

Comparisons of Ground Truth and Remote Spectral Measurements of the FORMOSAT and ANDE Spacecraft

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ABSTRACT

Determining the material types of objects in space is conducted using laboratory spectral reflectance measurements from common spacecraft materials and comparing the results to remote spectra. This past year, two different ground-truth studies commenced. The first, FORMOSAT III, is a Taiwanese set of six satellites launched in April 2006. The second is ANDE (Atmospheric Neutral Density Experiment), a Naval Research Laboratory set of two satellites set to launch from the Space Shuttle in November 2006. Laboratory spectra were obtained of the spacecraft and a model of the anticipated spectral response was created for each set of satellites. The model takes into account phase angle and orientation of the spacecraft relative to the observer. Once launched, the spacecraft are observed once a month to determine the space aging effects of materials as deduced from the remote spectra. Preliminary results will be shown of the FORMOSAT III comparison with laboratory data and remote data while results from only the laboratory data will be shown for the ANDE spacecraft.

1. INTRODUCTION

Astronomers have been using spectral reflectance data for years to determine composition of planets, comets, asteroids, and other celestial objects. Studies on spacecraft materials reflectance spectra have been conducted and then applied to remote spectra in hopes of determining the surface properties [1, 2, and 3]. From the first set of remote observations, a darkening of the objects was noted and expected but an increase in reflectance as wavelength increases was also observed and was not expected [4]. The increase, or reddening as it is termed in the astronomy community, appears to be material dependent and independent of orbit or age. Since the reddening is not seen upon returning to the Earth environment, the root cause of the reddening is believed to be a space environment effect. Therefore a study to determine when these changes occur was launched. Laboratory spectra measurements were needed prior to the spacecraft launch to obtain a time stamp on the environment changes to the materials.

Two sets of satellites were part of the investigation. The first is a set of satellites from Taiwan called FORMOSAT III. FORMOSAT III are satellites based on the Orbital bus structure of a flat cylinder body with a nadir pointing boom and solar panels at the top of the spacecraft. An artist rendition of the spacecraft in orbit is shown in Fig. 1. FORMOSAT III launched April 15, 2006 into an orbit of 500 km circular altitude. There are six identical satellites that will take approximately 13 months to get to their final orbit of ~ 800 km circular orbit, 72° inclination, and separated by 24° in ascending node. These satellites give a unique opportunity for observation because at least one of the satellites should be observable each night. In addition, because the satellites are taking 13 months to get to their final orbit, different orbit regimes will be studied in the process. The actual materials on the spacecraft will be discussed in Section 2.

The ANDE spheres were the second set of satellites for which pre-flight laboratory data were obtained. ANDE, Atmospheric Neutral Density Experiment, are two spheres to be launched from the Space Shuttle by the Naval Research Laboratory (NRL). The expected launch date is late November or early December 2006. The spheres, shown in Fig. 2, will be at 400 km circular orbit and 51° inclination. The orbital life time is approximately one year. The spheres are painted in four sections so that spin rates can be seen from ground observations. The black and gold sphere is called the MAA sphere and will purposely be given a spin rate at launch while the other sphere, FCal, is white paint and nickel coated brass.

