

Spacecraft Material Characterization Using Reflectance Spectra Extracted from RGB/IR Color Images

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The space environment is detrimental to the exterior of the spacecraft and imposes stringent requirements on spacecraft materials. Space materials are often expected to perform for 15-20 years in the harsh space environment without significant degradation of their optical, electrical, mechanical and thermal properties. Further, as commercial activities increase in the space domain, development of predictive capability for material evolution is critical for agile adaption of novel materials. Therefore, it is very important to understand the effects of the space environments on the spacecraft materials. The Materials on the International

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Space Station Experiment Flight Facility (MISSE-FF) has flown numerous material samples to investigate the effect of LEO space weather exposure on the performance and durability of materials and devices. We are manifest on the MISSE-16 mission, scheduled to launch in June 2022, to fly fifteen novel and well-characterized materials in the LEO environment for a duration of six months. Changes in spectral reflectivity will be measured in real time throughout the mission with an RGB/IR camera. These time-resolved data will function as a “space-truth” reference for our team’s ongoing laboratory-based space weather-material interaction experiments. Correlation of the MISSE-16 data with extensive ground testing of duplicate samples under simulated space weather conditions will enable development of fundamental chemical models for material degradation. This paper discusses preliminary results from the ground test campaign to collect the RGB/IR images for pristine and damaged materials and the development of machine learning algorithms to extract reflectance spectra from the color images.

I. Introduction

EXTERIOR spacecraft materials play an important role in protecting satellites from the harsh space environment and are disproportionately understudied in the literature. Research has shown that the physical, chemical, and optical properties of matter change continuously as a result of exposure to solar radiation and aggressive chemical species produced in Earth’s upper atmosphere [1]. Thorough knowledge of the material properties evolution throughout a planned mission lifetime helps to improve the reliability of spacecraft. Moreover, the establishment of correlation factors between true space exposure and accelerated space weather experiments at ground facilities enables accurate prediction of on-orbit material performance based on laboratory-based testing.

The Materials International Space Station Experiment Flight Facility (MISSE-FF) on the International Space Station (ISS) is the perfect test bed to generate benchmark data with which to validate the efficacy of ground-based space weather simulation experiments. Our ultimate goal is to fly several novel and well-understood materials on the MISSE-FF and monitor the changes in spectral reflectivity that occur as a result of exposure to different components of the low Earth orbit (LEO) environment. Energy deposition from the environment leads to chemical changes in the material that in turn alter the optical properties. Since unique damage occurs at each face of ISS, the mission will acquire spectroscopic data of identical material sets placed on ram (direction of travel, AO exposure), zenith (direction away from Earth, VUV exposure), and wake faces (opposite to the travel direction, electron exposure). MISSE flight duration will be approximately six-months; daily images of each sample will be taken for the first 30 days; weekly images of each sample for the next two months; monthly images are then taken for the remaining duration of the mission. This experiment will allow us to observe the progression of space weather damage in real time which can then be compared to ground-based space weather simulations. Figure 1 shows an illustration of the MISSE-FF concept of operations.

II. Experimental Details

MISSE flight sample collection comprises several different class of polymers including polyimides (PIs), polyethylene terephthalates (PET) materials, liquid crystal polymers (LCP), PI/Polyhedral Oligomeric Silsesquioxanes (POSS) materials and carbon and glass reinforced polymers (CFRP and GFRP). Table 1 below lists the materials and the material class that they belong to.

After deploying the MISSE-16 mission on the International Space Station (ISS) in June 2022, we expect to begin receiving red, green, blue and infrared (RGB/IR) images of the materials throughout the 6 months mission starting Summer 2022. These time-resolved data will function as a “space-truth” reference for our team’s ongoing laboratory-based space weather-material interaction experiments. The RGB/IR color data obtained from the experiment will be the first of its kind and allows for the observation of the space weather damage on the materials in real time. Further, within the framework of the same project, replica of the hardware used on MISSE to collect the reflectance data has been installed in the Jumbo space irradiation chamber at the Spacecraft Charging and Instrument Calibration Laboratory (SCICL) at the Air Force Research Laboratory [2]. Figure 2 shows the ground test unit of the MISSE camera and light setup installed in the SCICL facility.

