IN-SITU VIS/NIR MEASUREMENTS OF SPACE ENVIRONMENT EFFECTS ON SPACECRAFT SURFACES

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ABTRACT

Laboratory material characterization experiments have shown that passive observational techniques that measure the spectral energy distribution of reflected sunlight from spacecraft and space debris could potentially be used to determine an object's surface compositional make-up and even possibly its orientation. Such techniques, if proven to be reliable and consistent, would represent non-intrusive and cost effective tools that would benefit the overall space situational awareness (SSA) mission. However, to date, observations using either colour photometry or spectrophotometry to determine surface material characteristics of such objects have not produced encouraging results. One common problem that has plagued these attempts is the lack of understanding on how the spectral reflectance of the spacecraft surfaces evolves with time. There are a number of spacecraft materials whose spectral reflectance characteristics have been studied before and after spaceflight in LEO; there are no measurements on how the space environment gradually modifies the spectral scattering characteristics of these materials as a function of time. Furthermore, there are little or no in-situ observations of environmental effects on individually identifiable materials in MEO and GEO. This complicates the task of interpreting the spectral measurements of spatially unresolved spacecraft and orbital debris. This paper presents instrument concepts whose sole purpose will be to acquire on-orbit spectral reflectance measurements, at different observational geometries, of either witness samples or materials covering the surface of the host spacecraft. Such instruments could be flown as a hosted payload on an operational GEO satellite or as a dedicated payload on a microsatellite. Measurements would be acquired over the lifetime of the satellite and would observe how the spectral reflectance characteristics evolve during its lifetime. Furthermore, installation of one of the proposed instruments on multiple satellites would provide an opportunity to study the variation in space environment effects on the surfaces of spacecraft located in different orbital regimes, such as LEO, MEO, and GEO.

1. INTRODUCTION

The exterior surface of satellites mostly consists of wide variety of materials whose wavelength-dependent reflective properties are used to optimize the amount of solar energy that can either be absorbed or reflected. For example, solar cells are designed to absorb as much solar energy as possible to supply power to the spacecraft while other materials such as surfaces coated with white paints or silver or aluminum-backed Teflon are employed to achieve the opposite [1].A commonality to all materials found on the surfaces of a spacecraft or a launch vehicle is that they all contribute in reflecting sunlight from the spacecraft which can be used to track or characterize that object. Over time as the life of the space object progresses, the reflective characteristics of these surface materials will change due to exposure to the space environment and, as a result, the amount of sunlight that is reflected will also change.

Information providing insight as to how surface reflective properties of materials exposed to the space environment degrade as a function of time has been obtained using two methods. The first method that has been used is to use ground-based telescope to conduct photometric or spectrometric measurements of the spacecraft once it has arrived in orbit. An example of this approach is the colour photometric surveys of GPS satellites performed by Fliegel et al. [2]. These experiment showed that the intrinsic brightness of the satellites diminished with time on orbit and that the satellites appeared much redder than when measured before launch. Unfortunately, surveys conducted with ground-based telescopes must compete with telescope time as well as limitation of weather limiting observaiton to irregular periods that may not accurately measure how the reflective properties of an observed spacecraft evolve over time. Moreover, objects in Earth-orbit appear as unresolved points meaning that the degradation of invidual material types can't be studied.

The second method of studying how the surface reflectance of materials varies as a function of time spent in orbit consists in measuring the optical properties of the material in a laboratory before, sending the sample material in space, retrieving it and then measuring its properties again. NASA's Long Duration Exposure Facility (LDEF) experiment is an example of this method [3]. For this experiment, a spacecraft, covered with a number of various material samples commonly found on satellites, was launched in low-Earth orbit (LEO) in 1984 and retrieved 5 years and 10 months later. This experiment showed quite effectively the dramatic effects to various materials when directly exposed to the space environment. More recently, NASA's Materials International Space Station Experiment (MISSE) also showed how the effects degrade the surface properties material by measuring their surface characteristics before and after flight.