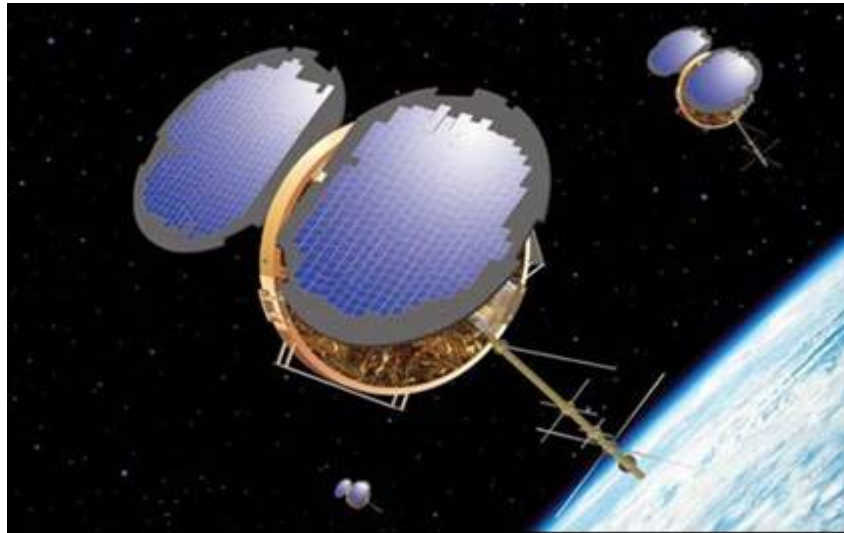


Fig. 1. Artist rendition of FORMOSAT III as seen from above the Spacecraft

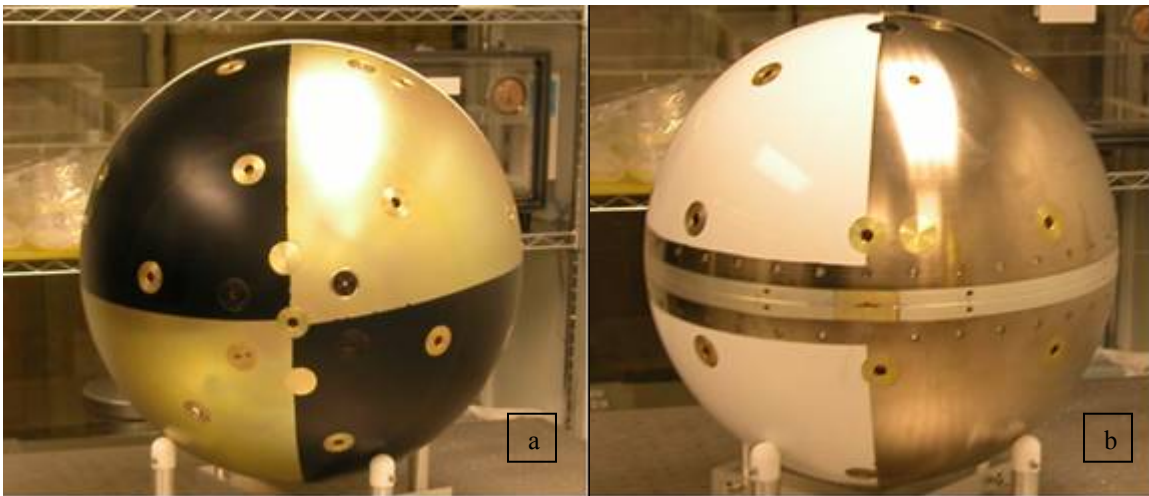


Fig. 2. a) MAA sphere (aluminum with black anodized/gold irritated finish) and b) FCal (brass Aeroglaze gloss white/nickel coated brass finish)

2. LABORATORY DATA

Both sets of satellites were measured with the same type and model of spectrometer. Measurements were taken using the Analytical Spectral Device (ASD) field spectrometer that has a wavelength range of 0.3 to 2.5 microns (μm) with a resolving power of 10 nanometers (nm) and 717 channels. The system only needs 210 channels in order to obtain the desired bandwidth, so using 717 channels is over-sampling, which results in less degradation of spectral resolution. An optical probe, attached to the spectrometer, was held in place by an optic pistol grip that was oriented so that the shadow did not interfere with the measurements. A computer equipped with ASD software was also connected to the spectrometer where the data are recorded and stored. An in-house program called Specpr,

which can be found at the United States Geological Survey Spectral Laboratory website (<http://speclab.cr.usgs.gov/software.html>), is used to reduce the data.

Each set of data were taken with the same phase angle between the light, object, and probe when possible. When the configuration was changed, a new white reference was taken so that the measurements have a common ground for comparison. The light source is a ProLamp (50 W) provided by ASD. The lights in the room were turned off so no light other than the light from the lamp contributed to the reflectance measurements. The optical probe can be placed at any distance from the material thus allowing for pinpoint measurements of materials or much larger views of the spacecraft in entirety.

The spectrometer was configured to take data every tenth of second. Every six seconds, the spectra were averaged, saved, and the results were graphed to the computer screen providing near real-time results of the sample. Each sample's averaged spectrum was recorded at least three times and those were averaged again later into one spectrum using Specpr. The system has three spectrometers within the housing unit, and correcting for the offset between them is necessary. This process is completed using Specpr. The first spectrometer ranges from 0.3 to 1 μ m, the second from 1.0 to 1.8 μ m and the final from 1.8 to 2.5 μ m. The bandpasses for the spectrometers are 7, 11, and 11 nm, respectively. The second spectrometer is the most stable and is used as the centering point for the other two.

