enbio, figure 15. BGS radiation requirements are > 2500 Mrad and Enbio exposed SolarWhite to high dosages of radiation as can be seen in figure 15, however it is unclear if the results from the graph meet BGS requirements, therefore additional tests need to be performed to ensure the paints are UV- and radiation-resistant. Previously, as described in section 3.6, Black Paint was tested at ONERA where the paint was exposed to 3298 ESH, which could be a relevant testing facility and method for SolarWhite and SolarBlack.

CTE and Tg Enbio communicated that the CTE and Tg values of SolarWhite and SolarBlack had not been directly measured. However, Enbio stated that the theoretical CTE value of SolarWhite was calculated to be approximately $10.4x10^{-6}\ m/mK$, which is within the requirements of BGS antenna radomes. Both CTE and Tg are important thermal material constants when dealing with components in high temperature fluctuated environments such as LEO and space. As previously mentioned, SolarWhite and SolarBlack have both been flown in space, including on ESA's solar orbiter to the Sun, exposing the paints to several thousand degrees °C. Therefore, considering the paints history, SolarWhite and SolarBlack should meet BGS antenna radomes CTE and Tg requirements. BGS will nevertheless conduct DMA-tests to get precise values of CTE and Tg, as well as ageing TVC-tests to deduct the lifetime of the paint in LEO-environments.

Surface Resistivity and ESD The surface resistivity of SolarWhite varies depending on the specific solution, environment and testing probe. Enbio shared three different measurements made by three different companies. All three surface resistivity values were within BGS antenna radome requirements with a mean value of approximately $\rho = 1.0x10^8\ \Omega/sq$, ensuring enough conductivity to prevent ESD. Furthermore, SolarWhite and SolarBlack are applicable on Aluminium and have previously been applied to Aluminum Association (AA) 2000s, 5000s, 6000s, and 7000s, perhaps ensuring applicability to Beyond Gravity's antenna chassis (see figure 4) to prevent ESD from the radome to chassis through the coating. BGS is still required to conduct additional resistivity tests, to investigate the practicality and method of applying the paints to the radome and chassis. Additionally, it is important to perform mechanical tests such as tensile tests to ensure the new radome-configuration does not fall below the ultimate stress limit of 160 MPa.

Outgassing Both SolarWhite and SolarBlack have low outgassing values, with both coatings having a Recoverable Mass Loss (RML) = 0.03. RML is the same as TML but without the absorbed water, as water is not always seen as a critical contaminator. Furthermore, the CVCM of SolarWhite was at a tenth of the maximum required percentage at CVCM = 0.01%, and SolarBlack was at a hundredth of the maximum required percentage at CVCM = 0.001%. These results suggest that SolarWhite and SolarBlack will not evaporate and condense volatile particles on other important satellite electronics and components in the near vacuum of LEO but BGS will conduct additional outgassing tests.

SolarBlack Inadequate Material Parameters The SolarBlack parameters can be seen in table 4, and the surface resistivity is very low ($\rho = 1.0x10^3\ \Omega/sq$), which could lead to interference with radio waves and RF-losses. Furthermore, the absorption and emissivity ratio (α/ϵ) of the paint is also too high at $\alpha/\epsilon = 1.26$, which could lead to high surface temperatures. For these reasons, SolarBlack is likely not a good coating for BGS-applications, but the paint is still of interest to BGS for testing adhesion with the PEI-radome. Moreover, the absorption and emissivity ratio also depends on the applied substrate, and the values in table 4 are given from applying SolarBlack on a metallic substrate. As mentioned in the theory section, Beyond Gravity's radome is made out of a PEI, which could mean that the the absorption and emissivity ratio being slightly lower than the theoretical value of $\alpha/\epsilon = 1.26$ which is worth testing.

To conclude, the potential benefits of using Enbio's SolarWhite coating for BGS antenna radomes are interesting. Not only does SolarWhite have similar material properties to the current radome surface paint, Black Paint, it also offers a number of advantages such as cost-effectiveness, faster curing times, better adhesion to radome, and easier handling and application. While further mechanical, electrical and material testing is required to ensure that SolarWhite meets all necessary qualifications, the new paint has the potential to provide a better solution for protecting BGS antenna radomes against harsh LEO environments, including AtOx and UV, while maintaining the critical transmission of radio waves without losses.