A variation of this method is to simulate the space environment instead of placing the sample in Earth-orbit. Bédard et al. [5] performed such an experiment in which they measured the spectral reflectance characteristics of set of sample consisting of the same material but having different surface roughness. The basic assumption for this experiment was thtat the effect of prolongued exposure to the space environment would increase the surface roughness of materials. One of the notable results shown during this experiment was that materials with the larger surface roughness exhibited different reflective properties than the same material with smaller surface roughness. As shown in Fig. 1, materials with larger surface roughness exhibited spectral reflectance that appeared redder compared to the same material but with smaller surface roughness. In all, the limitations of the work conducted by Bédard et al. are the same as those discussed above, namely that there is no data on the changes to the spectral reflectance properties of the material evolve over time. Hence this requires a new approach in answering this question.

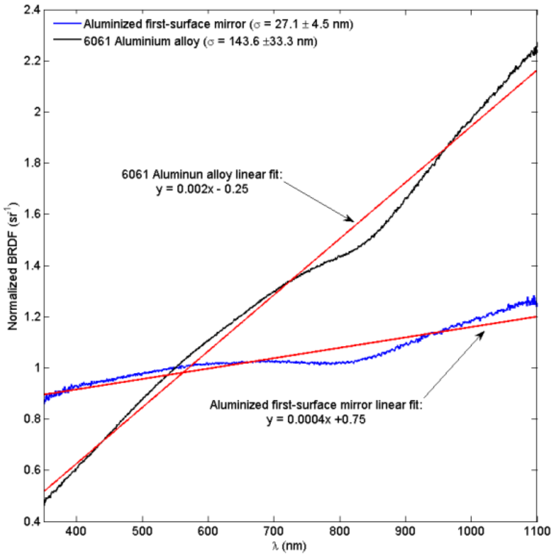

Fig. 1. Spectral BRDF of two aluminum surfaces, normalized to unity at 550 nm, taken at $\theta_i = 30^o$, $\theta_r = 30^o$.

1.2 This work

In this paper we present instrument concepts whose sole purpose will be to acquire on-orbit spectral reflectance measurements, at different observational geometries, of either witness samples or materials covering the surface of the host spacecraft. Such instruments could be flown as a hosted payload on an operational GEO satellite or as a dedicated payload on a microsatellite. Measurements would be acquired over the lifetime of the satellite and would observe how the spectral reflectance characteristics evolve during its lifetime. Furthermore, installation of one of the proposed instruments on multiple satellites would provide an opportunity to study the variation in space environment effects on the surfaces of spacecraft located in different orbital regimes, such as LEO, MEO, and GEO.

The paper discusses the mission aim and objective for which this experiment would be designed. Next, we present some of the main experiment requirements that will need to be satisfied in order to achieve the aim and objectives of the experiment. Finally, the paper present a brief description of three conceptual designs of instruments that could satisfy most of the experimental requirements. The paper concludes with a description of the work that will follow this initial study.

2. EXPERIMENTAL AIM AND OBJECTIVES

We propose to develop an instrument whose sole purpose would be to measure how the space environment affects the spectral reflectance characteristics of spacecraft materials as a function of time for the duration of the mission. In order to collect measurements from the widest array of spacecraft materials, this instrument will be designed such that it can be flown on a wide variety of space mission. The principal data product that will be spectral BRDF measurements, such as those presented in Fig. 1, from which other data products, such as spectral reflectance, can be derived.

From the experimental aim, we identify three objectives from which the experiment requirements and constraints have been defined:

1. To measure the effects for a variety of orbital regime.

2. To measure these effects over the duration of the mission.

3. To provide data that can be directly compared with ground based colour photometric measurements or spectrometric measurement.

The end product of the mission would be spectral BRDF obtained for a wide variety of spacecraft surface materials, over a the visible and near-infrared portion of the spectrum, preferably measured at a variety of incidence and reflection angles, and collected at a temporal resolution that would allow researchers to measure how the space environment affects the spectral reflectance characteristics of material as a function of time spent in orbit. Another benefit of this information is that will allow scientists to better understand ground-based photometric and spectrometric measurements of active spacecraft as well as space debris. Ultimately, these products should assist scientists to identify space debris and other resident space objects based on their photometric and spectrometric characteristics.

3. EXPERIMENTAL CONCEPT AND REQUIREMENTS

3.1 Experiment Concept

The proposed instrument will be capable of collecting spectrometric measurements of the main surface materials of the spacecraft hosting the instrument. For each individual material, spectrometric measurements, which can then be converted into spectral BRDF, for a wide variety of observational geometries. The illumination geometry will be entirely dependent on the position of the hosting spacecraft on its orbit as well as its orientation with respect to the Sun. Finally the instrument will collect measurements throughout the lifetime of the hosting spacecraft at a sampling rate that will allow for an accurate characterization of the rate of change of the spectral reflectance characteristics of the studied materials.

