The Oculus-ASR: An Orbiting Nanosatellite Testbed for Non-Resolved Object Characterization

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ABSTRACT

The Oculus-ASR is a 70-kg-nanosatellite specifically designed to advance USAF space situational awareness by providing calibration opportunities and validation techniques for AMOS's telescopic non-resolved object characterization program. This paper will describe the design and capabilities of the Oculus-ASR, its concept of operations, and report on its initial ground optical characterization.

Nearly every object orbiting the Earth, when viewed using all but the largest ground-based telescopes, appear as unresolved point sources of light. Although these unresolved objects seem to be featureless, it may be possible to determine characteristics related to an object's attitude and/or rotation rate by analyzing the spectral and temporal content of reflected sunlight off of the object. For instance, a faceted rotating object may produce a periodic cycle of bright glints when viewed from the ground. Alternatively, a spectrally distinct surface coating on the object may be detectable from the ground using a spectrometer.

The design of Oculus-ASR uses specific shape properties as well as spectrally distinct materials on the spacecraft in order to emphasize, to the ground observer, changes in light intensity and spectral characteristics when viewed from the ground. Additionally, the nanosatellite has the ability to change its shape (and therefore its visible characteristics) while in orbit. It also possesses 3-axis control capability, allowing the Oculus-ASR to present different structural features and maneuver states to the ground observer.

In order to accurately recognize the visible properties of the vehicle while in space, the nanosatellite has been optically characterized in an AFRL ground facility to determine reflective signatures that can be expected on orbit. Once on orbit, the Oculus-ASR will be monitored by ground-based telescopes and these observations will be reconciled against the 'truth' attitude data recorded by the Oculus-ASR during various overpasses.

Operations of the Oculus-ASR will require coordination between AMOS, AFRL, and Michigan Tech University's (MTU) ground operators. Aside from controlling the vehicle, 'truth' data, overpass scheduling, and maneuver planning will serve as key points of communication between all organizations involved.

INTRODUCTION

As access to space has become more common, the number of objects orbiting Earth has increased drastically. Some of these objects are functional satellites that perform vital operations for commercial or military purposes. However, many of the objects orbiting Earth are debris made up of defunct satellites, spent rocket stages, and wreckage of satellites destroyed in anti-satellite weapon tests or collisions. These objects pose a growing threat to functional satellites. Collisions with orbital debris can cause damage to essential commercial and military assets that would render them useless. Therefore, it is beneficial for the space community to have an accurate knowledge of current and future locations of orbiting objects. The effort to identify, catalog, and track the objects orbiting Earth, both functional and nonfunctional, is part of the overall Space Situational Awareness (SSA) activity.

Ground-based optical telescopes are one key instrument in achieving SSA. In addition to determining the trajectory of an orbiting object, optical telescopes can also be used to determine the object's attitude characteristics, physical profile, and external features. A drawback of using optical telescopes for such Attitude and Shape Recognition (ASR) is the fundamental limitation of resolvability. Orbiting objects become unresolvable at high orbits or when small telescope apertures are used. In fact, most objects in orbit fall outside the resolvable range of most ground-based telescopes. Under these conditions, a telescope sees the object as a point-source of light and it is impossible to distinguish features of the object from the telescope image.

While spatial features cannot be determined from unresolved 'dots' of light, these dots contain spectral and photometric information that can be used to deduce properties of the object. Using unresolved imagery to observe and characterize orbiting objects with the goal of determining their attitude and detecting configuration changes (e.g. panel deployments, etc) is important. This is accomplished by analyzing the spectral frequencies and temporal changes in the intensity contained in the point-source of light and referencing the measured signals with known spectral signatures. If successful, this technique could lead to an inexpensive network of sensors with broad coverage.

Given an orbiting object with known optical properties it is relatively straightforward to predict the observed signature if the object's attitude or maneuver is specified. This paper focuses on the inverse problem: given a measured optical signature generated by an object with known properties is it possible to calculate the object's attitude? While, in principle, this problem can be addressed the algorithms are non-trivial and require validation and/or calibration. Calibration opportunities are rare as they require pre-characterization or at least optical modeling of the orbiting object to create a signature database prior to launch.