Moreover, it is important to note that due to the short time-frame of this master's thesis project, I was not able to complete the testing for SolarWhite. Therefore, necessary verification testing remains before considering SolarWhite for use in space. In section 6, I describe a methodology for future verification tests, drawing inspiration from the previous Black Paint verification tests mentioned in section 3 and older Black Paint qualifications. These tests will be essential for verifying whether SolarWhite meets all the necessary qualifications for BGS antenna radomes in LEO.

5.3 Metal-Oxide Coatings

In theory, deposition of metal-oxide coatings on satellite components used for LEO has proven to be efficient, reliable and potentially a good candidate for protecting BGS radomes. However, further testing and investigation needs to be done in order to make any final conclusions. The Ultem radome needs to be compatible with the deposition machine and technique. We know from the theory section 3 that the technique PDCMS is compatible with temperature sensitive materials such as Ultem, but we do not yet know if the dimensions of the radomes are compatible with the technique. This depends on the specific PDCMS provider and their specific machine. The price and lead times will also vary accordingly, all which is of relevance for Beyond Gravity. It is worth mentioning that traditional sputtering machines commonly are used to deposit on flat surfaces, and not cone-shaped (such as Ultem radomes). A solution to work around this problem could be to deposit the metal oxides before shaping the Ultem into the radome cone shape, but oxides are brittle and this needs further investigation.

One supplier that provide an interesting PDCMS-machine is the supplier CY located in China. The company was discovered from online research and I conducted two online meetings with their technical department. After gathering more information on the specifics of the machine and their technique, I proceeded to finding out more about the price and time it would take to follow through with this supplier. In section 4.2.1 the results are presented on this relatively short study. As can be seen in table 10 the projected timeline of 13 months, is too long for the scope of my thesis project. Although it is worth mentioning that material-testing could be initiated after the third task. However, the projected time before completing the third task in table 10 would still be approximately 6 months, which would enable us to start performing tests in August of 2023, 2 months after my thesis project is due (June 2023). Furthermore, the price of 37612 USD/machine, along with the long lead/preparation time presented in table 10, resulted in me not advancing with this specific supplier and method.

In section 4.2.2 I presented the possibilities of depositing Tantalum peroxide in Sweden. Different universities across Sweden offer a range of deposition methods, and finding an institution willing to collaborate with us was challenging due to our specific requirements. However, LiU and KTH offered interesting services of magnetron sputtering deposition methods. After discussion with researchers at KTH, I discovered that KTH offers a range of different sputtering deposition methods and machines, where the best match was the *AJA 3 Sputter Albanova* machine. Further discussions with professor in Nanostructure Physics and Director at the Albanova Nanolab, Vladislav Korenivski, concluded that the process could be possible with available Tantalum target material. However, professor Korenivski highlighted the challenges of achieving a crystalline crystal structure. Normally this is achieved with high temperature annealing at 400-600 °C, but as the composite material is temperature sensitive, annealing is inconceivable. Therefore, the material properties of the deposited metal-oxide could not be guaranteed without extensive testing and research extending beyond my thesis project timeline. However, it's worth mentioning that professor Korenivski extended his interest in collaborating on a longer project, developing and optimizing the process. [20]

Per Eklund from LiU has years of experience working and teaching thin film physics, he is also working on a LiU related start-up, focusing on magnetron sputtering techniques. My mentor Martin Ek, Per Eklund and myself conducted several email conversations and a meeting, discussing the possibility of using Eklund's facilities to deposit a metal-oxide film on BGS antenna radomes. Professor Eklund investigated the price of acquiring Zr, and Ta-target material and unfortunately the materials where too expensive for this thesis project. The pricing of 1900 USD for Zr-target was more reasonable than the 6000 USD Ta-target material, but still beyond BGS price range. Therefore, professor Eklund suggested alternative target materials: TiO_2, SiO_2, SiON,and Al_2O_3. After further internal discussions at BGS on testing the mentioned target materials, it was decided not to progress with this method due to the additional reacquired research on the specific materials and no guarantee of feasibility, and demand of progressing with a method, namely the results described in section 4.1. [21]

5.4 Discussion on Prepreg Cyanate Ester Results

While the results of this study were promising, it is important to note that the addition of a coating or protective layer is necessary for optimal performance in space environments whilst using Toray's materials. This is in line with industry standards, and TAC more specifically recommends the use of protective coatings such as conductive silicone based paints such as Black Paint.