2.1 FORMOSAT III Measurements

The satellite was enclosed in a clean room and therefore, the scientists and the instrumentation followed the procedures laid out by the FORMOSAT team. The measurements were collected in July 2005, prior to the satellites being sent to the United States for stacking and launch. All six satellites were launched at the same time on April 15, 2006. All of the individual materials were tested, as well as broad views of the entire spacecraft, resulting in over 200 spectra. The satellite was oriented such that the normal nadir pointing of the satellite was toward a wall instead of the floor. This was advantageous for the data collectors because the solar panels were easier to measure in this configuration. The satellite configuration is shown in Fig. 3.

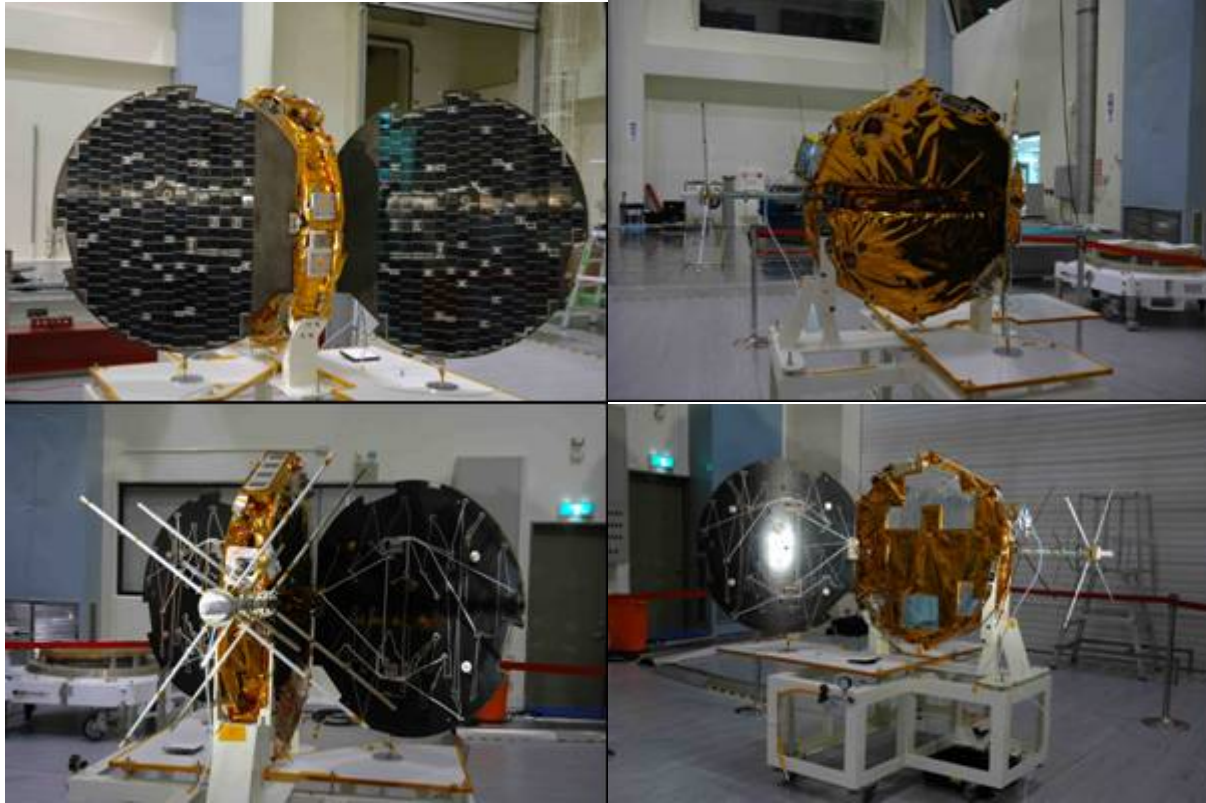


Fig. 3. Various views of the FORMOSAT III in the laboratory



Fig. 4. Side view of FORMOSAT to illustrate the solar panel orientation to the spacecraft body