The reflectance data of control (pristine) and material aged under the LEO-simulated environment (i.e., electron and VUV – exposed) will be collected using the same lighting and camera system as installed on board the MISSE-FF. Figure 3 shows the MISSE camera hardware with the “white” LED illumination spectrum and the camera response for

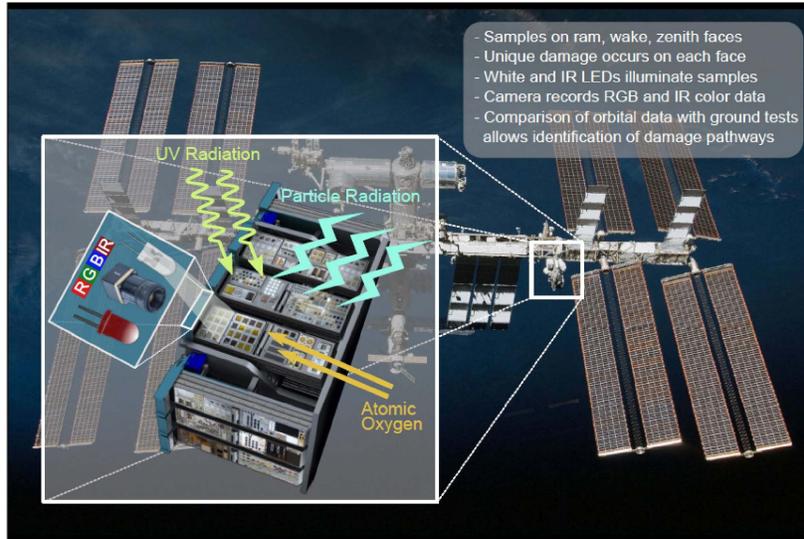
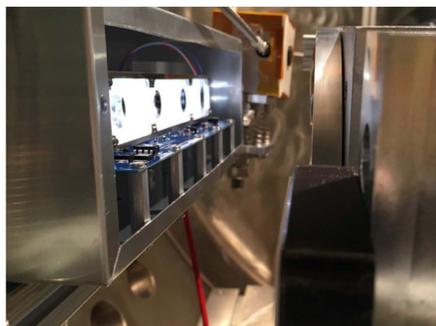


Fig. 1 Planned MISSE experiment aboard the ISS in 2022. Materials will be illuminated with infrared (IR) and white light sources, and imaged with an RGB/IR camera on a periodic basis. Materials will be mounted in positions of varying ultraviolet radiation, ionizing particle (electron) radiation, and atomic oxygen exposure.



(a) Camera and lights in front of the sample carousel



(b) Camera apparatus with only the white lights on

Fig. 2 MISSE camera board installation in SCICL Jumbo Chamber

each RGB/IR band.

III. Preliminary Analysis

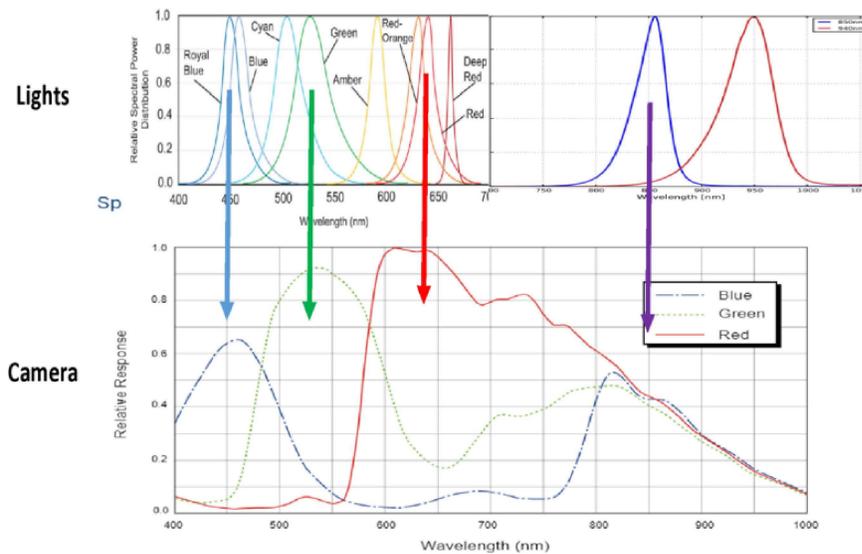
The large amount of data collected for these experiments will be analysed using machine learning techniques developed by our colleagues at the Georgia Tech Research Institute (GTRI). To train the machine learning algorithm initially, color and IR images of Spectralon color standards with well-characterized reflectance spectra were collected using the MISSE camera hardware. Figure 4 shows several of these images and illustrates the difference between visible and IR images. For each of the materials, pristine visible and IR images as well as the directional hemispherical reflectance (DHR) spectra were collected.