In conclusion, the collaboration with TAC has shown that the use of bare composites in LEO environments is limited due to the effects of AtOx and radiation. While the addition of coatings can improve resistance to these environmental factors, it may not be the optimal solution for Beyond Gravity's needs, as we already have a coating solution, XCoating's Black Paint. Therefore, further research is needed to develop a composite radome with both AtOx and radiation resistance properties, which is further discussed in section 5.5. However, due to the limited time frame of this master's thesis project, I needed to prioritize other solutions for solving the specific challenges related to the design of our antenna system. The collaboration with TAC has shown great potential for future research in this area, and Beyond Gravity remains interested in continuing research on composites in LEO.

5.5 Carbon Nano Tubes Infused in Composite Glass Weave Matrix

The RISE study on additive manufacturing of radome parts for BGS antenna radomes has highlighted the potential as well as the challenges of using composite materials, without the use of external coating paints. The RISE screening revealed that there are limited options of materials that can be used, and there are also limitations on the size of the parts that can be 3D-printed. Fiber composite printing technology has excellent mechanical properties, but is still in the early stages of development and not yet suitable for industrial use.

RISE also investigated the BGS composite Ultem design, and it was concluded that the current BGS-issues with Black Paint coating adhesion could potentially be addressed by mechanically integrating the outer layer into the bulk layers in the laminate glass weave design. The conductivity could be provided by the CNT additive, and the AtOx protection by the glass weave. An alternative that RISE mentioned in their report is an outer carbon-filled silicone resin impregnated in an outer surface layer of glass weave.

During the study, samples of Ultem were printed and filled with CNT, while others were reinforced with 30 wt% glass. These materials were combined by 3D-printing a thin layer of CNT-Ultem on top of the glass fiber Ultem sample, and their reflectivity was measured. The results were promising, but the combined sample would not provide sufficient AtOx protection due to the lack of glass fiber in the outer coating layer. Therefore, a potential solution would require the compounding of 30 wt% glass fiber into the CNT-layer in order to improve AtOx resistance.

The strength of the composite material used for radome parts is heavily dependent on the type of fiber used, and the matrix strength being negligible in comparison. Adding CNT or carbon black to the resin can increase adhesion and prevent ESD while the glass fiber weave protects against AtOx degradation and maintaining mechanical strength. Verification testing needs to be performed in order to determine the right combination and structure of carbon black/CNT for the right viscosity, conductivity and AtOx resistance. Ultem (PEI-CNT) was within an acceptable range for resistivity, and RISE estimated 40-45 wt% CNT to be a reasonable level to prevent ESD.

In conclusion, while the study has shown that there are promising directions for the development of additive manufacturing of composite materials, there are also challenges to overcome. The limitations of current printing technology and AtOx resistance are just a few of the issues that need to be addressed. The study underscores the importance of continued research and development in this area to meet the needs of BGS. [27]

5.6 Innovative Approaches to Addressing the Problems of Beyond Gravity's Current Solution

As previously mentioned in the Theory section 3, the production of radomes is time consuming and the surface paint Black Paint is sensitive to mechanical touch and is too easily scratched off. Resulting in the paint needing re-work, which greatly adds to the overall costs and lead time. For these reasons, Beyond Gravity wants to see an improvement, and this problem can be tackled from many different directions. One potential solution that Beyond Gravity consulted RISE on prior to my thesis, was using additive manufacturing technology of composite materials to achieve shorter manufacturing times, flexibility, and sufficient material properties in order to eliminate the need of a surface paint or coating. Beyond this approach I explored the options of: PDCMS deposition of Metal-Oxide coatings such as Ta_2O_5 and AZO, improving adhesion of the current Black Paint solution, new composite radome materials such as Cyanate Ester Matrices with Glass Fiber Reinforcement, and other anti-static AtOx resistant paints such as SolarWhite from Enbio. I considered Enbio's coating solutions to have the highest probability of success. As a result, I directed more attention towards their solutions, resulting in a more detailed analysis and discussion. Additionally, we ordered Ultem test samples, that we later shipped to Enbio's offices in Ireland for coating and preparation in readiness for the verification testing phase.