The top left image in Fig. 3 is from the top surface and likely a side that ground observers will not see. The solar panels are set off-axis to the body making a larger angle between the panels and the body on one side of the spacecraft than the other. The angles are 59° degrees on one side, and 121° on the other in reference to the body. The solar panels do move around the y-axis (x-axis is down the body of the spacecraft) to track the sun, but keep the same angles to the body of the spacecraft. This is illustrated in Fig. 4. The solar panels are near 100% populated with a very dark backside. The top right image in Fig. 3 shows the acute angle of the solar panels to the body. Multi-layer insulation (MLI) that has an outer layer of Kapton covers the main body and is seen in the photo with the normal orange/copper color. The bottom left image in Fig. 3 shows the side view with the nadir-pointing boom, a view that the observer would see if the objects were directly overhead. The bottom right image in Fig. 3 shows the larger angle of the body to the solar panels. All materials were considered flight ready, which means all the paints and coatings on the spacecraft are the same when we measured it as when it launches.

The white nadir-pointing antenna was difficult to measure for it was not very wide. A black mouse pad was used as a background and later divided out of the spectrum. The results are shown in Fig. 5. This sample is very similar to other white paints measured previously with the strong band gap for white paint at 0.39 μm and the water absorption features near 1.4 and 1.9 μm . A C-H feature is seen at 1.65 and 2.3 μm . The white paint has a decreasing slope once past the band gap that could be used as a distinguishing overall feature. Paints with a silicon binder have been known to outgas and turn the white paint a brownish color. If this happens to the paint on the nadir boom, the band gap height will be lessened and the slope will decrease toward the longer wavelengths.

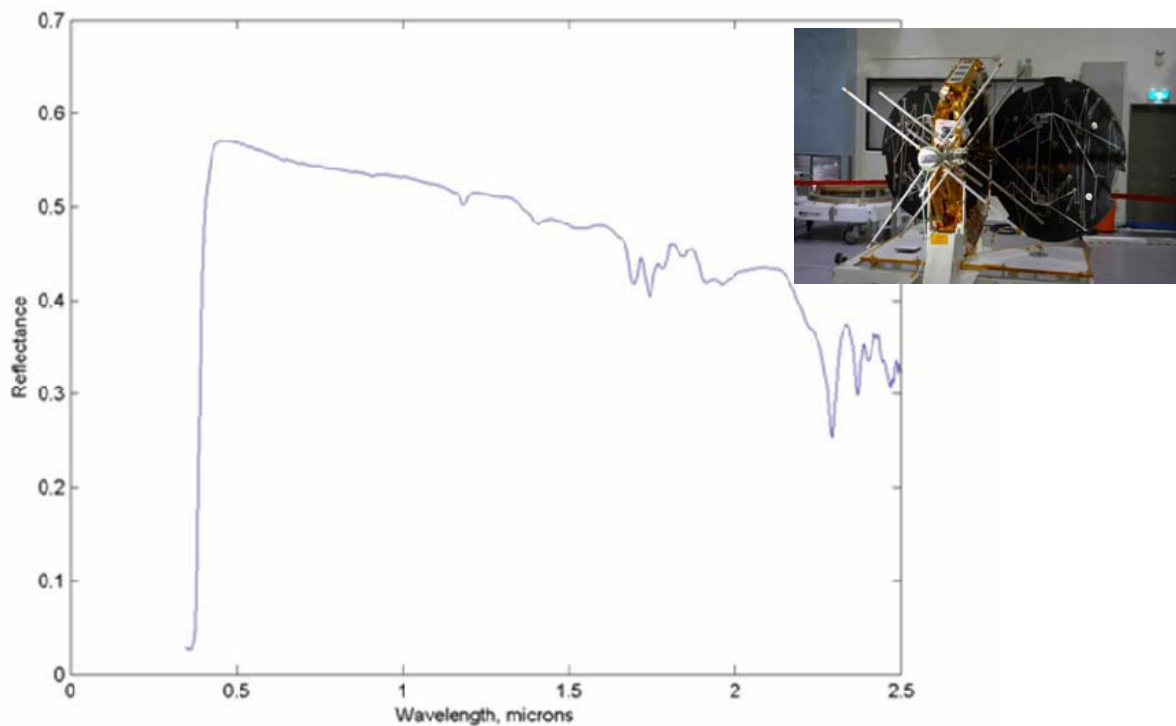


Fig. 5. Reflectance Spectra of the Nadir pointing boom. Strong band gap feature due to white paint seen at 0.3 microns and absorption features due to organics in the paint at 1.7 and 2.3 microns.