The Oculus-ASR is a nanosatellite being developed through the collaboration between Michigan Technological University (MTU), the Air Force Maui Optical Site (AMOS), and the Air Force Research Laboratory, (AFRL). In January 2011 the Oculus-ASR team won the sixth University Nanosatellite Program competition (UNP). The UNP is a national, university-level competition run by the Air Force Research Laboratory and funded by the Air Force Office of Scientific Research. As the winner of this competition, the Oculus-ASR team of undergraduate students has been getting ready for flight preparation with assistance through the AFRL.

OCULUS-ASR MISSION

The Oculus-ASR's mission is to provide calibration opportunities for ground-based observers at the Air Force Maui Optical Site (AMOS) attempting to validate and/or anchor algorithms capable of determining spacecraft attitude and configuration using unresolved optical imagery.

Once in orbit the Oculus-ASR will serve as a cooperative imaging target for AMOS, and other ground-based telescope facilities. Ground controllers at MTU will command the vehicle to perform various attitude maneuvers and profiles during overpasses of these observation facilities. After each viewing opportunity the MTU team will provide the down-linked attitude truth history from the Oculus-ASR to the AMOS team for comparison with their observations from the ground. The primary goal behind the Oculus-ASR is to exercise at least three key capabilities of telescopes using unresolved optical imagery: determine a spacecraft's attitude, detect configuration changes, and measure the change in signature due to a small resident space object in close vicinity to the main vehicle.

It should be noted that the optical signature of the vehicle has been extensively characterized in ground facilities; the optical characterization section of this paper describes some of the results of these tests. A final flight optical characterization will be carried out again prior to launch.

OCULUS-ASR DESIGN

Oculus-ASR is a 70-kg satellite with a structural volume envelope of 50 cm by 50 cm by 80 cm. It consists of two modules that are permanently attached. An octagonal module, referred to as the Oculus module, sits atop a square module, known as the ASR module. Figure 1 shows the flight Oculus-ASR satellite as a 3D Model.

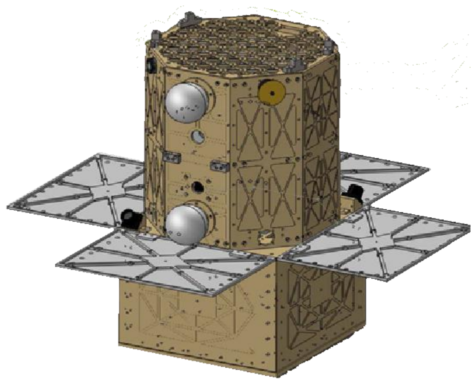

Figure 1: The Oculus-ASR vehicle

Each of the four sides on the ASR module has a deployable panel, which will allow the satellite to change its shape while in orbit. Three of these panels are covered in solar cells on the top face (Not Shown). The fourth is covered in Duraflect material. Duraflect is a highly reflective, diffuse white coating used as an optical standard for characterization and calibration measurements. Under and on the back of each deployable panel are specific materials requested by AMOS for their distinct spectral characteristics. These materials will be red, blue, yellow, and clear anodized aluminum (or similar). Each panel is deployed separately through the actuation of Frangibolt actuators. Spring-loaded hinges then lift the panel until it locks in place 90° from its undeployed position. These individual deployable panels with their anodized coatings allow the spectral signature of Oculus-ASR to be changed multiple times over the course of the mission by altering the vehicle’s shape and exposed materials.

Two releasable objects are mounted to the Oculus module in order to assist ground observers with the “closely spaced object” problem. These white spheres are approximately 10 cm in diameter and will be used to provide ground observers an opportunity to view small, closely spaced objects. The releasable objects are coated in the same Duraflect material used on the deployable panel, and can be released individually using the same style of Frangibolt actuator used for the deployable panels. These objects then drift from the vehicle due to the force exerted from the actuator.

In order to keep track of the vehicle roll rates and pointing direction, the Oculus-ASR employs two attitude determination components. This attitude determination is accomplished using a Honeywell HMR2300 Digital Magnetometer and three Silicon Sensing SiRRS01-05 gyroscopes. These sensors are able to provide an attitude reading accurate to within 5 degrees of error. Oculus-ASR is also a three axis stabilized spacecraft. Three magnetic torquers (one for each axis) are used to control the vehicle’s attitude. The magnetic torquers were designed, built, and tested by students at Michigan Tech University.