Although the current solution that Beyond Gravity uses with XCoating's Black Paint has flaws, the surface paint is efficient when in orbit. For this reason, Black Paint's properties sets a good set-point for which requirements and material properties need to be met, see table 2. Therefore, it is important that the alternative solution that this thesis proposes meets all material requirements, but also reduces costs and improves efficiency, in order to be beneficial for Beyond Gravity.

6 Future Work

This section marks out the future work that needs to be conducted in order to evaluate Enbio's coatings SolarWhite and SolarBlack. The various verification testing methods outlined in table 11 have previously been summarized and described in section 3.6. The verification testing methods are divided into local tests that can be performed at BGS premises and external tests that need to be sent externally for testing. Figure 16 demonstrates a flow chart outlining the sequential order of which the verification tests for a sample specimen should be conducted, inspired by previous qualification done by BGS [28]. When testing the coatings against AtOx- and UV-exposure, additional samples to the ones in the flow chart in figure 16 are necessary.

In addition to the mentioned verification testing and order of testing, it might be beneficial and educational to test different types of sample specimens to find the best configuration of radome, primer and coating. This includes examining different radome materials and thicknesses, exploring primer options, and evaluating varied coating thicknesses.

Local Test that can be performed at Beyond Gravity Sweden premises					
Verification Testing Method	**Material Parameter**	**When to be Performed**	**Location**	**Comment 1**	**Comment 2**
Visual Inspection	Appearance, flaws, cracks, blisters & contaminations	The samples should be inspected prior and after any thermal cycling and thermal vacuum cycling.	Beyond Gravity		
Adhesion Testing: Cross Cut Tape	Adhesion to sample	Suggestion: Prior and after any thermal cycling and thermal vacuum cycling, see flow chart.	Beyond Gravity	"Cross cut tape" tests is one example of an adhesion test.	Suggestion to perform according to: International Organization for Standardization (ISO) [EN ISO 2409, Paint and varnishes – Cross-cut test] with tape M No.92
Surface Resistivity Probe	Surface resistance (ρ)	Suggestion: Early stage as well as after handling and thermal cycling, see flow chart.	Beyond Gravity	Suggestion: Perform according to [ASTM D 257, Standard Test Methods for DC Resistance or Conductance of Insulating Materials]	
Humidity Test	Relative Humidity (RH)	No Specification.	Beyond Gravity	Suggestion: 40 °C and 93% Relative Humidity (RH) for a period of 240 hours.	
Thermal Vacuum Cycling (TVC)	Thermal resistance and exposure to similar LEO enviornments	In between various tests, see flow chart.	Beyond Gravity	Number of cycles and temperature ranges depend on specific project. Ramping up with approximately 10 °C/min and holding each temperature for at least 15 min at a time.	Suggestion 1: 10 cycles from -145 °C to +140 °C Suggestion 2: 100 cycles from -180 °C to +180 °C
Radio Frequency-Loss and Reflectance Testing	RF-losses and reflectance	In between various tests, see flow chart.	Beyond Gravity	Vital to test at an early stage when testing new paints/coatings.	Test substrate with and without coating.
Dynamic Mechanical Analysis (DMA)	Glass Transition Temperature (Tg), Coefficient of Thermal Expansion (CTE), and Elastic Modulus (E)	After visual inspection, depends on method.	Beyond Gravity	Previously done according to [Beyond Gravity document: D-P-REP-01301-SE, Mechanical properties of white paint SG121FD and primer PS]	At Beyond Gravity, flat samples can be tested, not cone shaped radomes.
Tensile Test	Ultimate Tensile Strength, (σ)	No Specification.	Beyond Gravity	Depends on sample size and dimension.	At Beyond Gravity, flat samples can be tested, not cone shaped radomes.
Resistance Between Top Layer and Metal Substrate	Resistivity between chassis and radome (R)	Before and after TVC-exposure	Beyond Gravity		
External Tests outside Beyond Gravity Sweden premises					
Verification Testing Method	**Material Parameter**	**When to be Performed**	**Location**	**Comment 1**	**Comment 2**
Outgassing Test	Outgassing constants: TML, RML and CVCM	Perform at early stages to get maximized outcome.	Suggestion: National Institute of Aerospace Technology (INTA) in Spain	Suggestion: Perform according to: European Cooperation for Space Standardization (ECSS) [ECSS-Q-70-02, Thermal vacuum outgassing test for the screening of space materials]	
Atomic Oxygen Exposure	Resistance to Atomic Oxygen fluence	Separate testing specimens (Supplementary to flow charts)	Suggestion: ESA ESTEC	Complex test that requires special facilities, ESTEC is one suggestion.	
UV-Radiation Exposure	Resistance to UV-radiation.	Separate testing specimens (Supplementary to flow charts)	Suggestion: French Aerospace Lab (ONERA)	The description of the system and irradiation conditions done to Black Paint are given in the ONERA report referenced [RTS 2/09067 DESP (December 2004)]	
Solar Absorptivity Test	Absorption and Emission coefficients.	See flow chart	Swedish National Testing and Research Institute	Swedish National Testing and Research Institute, and the measurements were performed according to American Society for Testing and Materials (ASTM) [ASTM E 408, Standard test method for total normal emmitance of surfaces using inspection-meter techniques] and [ASTM E 903, Test method for solar absorptance, reflectance, and transmittance of materials using integrating spheres	