The solar panels, as shown in Fig. 3, were very dark to the eye. The spectrometer is not set up to take highly specular measurements. Therefore only non-specular measurements were made and shown here. In Fig. 6, the reflectance is very dark spectrally and shows a flat spectrum until 1.5 μm . This is shown as the blue or lowest line in the reflectance curve. There is a small emission feature near 0.8 - 0.9 μm that is likely from the type of material used in the solar panel. Similar features have been seen on GaAs cells. Solar panels that are specular will show a strong blue emission prior to 0.4 μm . There is only a slight bluing trend in this figure, however, since the data were taken to highlight the diffuse reflectance.

Multi-layer insulation (MLI) covers both sides of the spacecraft body. This material is orange in color but can bend and move like aluminum foil. Because of that aspect, MLI is difficult to get a spectrum of because the light reflects to different areas. In the spectrum shown in Fig. 6 labeled as “mli small”, the MLI appears to be much dimmer than it actually seems in person. There is a strong color band gap near 0.5 μm which is consistent with the orange/copper color of the material. In addition, one can see the absorption feature near 0.85 μm , which is usually associated with aluminum. The MLI outer surface is consistent with other measurements of MLI with a Kapton surface. The next features that can be used to identify material are those associated with C-H in the material near 1.7 and 2.3 μm . Again, these are consistent with other Kapton spectra measured.

Due to specular reflectance, the small sample is difficult to obtain a true diffuse reflectance so the entire MLI side of the spacecraft body was measured. The spectrometer probe was placed at a greater distance from the spacecraft.

The results show a larger reflectance but with similar absorption features as seen in the Fig. 6 curve labeled as “mli entire”. Within this spectrum are absorption features due to the color of the MLI ($0.5 \mu\text{m}$), aluminum ($0.8 \mu\text{m}$), water (1.4 and $1.9 \mu\text{m}$), and C-H (near 1.7 and $2.3 \mu\text{m}$) among others. This is a good result from the body of the spacecraft and can be used to distinguish the materials being shown in the remote measurements. Studies have shown that Kapton erodes in the LEO environment due to atomic oxygen interactions. If that is the case here, the band gap due to the copper-color of Kapton will be absent and the aluminum feature will be more apparent because the spectrum will be showing the lower layers of the MLI.

While taking the measurements of the broader and larger views of the spacecraft, we tested pseudo-terminator views. The resultant spectrum is shown in Fig. 6 as the red or top line labeled as “reflection off the back”. An interesting, not seen result in prior experiments was the back scattering of the light off the MLI onto the back on the solar panel and then back to the observer. This situation is exaggerated in this orientation because of the orientation of the solar panels to the spacecraft body and is only seen on the smaller-angle side of the spacecraft. The spectrum of the solar panel back is shown with a sample of MLI only and the back of the solar panel with direct light. Notice how dark and flat the back is without the MLI reflection. This situation will be advantageous for ground observers because the back of the solar panels can now contribute to the overall reflectance of the spacecraft.