The materials will then be subjected to electron irradiation and VUV irradiation to simulate damage seen by the samples on each face of the ISS. Visible and IR camera images and DHR measurements will be performed at varying time intervals to monitor the changes in the optical properties of the materials and will be used to continue training the machine learning algorithm. Figure 5 is an example of visible and IR images for two of the pristine materials Kapton HN and GFRP.

Table 1 List of materials studied for the MISSE-FF

No.	Material	Abbrev.	Trade Name
1	Polyimide (PMDA)	PI	Kapton CR®
2	Polyimide (PMDA)	PI	Kapton CS®
3	Polyimide (PMDA)	PI	Kapton WS®
4	Polyimide (PMDA)	PI	Kapton XC®
5	Polyimide (PMDA)	PI	Kapton TF®
6	Polyimide (PMDA)	PI	Kapton 200DR9®
7	Polyimide (PMDA)	PI	Kapton HN®
8	Carbon Fiber Reinforced Polymer	CFRP	Economyplate™ Carbon Fiber
9	Glass Fiber Reinforced Polymer	GFRP	G-10/FR4 Glass Epoxy
10	Liquid Crystal Polymer	LCP	Zenite®
11	Polyethylene terephthalate	PET	Melinex®454
12	Polyethylene terephthalate	PET	Mylar®MO21
13	PI/Polyhedral Oligomeric Silsesquioxane	POSS	CORIN®XLS
14	PI/Polyhedral Oligomeric Silsesquioxane	POSS	Thermalbright®N
15	Aluminum Oxide	ALUM	Alumina

a *Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.



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Fig. 3 Illumination/Detection scheme for the MISSE experiment

IV. Machine Learning

A key factor in fully characterizing the materials flying on MISSE is the ability to extract reflectance spectra from RGB/IR images. Materials damaged in the terrestrial vacuum chambers can be characterized with a suite of