In the remainder of this section, we provide the initial experimental requirements and constraints that have been identified in the preliminary mission analysis design phase of the instrument.

3.2 Experimental requirements

3.2.1 Multi-mission design

Since one of the objectives of the proposed experiment is to study how the space environment in different orbital regimes modifies the spectral reflective properties of material, the instrument will be designed in a manner that it can be flown as a hosted payload on a variety of spacecraft, operating anywhere between LEO to Molniya and GEO, to other space vehicles such as either the International Space Station (ISS), in LEO, or even the upper stage of a launch vehicles that are launched in GTO.

In order to maximize the likelihood of being flown on the widest variety of space mission possible, the instrument must be self-contained with clearly defined interfaces for all of its subsystems such as communications, power, thermal and structure. Given that it might be flown on large or small spacecraft alike, it power requirements as well as it volume must be kept to a minimal. Moreover, it should not have any moving part and the footprint of the numerous detectors that will be required to collect the spectrometric measurement must be kept to a minimum.

3.2.2 Material sampling

The instrument will be designed in such a way as to collect spectrometric measurements from the major reflecting materials on the surface of the space vehicle. This includes materials that are forming the highest percentage of the surface area and those with the highest spectral BRDF, namely specular materials. In general, measurements will be taken from the material that should reflect the most sunlight to ground-based and space-based detectors.

For a given material, measurements will be collected from at least three reflection angles such that changes in spectral BRDF caused by different observation geometry can be measured. The number of measurements, and hence sensors, will depend on the characteristics of this material. For example, specular materials may require having sets of detector closely space apart to adequately sample the very narrow reflection lobe that is typical of this material type. To obtain sample at different reflection angles, a given number of these detectors sets would be installed over the spacecraft. On the other hand, diffuse material would not require detectors that are as closely spaced as for specular surfaces.

3.2.3 *Knowledge of illumination and observation geometry*

Each spectrometric measurement collected by the instrument will require to be accompanied with the illumination and observation geometry at the time of the measurement. One of the simplest methods to implement this requirement will be to include this information in the header of the final measurement file.

The observation geometry will be easily determined if the detectors are fixed to the spacecraft as desired. In the case of the illumination geometry, this information will be reconstructed using the satellite's state vector and attitude data at the time of the measurements. The latter data implies that the operators of the hosting spacecraft will need to make the state of the satellite orientation available to science team.

3.2.3 Spectral range and resolution

Most space surveillance sensors, whether operational or for research, are limited in the visible to near-infrared portion of the spectrum [6-16].Hence, the minimum desired spectral range of the instrument will be from approximately 350 to 1100 nm. If possible, the spectral range should be extended into the near-infrared up to 1800 or even 2500 nm to provide information to those interested in the characterization of space objects in the NIR portion of the spectrum.

Spectrometric characterization of common spacecraft materials have shown that a spectral resolution, R, of approximately 500 would be sufficient for the science objectives to be satisfied. Laboratory characterization of spacecraft materials has shown that almost all spacecraft materials have few, if any, spectral features.

3.2.4 Sampling rate

The sampling rate at which measurements are collected will depend on at least two factors. First is that the sampling rate will have to be set such that the effects of the space environment on the spectral reflectance of the materials can be properly characterized. Since it is highly likely that the rate of change of the spectral reflectance will decrease with mission time, then the sampling rate will need to be adjusted so as to not collect unnecessary measurements.

Second the sampling rate will also depend on the mission profile of the hosting spacecraft and the rate at which its orientation with respect to the Sun varies. For example, a spacecraft in LEO will be exposed to a wide range of illumination geometries in very short periods of time due to its rapid displacement on its orbital trajectory. Mission profiles such as this will require sampling rates that are high enough such that the measured spectral reflectance is taken at a discrete illumination angle. At the other extreme, the illumination geometry of geostationary satellite changes very slowly, hence, the sampling rate for this type of mission will be much lower than the previous example.