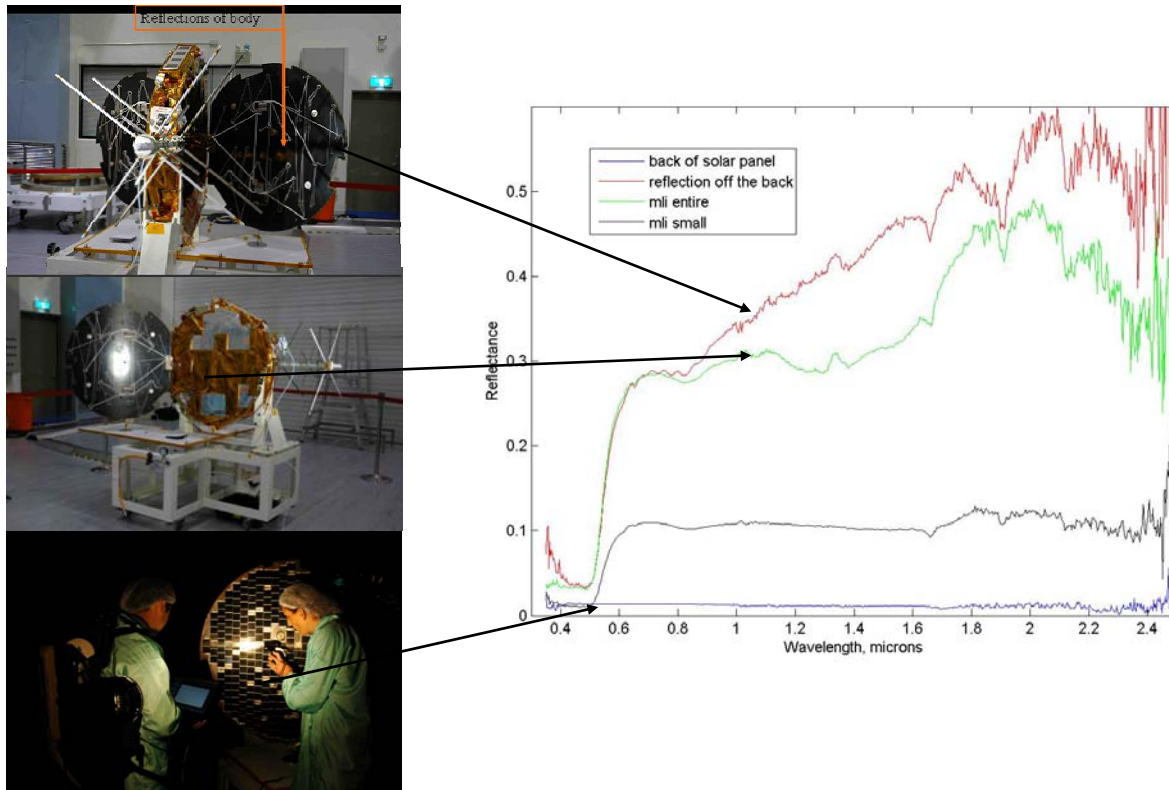


Fig. 6. Reflectance Spectra of the side of the spacecraft due to terminator lighting. The blue line is the back of the solar panels with direct lighting, the black line is the spectrum of a small piece of MLI, the green line is a larger section of MLI, and the red line is the reflection off the back of the solar panel with side lighting.

2.2 ANDE Measurements

The ANDE measurements were taken with the similar spectrometer as the FORMOSAT measurements. The data were taken in the clean room in Washington, DC, at the NRL facilities. Sixty spectra were taken on each sphere and were reduced in the same process as discussed previously. The MAA sphere is black anodized aluminum and gold surface coating (irridite) finish on aluminum. MAA is 48 cm in diameter and 50 kg in mass. As mentioned previously, this sphere will be given a spin rate of 1 – 3 revolutions per minute (RPM) at launch. Around the spacecraft body are laser reflectors and a white plastic band used as a connection between the two halves of the

sphere. The second sphere, FCal, is part Aeroglaze glossy white paint over brass and a nickel coated brass finish. It is 44 cm in diameter and 75 kg in mass. This sphere will not have a spin rate induced at launch

The two colors of the MAA sphere reflect differently through the visible region as seen in Fig. 7. The black anodized aluminum is very dark through the visible until the thickness of the coating is less than the wavelength being measured. Absorption features due to water are seen at 1.4 and 1.9 μm but otherwise the spectrum is relatively featureless. The gold irridited aluminum shows a strong band gap near 0.45 μm due to the gold color and the absorption features due to aluminum are shown near 0.85 μm .