The solar cells on Oculus ASR are 28.3% Ultra Triple Junction (UTJ) Solar Cells with interconnects, and were donated by Spectrolab. The satellite will consist of 15 strings of 13 cells, and will supply power to the charge controller, which will then supply power to the battery and the satellite subsystems. They will be soldered together into strings of 13 and then attached to PCB. The PCB will then be attached to the satellite.

Concept of Operations

On-orbit, one of Oculus-ASR’s roles will be to fulfill requests to view specific attitude profiles during overpasses of the observatory. These attitude profiles are described with regards to a body coordinate system (BCS) and an orbital coordinate system (OCS).

AMOS and any participating telescope operators may select maneuvers and attitude profiles from a list of predetermined attitude profiles. These include, but are not necessarily limited to:

Ready: Rotation rate about any axis is less than 2 °/s; the angles between the BCS and Orbital Coordinate System are uncontrolled

Inertial Fixed Attitude Satellite attitude can be fixed inertially, which is taken to be with respect to a coordinate system centered at the center of mass of the Earth and not rotating with time.

Roll: Roll around the specified body coordinate axis or axes at a specified rate. If this must take place in a certain location above a point on Earth's surface, the appropriate attitude must be reached ahead of time via inertial pointing.

Earth Pointing: A vector in the BCS is kept pointed at a fixed location on the Earth's surface.

Orbital Coordinate System Fixed Attitude: Constant angles between the BCS and OCS with zero rotation; attitude is constant with respect to the OCS.

Sun Pointing: A vector in the BCS is kept pointed at the Sun.

Interaction with AMOS for the primary mission will take place during two four-month data campaigns, termed Campaign I and Campaign II. These campaigns will be chosen to coordinate with the MTU academic calendar if possible. Each campaign will consist of a number of pre-planned viewing opportunities called Passes. A Pass is defined as a single over-flight of the AMOS ground-viewing station during which AMOS researchers will task their observatory to monitor the Oculus-ASR. The first campaign will be scheduled after the Oculus-ASR has successfully completed Initialization and Testing.

Approximately one month before each campaign MTU will provide AMOS with a list of all possible pass opportunities that will occur within the campaign window. AMOS will return this list with their preferred pass events identified and requested attitude profiles/actions for each potential pass. Based on this input MTU will prepare a Campaign Plan that defines the schedule that will be followed for the duration of the campaign. At the end of Campaign I, Michigan Tech will collaborate with AMOS and plan out a second four-month campaign of a similar format. During an individual campaign MTU will consider requests from AMOS to deviate from the plan and will evaluate these requests based on availability of ground resources.

During pre-determined viewing overpasses, Oculus-ASR will be recording a time-indexed history of its attitude. After an overpass maneuver, this attitude history will be downloaded to the MTU ground station, where it will be delivered to the Air Force Maui Optical Site personnel.

As discussed previously, the Oculus-ASR will also change its physical configuration and shape through the use of the deployable panels. Deployment of a panel changes both the projected profile of the vehicle and the exposed materials on the exterior of the vehicle. Each panel exposes a spectrally distinct material. There are a total of four deployable panels on the satellite, which can be deployed individually to provide four distinct changes in Oculus-ASR's physical configuration. Once deployed the panels cannot be retracted. After establishing baseline measurements of the vehicle in its as-launched configuration, telescope operators will request the deployment of a panel. The operators of Oculus-ASR will command the deployment and confirm the successful opening of a panel. Telescope operators can then take further measurements and compare these to the baseline measurements in order to determine which panel was opened and when the actuation occurred.

Once all missions have been either completed or the satellite has been disabled by hardware failure, the satellite will enter Repeater Mode. Normal mission operations will cease and the satellite will be commanded to function as a digital repeater for amateur radio use. In the case of failures causing harmful satellite operations, the option is retained to "kill" the satellite by commanding it to power down all systems. Once all systems have been powered down the Oculus-ASR will not be able to be revived and will be considered dead.