3.2.5 Design Life

In order to satisfy the objective of measuring how the spectral reflecting characteristics of material evolve over time, the instrument must operate for as long as these characteristics vary. This is currently not well known so we can estimate a desired lifetime or we can state for the duration of the host spacecraft mission. Depending on the type of mission and the orbit at which the hosting spacecraft will operate, this may impose a design life of a anywhere from 1 year for technology demonstrator to more than a decade for geostationary missions.

3.2.6 Spectrometric Calibration

Given that the purpose of this experiment will be to quantify the changes to the spectral reflectance of surface material over time and also compare these variations at different orbits, the spectrometric measurements will need to be calibrated before launch and at regular intervals throughout the lifetime of the instrument once in orbit. This will enable scientist to ensure that any observed change is not due to changes in the instrument over minimum 10 year mission lifetime. It is noted here that the instrument calibration before launch will pose no significant problem however this may not be the case for the calibration of the instrument post-launch. More precisely, any witness sample flown on the spacecraft for calibration purposes will also be degraded by the space environment. Furthermore, the instrument itself will also be exposed to the space environment. Proposed concepts to satisfy the spectrometric calibration requirement range from using calibration light sources contained within the instrument to using standard spectrophotometric stars. In the end, the strategy that will be selected will be a compromise between obtaining a calibration method that will be sufficient to achieve the desired result and a solution that will minimize the volume, power consumption and complexity of the instrument.

4. DESIGN OPTIONS

In this section we present three conceptual designs to provide a better sense as how the experiment could be executed.

4.1 Design option #1: Multiple-material and multiple illumination and observation geometry

The first design that is proposed is a fiber-fed spectrograph such as show in Fig. 3. In this design, the spectrograph is located within the bus of the hosting spacecraft and linked, by fiber, to the various detectors that are installed at various locations over the spacecraft. For each specific material, a set of detector would be needed such that measurements could be obtained for a wide range of reflection angles.

The first advantage of this design is that the instrument can easily be contained within a constrained volume with easily defined interfaces for power, thermal, structure and communications. Next, the use of fibers would allow positioning the detector at optimal location to obtain spectral reflectance measurements from a wide variety of surface materials.

On the other hand, a disadvantage of this approach is that there could be a high number of fiber cables that need to be installed and secured inside and outside of the spacecraft. Furthermore, while there are optical fiber cable assemblies that have been tested and could be used in space the questions of whether they could survive the space environment over a mission duration of more than a decade is uncertain. Additionally, the question of how their degradation over time would affect measurements will also need to be addressed. Given that the detectors would also be located outside the spacecraft and be subject to degradation as well is another factor that will need to be assessed.

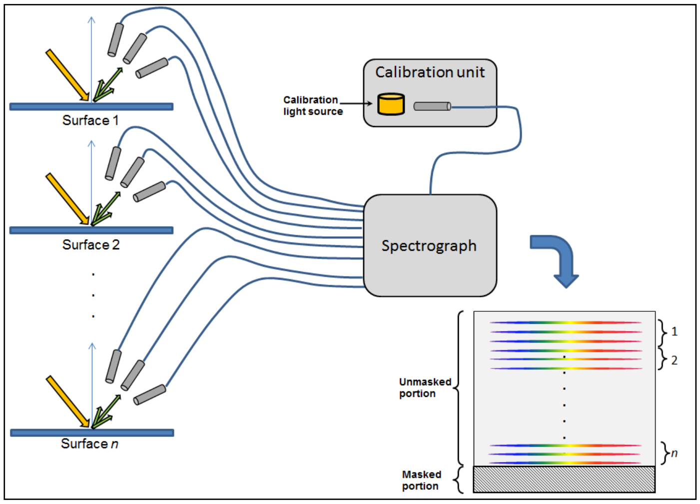

Fig. 2. Conceptual representation of the multiple materials and multiple illumination and observational geometry design option.

4.2 Design option #2: Single illumination and observational geometry

The second design option is based on the highly likely assumption that design teams of hosting spacecraft would not permit installing fiber optic cabling within or on the exterior at multiple locations on the spacecraft since this will increase design risk. With this in mind, the second design concept would consist of a single probe within which the illumination source and the detectors would be contained. As shown in Fig. 4, this concept would limit the collection of measurements to one material on the surface of the spacecraft and an incidence and reflection angle normal to the surface. A variation of this design could consist in having more probes distributed over other materials found on the spacecraft.