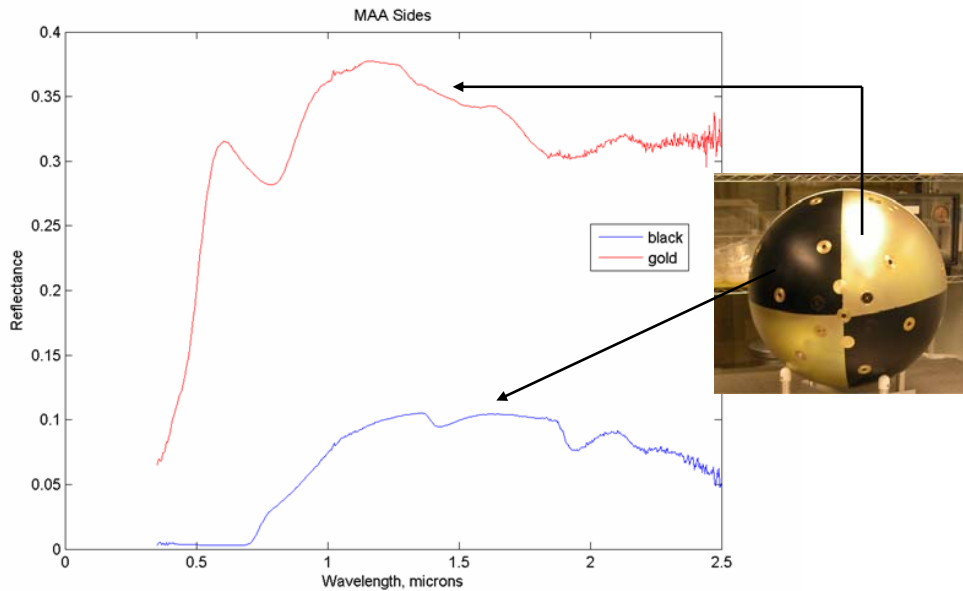


Fig. 7. The reflectance spectra for the sides of the MAA sphere. The blue line represents the black anodized aluminum while the red line represents the gold surface coating (irridite) finish.

The spectra from the FCal sphere are different than the MAA sphere as seen in Fig. 7 and Fig. 8. The Aeroglaze white gloss paint has a strong band gap at 0.39 μm . The descending slope with organic features is very common with this type of paint. The white paint also shows evidence of organics (C-H) near 1.6 and 2.3 μm . This is the first sample of nickel coated brass that the authors have measured. The sample shows an increase in slope through the visible regime, which is in sharp contrast with the white paint. There are no organics in the nickel coated brass spectrum. The differences between the spectra of the two ANDE spheres will be advantageous for identification, with no similar materials on the spacecraft.

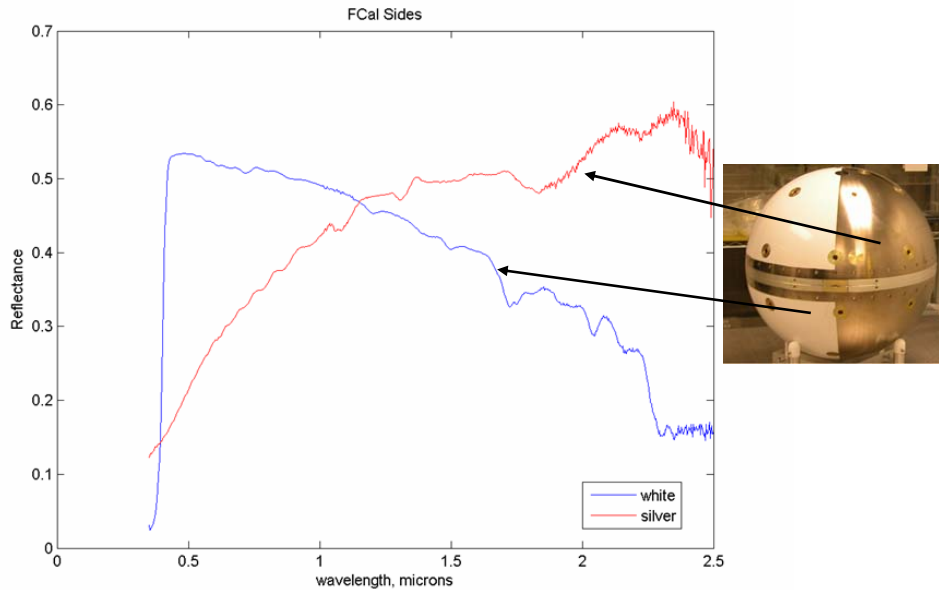


Fig. 8. The reflectance spectra of the FCal sphere sides. The blue line is the white side and the red line is the nickel coated side.