PRE-LAUNCH CHARACTERIZATION

SSA relies not only on measurements of space objects but on an understanding of what those measurements mean. In order to understand the signatures of space objects, it is necessary to measure, model, and simulate the spatial characteristics of spacecraft. One of the objectives of the Oculus-ASR characterization experiment was to provide ground-truth satellite data for the construction and validation of predictive computer models such as those used in Time-domain Analysis Simulation for Advanced Tracking (TASAT), a satellite modeling code used throughout the SSA community. Another objective of this experiment is to establish if pose determination is possible solely from on-orbit spectral returns. Imaging the satellite on the ground will help ascertain whether or not this objective can be met.

Multispectral optical measurements of the Oculus-ASR satellite were conducted at an Air Force Research Laboratory (AFRL) far-field optical measurement facility by an AFRL program. This facility allows accurately simulated observations of space objects without significant atmospheric effects. This ability provides the opportunity to measure the optical signatures of satellites and then modify corresponding satellite models to improve agreement with these ground-truth optical signatures. This characterization experiment obtained accurate far-field imagery, Optical Cross Section (OCS), and spectral-polarimetric glint and off-glint data helpful in validating remote observations.

The use of anodized colored panels on the Oculus-ASR satellite base was intended for the purpose of inferring satellite pose or attitude from observations. Satellite imagery for typical on-orbit viewing geometries will not be resolved. In certain poses, when the satellite is observed from the ground, metallic glints or non-colored panel reflections will often dominate the OCS and mask the colored panel contributions. It is important to understand which spectral filtered wavebands will contribute the most attitude information. Common astronomical filters are V-band (550nm center wavelength with a nominal full width half maximum specification of 90nm), and I-band (800nm center wavelength with a nominal full width half maximum specification of 150nm); often, these bands along with broadband images are obtained. The Oculus-ASR ground-truth characterization acquired broadband, V-band, I-band, and 650nm narrow band (10nm bandpass) filtered images as well as spectral data spanning the 350nm – 2500nm wavelength range.

TASAT MODELING AND SIMULATION

Several different predictive models of the Oculus-ASR satellite were built for use in TASAT. The models were built using engineering diagrams, documentation photos, and visual inspection of the satellite. A total of four models were built, with different features on each. The first and second models have the wing panels secured down, both with and without the deployable spheres attached. The second and third models have the wing panels deployed, both with and without the spheres attached. The left side of **Figure 4** shows a rendered image of the satellite model with the colored wing panels secured down and the sphere deployed; the right side of the figure shows a rendered image of the satellite model with the wings deployed but the spheres attached. These renderings were generated directly from the 3D satellite model.

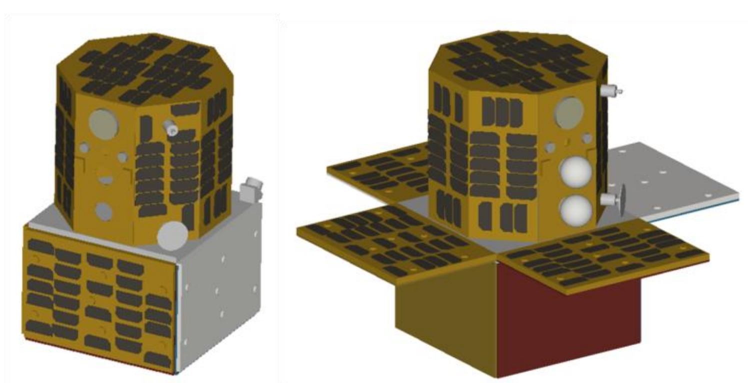

Figure 4: Rendered Oculus-ASR satellite 3D models with (a) wings secured down, no spheres and (b) wings deployed, with spheres

Figure 5 shows the material breakdown on two of the models. The materials used on the model are shown in decreasing order of percent contribution to the surface area given the orientation. The materials were selected based on a description of the materials visible on the satellite. Note that two additional models were built similar to this, the only difference being that the spheres were removed. The same materials were used for those models as well.