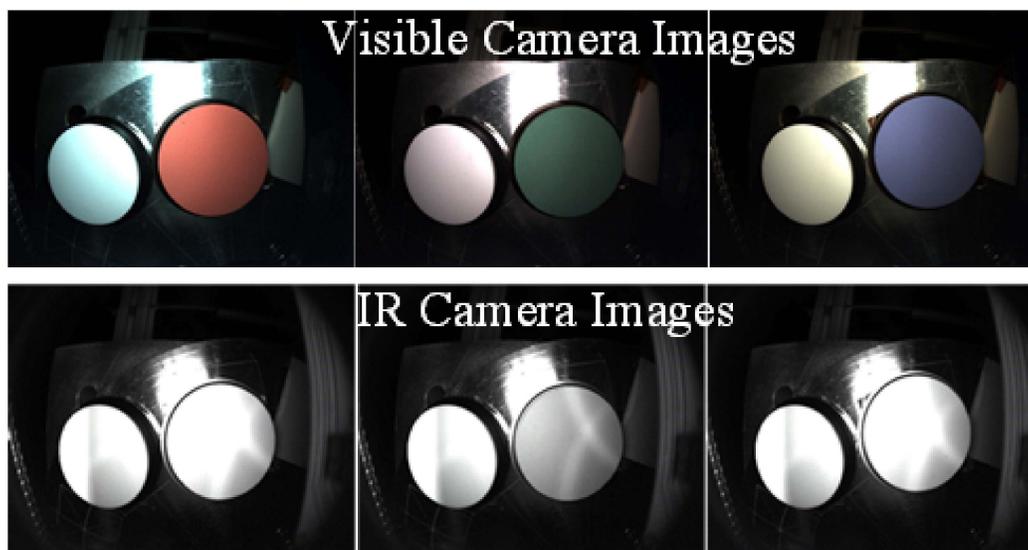


Fig. 4 Visible and IR LED camera calibration with colored Spectralon standards

laboratory instruments. On-orbit experiments, however, are typically limited to only capturing pictures or very limited characterizations of material properties. Therefore, we are developing a method to extract reflectance spectra from RGB/IR images. Prior work has addressed how reflectance spectra can be used as a proxy to determine other important material properties such as conductivity and embrittlement (i.e., [3, 4]). Thus, developing a method to estimate reflectance spectra from camera images will allow future experiments to obtain more detailed information about material evolution.

Spectral extraction from camera images is an under constrained problem since it involves mapping from a low-dimensional space (RGB/IR pixel counts) to a high-dimensional space (reflectance as a function of wavelength). In other words, there are an infinite number of spectra which can produce a given RGB/IR image. Machine learning techniques are often used to approach such problems. We are developing a machine learning approach which uses a radial basis function (RBF) network [5]. The model will be trained using camera images and DHR spectra for numerous pristine and damaged material samples collected in the ground test campaign. When images are downloaded from the on-orbit MISSE camera, the RGB data will be selected from a non-over-saturated region under both visible and IR lighting conditions. Next, these pixel counts will be white balanced given the scene context, which is possible because the same settings have been applied to the flight and ground test cameras and a white Spectralon standard will be visible in each of the ground test images. Finally, the RGB data from MISSE will be converted into $L^*a^*b^*$ color space and fed into the trained Radial Basis Function (RBF) network. The machine learning algorithm will then give an estimated reflectance spectrum for each image.

V. Conclusion

Correlation of the MISSE data with extensive ground testing of flight duplicate samples under simulated space weather conditions will enable development of fundamental chemical models for material degradation. Spacecraft designers will benefit from the insight into material behavior changes throughout a mission lifetime. Further, a detailed predictive knowledge of space weather-induced material color change will enable more robust and accurate space domain awareness by allowing remote observers to glean knowledge about a spacecraft by examining the spectral signature of unresolved images. Use of spacecraft color in this way will reduce spacecraft cross-tagging and enable remote diagnosis and anomaly resolution.

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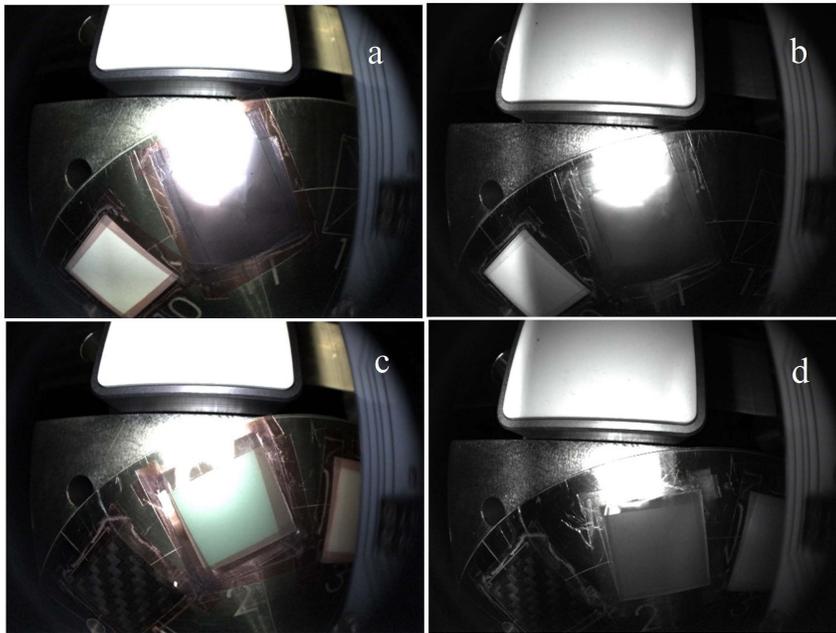


Fig. 5 Visible and IR illuminated camera images for pristine Kapton HN®(a and b) and pristine GFRP (c and d)

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VII. Disclaimers

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