3. MODELING

Modeling of the predicted remote spectra of spacecraft or rocket bodies has begun for FORMOSAT III and ANDE. Using MATLAB®, a user can see what the spacecraft orientation to the observer would be at a given time or given pass. To predict a pseudo-pass, the user must specify the object catalogue number, two line element set, time span of the observation, a time step, and the observer's location in longitude, latitude, and altitude. The MATLAB® program uses code written by Tom Kelecy [5] to calculate the state vectors in J2000 coordinates for the object, observatory, and sun as well as the object's longitude, latitude, and altitude. The program also calculates the object's right ascension, declination, azimuth, and elevation. The sun's elevation and solar phase angle are also computed along with whether the spacecraft is in the umbra, penumbra, or illuminated. Continuing software development will determine eligible passes (when the spacecraft is above a certain elevation and the sun is below a certain elevation) that can be used to model the spacecraft orientation. The pseudo-pass will be used to model what materials on the object will be facing the observer along with what part of the object is illuminated. From that information, the resulting spectrum can be produced. Fig. 9 shows one frame of the pseudo-pass generated from the code. Shown in this example is the FORMOSAT III with the nadir antenna, the spacecraft body, and the two solar panels.

The resulting spectrum from this model is currently in its pristine form, meaning no space weathering effects have been applied. In the future, the authors would like to predict a space weathered spectrum as well as the pristine sample to show the level of degradation with time. In this conference, Michael Guyote will give a paper regarding the prediction of space weathering based on laboratory data [6].

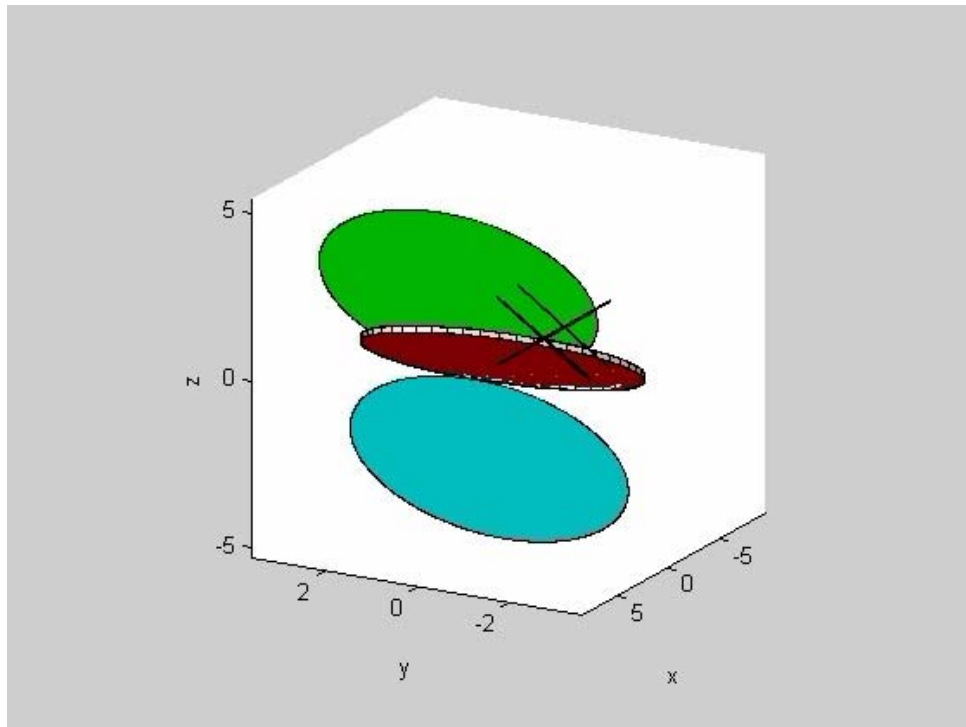


Fig. 9. One frame of the MATLAB generated model used to determine the percentage of material showing to the observer.

4. REMOTE DATA VS. LABORATORY DATA

Due to weather constraints and instrument problems, no remote data was collected on the FORMOSAT III unfortunately. The current schedule for data collection is to begin in late September 2006.

5. CONCLUSIONS

Using laboratory spectral reflectance, a predictive model of the remote spectral response of spacecraft has been built. Two sets of objects, FORMOSAT III and ANDE, have been tested in the laboratory and the results are presented. The FORMOSAT III spacecraft, with more materials and a more complex shape, has been more difficult to model. In addition, results stemming from the laboratory data show a backscattering component on the acute-angle side of the spacecraft. Using the model, it is possible to determine how this orientation will affect the remote measurements. Strong absorption features due to MLI and white paint will help to identify the object in space. The ANDE spheres have two basic materials for each sphere. Once the spheres launched, tracking the changes in the spectral response due to the LEO environment will provide more insight into space weathering.

6. ACKNOWLEDGEMENTS

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