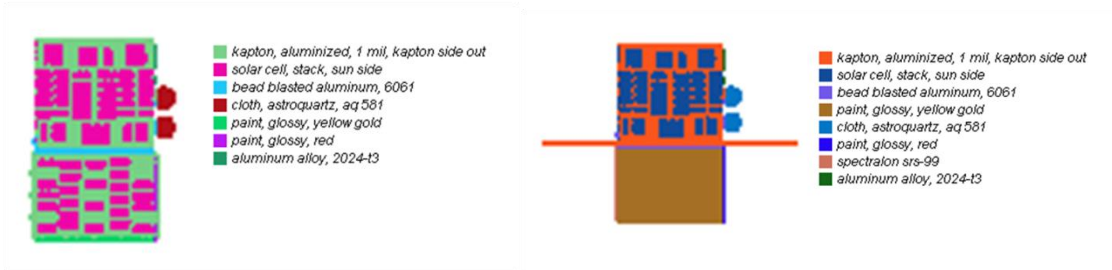

Figure 5: Oculus-ASR model showing two different wing configurations, but both with the spheres attached

TASAT simulations were conducted in order to compare predicted imagery with the ground truth imagery. The satellite was "posed" in TASAT to simulate facility measurement geometries. The same wavebands were also used in the simulations. The simulated OCS data for all wavebands is shown in **Figure 6**. Eight strong glints are prominent in the plot corresponding to the solar panel glints. The strongest glints represent the reflection from the solar panels on the octagonal structure and the solar panels on the base. The weaker glints correspond to only glints from the octagon, as the base was at a corner at these rotation angles.

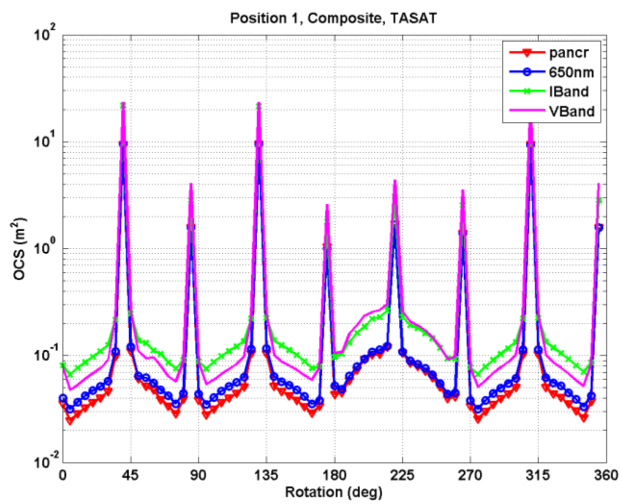

Figure 6: TASAT simulated imagery of Oculus-ASR in position 1

OPTICAL MEASUREMENT RESULTS

A detailed optical characterization of the Oculus-ASR vehicle was reported previously by King, Hohnstadt, and Feirstine(1); these results are summarized here

PIXIS Imagery

Figure 7 shows PIXIS imagery for satellite rotations of 20° (off-glint), 90° (octagon glint), and 135° (octagon and base glint) in the I-band for two positions, position 1 with the panels secured down and position 2 with the panels deployed. Note that because of the choice of reference material (based on the satellite radiance), the image scaling is different between the first image and the next two images. Because of the large dynamic range between the glint and off-glint rotations, both glass and Spectralon were used as references. These PIXIS images are used to calculate the OCS data that follows.