Table 11: Table marking out the relevant testing methods when determining the various material parameters of Enbio's coatings SolarWhite and SolarBlack. By conducting each verification testing method listed in the rows, all material properties relevant to BGS antenna radomes in LEO can be obtained. The verification methods listed in the orange section have all previously been conducted at BGS on other materials and coatings. The table has separated the tests into tests that can be performed at BGS premises as well as tests that are available at external sites. The table also suggests when and where to perform the tests, based on previous Black Paint qualifications made by BGS.

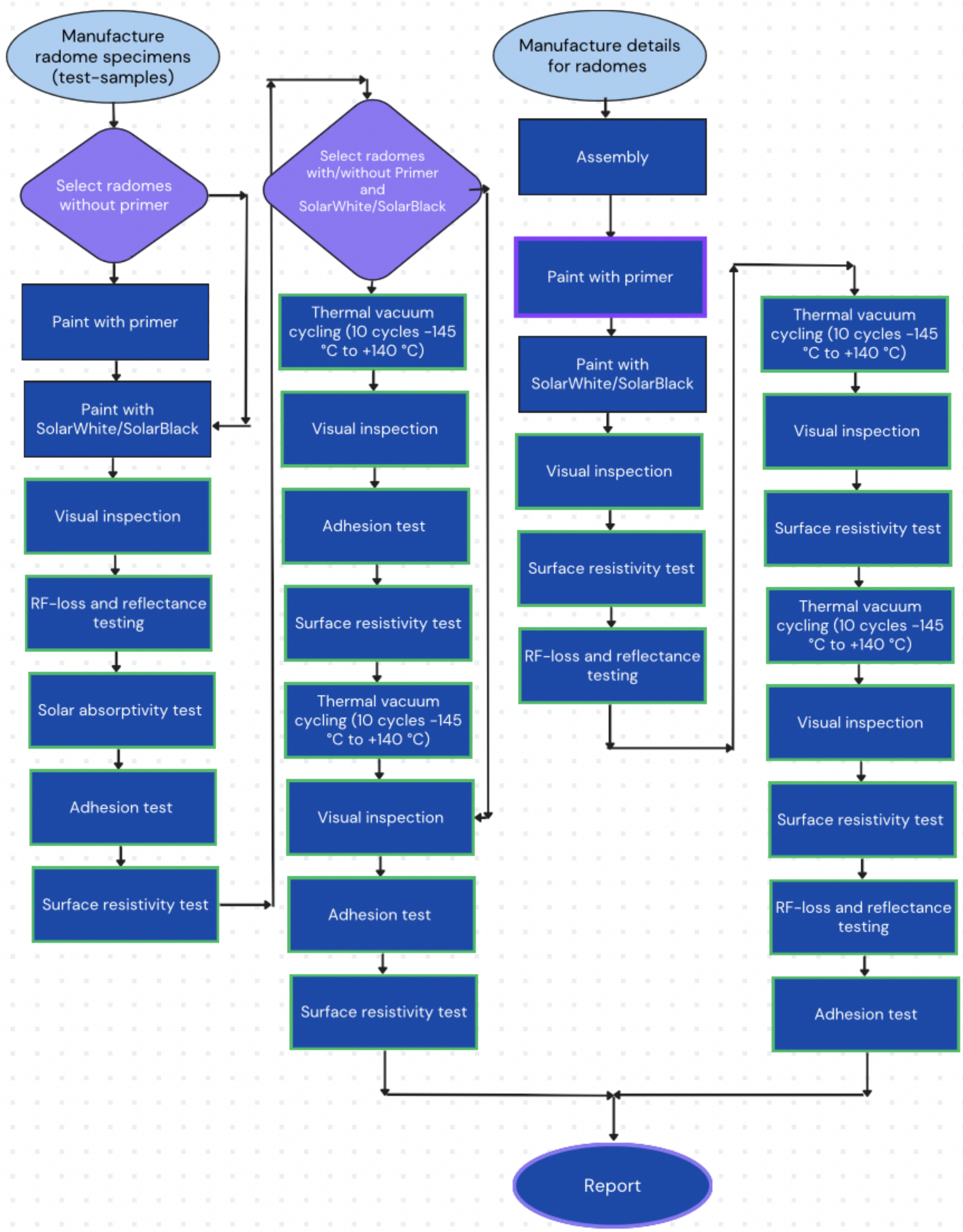

Figure 16: Flow chart demonstrating the sequential order of which the radome samples should be manufactured, painted with primers, painted with SolarWhite/SolarBlack, inspected and tested. The flow chart demonstrates 2 flows, 1 with flat test-samples and 1 with detailed, assembled radomes. The verification tests described in section 3.6 and table 11 are highlighted in green. The flow chart is inspired by previous Black Paint qualification [28]. Additional samples are required for testing AtOx-exposure and UV-exposure respectively, and these tests are supplementary to the flow chart.

7 Conclusion

In conclusion, in this master's thesis I have explored the challenges faced by BGS in the materials used for their antenna radomes in LEO. The current solution of using XCoating's Black Paint as a surface coating to protect against AtOx and prevent ESD, has limitations that result in high costs and long lead times. This master's thesis has proposed several alternative solutions to