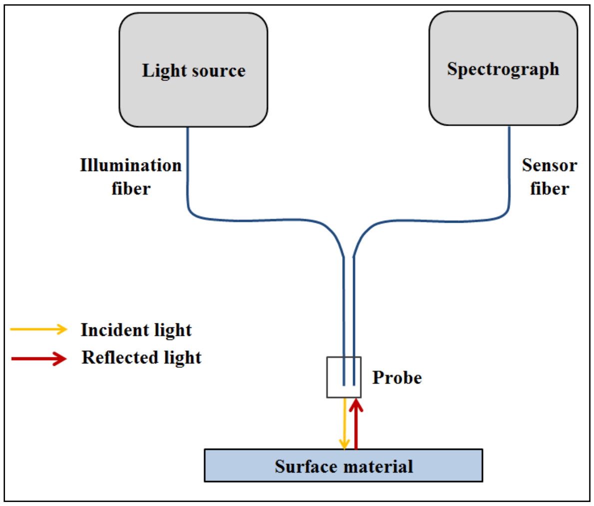

Fig. 3. Conceptual representation of the single illumination and observational geometry design option.

The major disadvantage of this design option is that it would preclude the acquisition of spectral BRDF measurement collected in a wide area of illumination and observation geometry. As a result this could prevent the science team from measuring if and how the specular reflection lobe widens as the material's surface roughness increases with time. This disadvantage could disappear altogether if the sensor can be designed to measure either reflection from the artificial light source or from the sunlight. In this case, it might be possible to measure this phenomenon.

The advantage of this design option is that the probe would supply its own illumination source which could be used also as a calibration source. This could be achieved by having a fiber direct light from the source directly to the spectrometer. This would allow for a characterization of the light source however this strategy would not address how to characterize the degradation of the detectors contained within the problem.

4.3 Design option #3: Single payload/multiple material

The third design option that is proposed consists of an arrangement of targets and sensors is to observe the effects of the space environment on several materials at several spectral wavelengths at several incident and reflective angles. A number of spheres are each covered with a different material. Several same-wavelength sensors on the ends of optical fibre are arranged to observe small fields-of-view on different parts of a sphere thereby observing several reflective angles. Additional sensors are added at the other wavelengths to make a small pack of sensors for each sphere. The arrangement is repeated for the other spheres (materials). The varying incident angles are achieved by the varying angles that the sun shines on the spheres as a function of spacecraft movement. For some of the materials, it may be more convenient to mount the material (such as a solar blanket) on the surface of a multifaceted sphere rather than on a smooth sphere. Economy of available space may be achieved by using hemispheres or quarter-spheres which can provide the same range of angles.

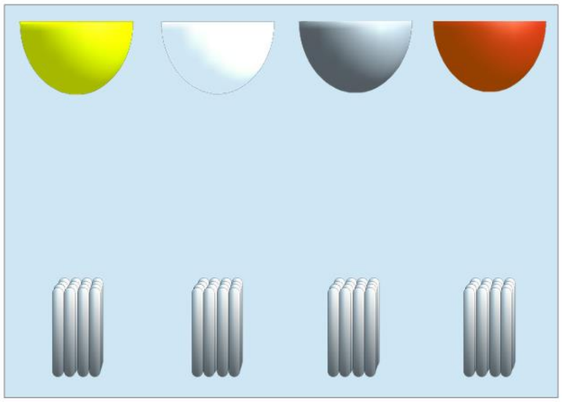

Fig.5. Depiction of the Arrangement of Spheres and Sensors.

5. CONCLUSION

In this paper, we have presented an experiment aimed at collecting in-situ VIS/NIR spectral measurements of spacecraft materials in various orbital regimes. The proposed instrument consists of a minimally invasive payload that could be hosted on a wide variety of space mission thereby allowing researching to gain a better understanding of how the space environment in LEO, MEO, GTO, GEO and Molniya affects the spectral reflectance characteristics of spacecraft material as a function of time spent in Earth orbit.

The next step in this project will be to refine the experimental concept and begin work on a laboratory technology demonstrator. As part of this process, we will seek to evaluate the optimal conceptual design and answer basic questions related to instrument calibration issues as well as data management.

In all, we expect that this information will allow scientists to better understand ground-based photometric and spectrometric measurements of active spacecraft as well as space debris. Ultimately, these product should assist scientist to identify space debris based on their photometric and spectrometric characteristics.

6. REFERENCES

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