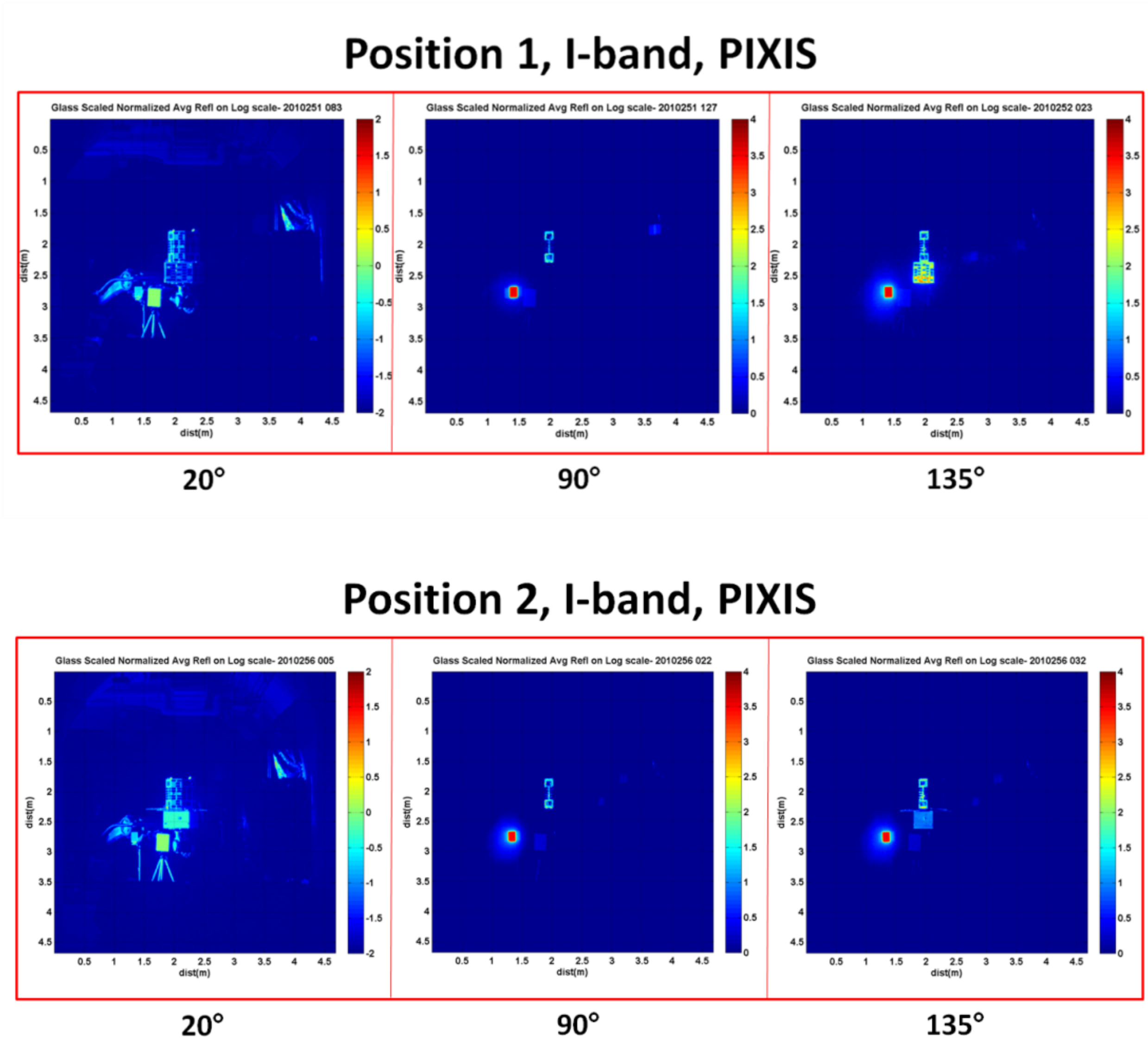

Figure 7: PIXIS I-band images at three rotation angles for two positions

Note that in position 2, the colored panels on the base of Oculus-ASR are deployed. For rotation angles of 45°, 135°, and 315°, both the colored panel and the top solar panel glint; for rotation angle 225°, only the red colored panel glints. The solar panel peak glints (0°, 90°, 180°, and 270°) are not resolved and the solar panel glint width is smaller than that for the colored panels. This is evident in **Figure 8**.