address the challenges of materials in LEO, including Enbio's SolarWhite and SolarBlack coatings, PDCMS of metal-oxide coatings, and new composite materials for the antenna radomes. Among these alternatives, Enbio's coating SolarWhite has shown the greatest potential to substitute the current solution due to their similar material parameters, lower cost, shorter curing time, and enhanced resilience against mechanical contact. However, further testing and analysis is required to verify the effectiveness.

Overall, the proposed solution has the potential to improve lead times, and reduce the costs of LEO antenna radome manufacturing for BGS while meeting the material requirements. The desired material properties presented in tables 2 and 9 allow for a clear comparison between Black Paint and SolarWhite, and the discussion in section 5.2 evaluates the effectiveness of SolarWhite in the harsh environment of LEO. Additionally, the descriptive future work section 6 outlines the essential verification testing and order of testing that needs to be conducted to evaluate the material properties of Enbio's coatings on BGS antenna radomes.

As the demand for LEO communication continues to grow and more satellites are being launched, it is essential for companies like BGS to explore new and innovative approaches to manufacture components such as protective antenna radomes. This master's thesis contributes to this venture by identifying alternative solutions and proposing a future way of continuing the research. It is awaited that this research will encourage further examination and development of these alternative solutions and help advance the state-of-the-art components in LEO such as antenna radomes.

8 Bibliography

References

[1] European Space Agency, Enabling & Support, ESA–L. Boldt-Christmas, 02/03/2020, LINK

[2] Pellicori. S. The Effects of Space on Coatings & Optical Materials. Coating Materials News & More. Vol 31 Issue 4. November 2021

[3] Pellicori. S. Development and testing of coatings for orbital space radiation environments. Applied optics. Vol. 53, No 4. February 2014

[4] Vac Coat. Pulsed DC Magnetron Sputtering. VAC COAT. March 12th, 2022.

[5] C. Huang. Advances in atomic oxygen resistant polyimide composite films. Elsevier. Composites Part A 168. January, 2023. LINK

[6] XCoating. XCoating BlackPaint. Anti-Static Silicone Coating Low Outgassing. April 4th, 2022.

[7] Woodford. C. Anti-static products and coatings. Explain That Stuff. (2009/2020). LINK

[8] Polytech, Industrial Inc. Ultem 2300 (30% Glass Filled Polyetherimide). Jan, 2011. LINK

[9] Stallard. C. Enbio Data Sheets. SolarWhite. INORGANIC HIGH TEMPERATURE BLACK COATING. Anti-Reflective Coatings. Mars 1st, 2023.

[10] Stallard. C Enbio Data Sheets. SolarBlack. INORGANIC HIGH TEMPERATURE BLACK COATING. Thermal Control. Mars 1st, 2023.

[11] European Space Agency. Atomic Oxygen Erosion. May 29th, 2017. LINK

[12] Tighe. A. European Space Agency. LEOX MACHINE FOR GENERATING ATOMIC OXYGEN. Jun 24th, 2016. LINK

[13] Niehoff. B. Samtec. What is Outgassing and How is it Tested. April 1st, 2020

[14] Image: LINK

[15] European Space Agency, TTC and PDT Systems and Techniques section, Radio Frequency Systems. 2022.

[16] Stallard, C. (2023) charlie.stallard@enbiomaterials.com. E-mail to Mathias Gren. 14th of March

[17] Stallard, C. (2023) charlie.stallard@enbiomaterials.com. E-mail to Mathias Gren. 21st of March

[18] Stallard, C. (2023) charlie.stallard@enbiomaterials.com. E-mail to Mathias Gren. 1st of March

[19] Stallard, C. (2023) charlie.stallard@enbiomaterials.com. E-mail to Mathias Gren. 3rd of May

[20] Korenivski, V. (2023) vk@kth.se. E-mail to Mathias Gren. 23rd of February.

[21] Eklund, P. (2023) Per.Eklund@liu.se. E-mail to Mathias Gren. 1st of March.

[22] Vellinge A. Fractory.com. Ultimate Tensile Strength. Aug 1oth, 2020

[23] Beyond Gravity Classified Internal Documents. U-MTRL-REP-1316625-RSE

[24] S-QSTD-MPRC-03503-SE, Routines for Outgassing-test of Materials and Mechanical Parts

[25] Beyond Gravity Classified Internal Documents. D-P-REP-01301-SE, Mechanical properties of white paint SG121FD and primer PS

[26] Beyond Gravity Classified Internal Documents. Jonas Leijon. Environmental Test. RUAG Space AB. Gothenburg Sweden. 2021-10-20

[27] Beyond Gravity Classified Internal Documents. Hedlund. E. Trey. S. RISE. Material screening, feasibility study of 3D printing, and laminate fabrication for radomes for LEO and MEO applications. October 24th, 2022. Reference O100106-172913

[28] Beyond Gravity Classified Internal Documents. S-ASTD-NOT-00016-SE. Plan for verification of the Black Paint. 2006-11-15.

[29] Beyond Gravity Classified Internal Documents. QUALIFICATION REPORT OF Black Paint ANTI-STATIC BLACK SILICONE NEW PAINT XCoating REF: DCT/TV/TH/NT04-822. (Results from ESA report, referenced 4136 dated 10/03/2005)