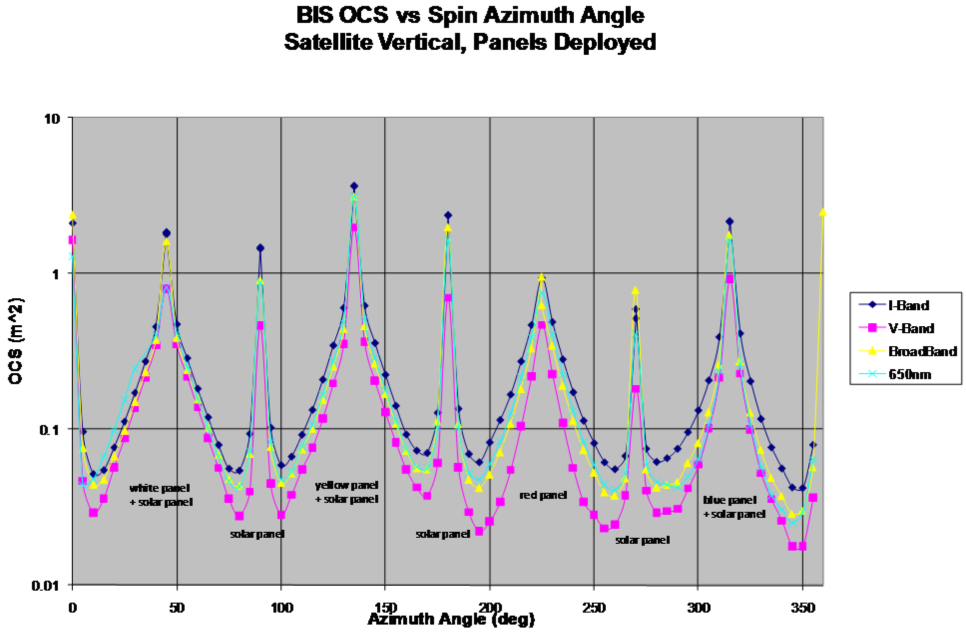

Figure 8: PIXIS OCS data for position 2 in all 4 wavebands

It is not likely for ground-based telescopes to observe sharp solar panel glints unless special efforts are made to align the satellite appropriately. More likely geometries are off-glint positions where the satellite is not completely nadir-pointing, as in position 2.2. Please note the glyph in the top right corner of **Figure 9**. In some figures, the glyph has been transposed so the illumination angle is different. This does not affect the analysis. OCS results for the Oculus-ASR satellite while in position 2.2 are shown in **Figure 9**. Because the geometry is off-specular, the OCS values are less than $0.1m^2$. The visible colored panel is labeled in the figure. Sharp solar panel glint contributions are not apparent in this position; the four peaks in the plot are associated with the colored panels.

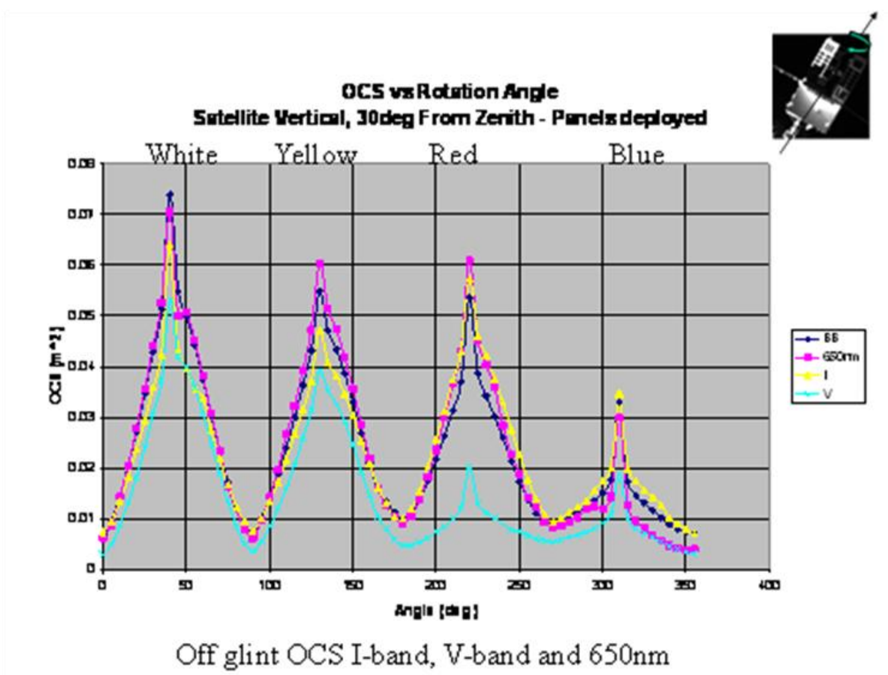

Figure 9: OCS values as a function of spin azimuth and waveband for position 2.2

The spectral angles or correlations are shown in **Figure 10**. As seen in the figure, when the red coupon serves as the reference (the red line), the spectral angle is minimum when the red panel is prominent on the satellite. Similarly, the spectral angle when the blue coupon is used is minimum when the blue panel is prominent. In further examination of the plot, when the yellow coupon is used as a reference, there are a few minimums suggesting that the yellow-gold reflection of the satellite bus rather than just the yellow colored panel is influencing the results. Also as seen in the figure, the yellow coupon reference correlates strongly with the white panel. Because of the choice of filter bands, the discrimination between the yellow, red, and blue panels is not good.

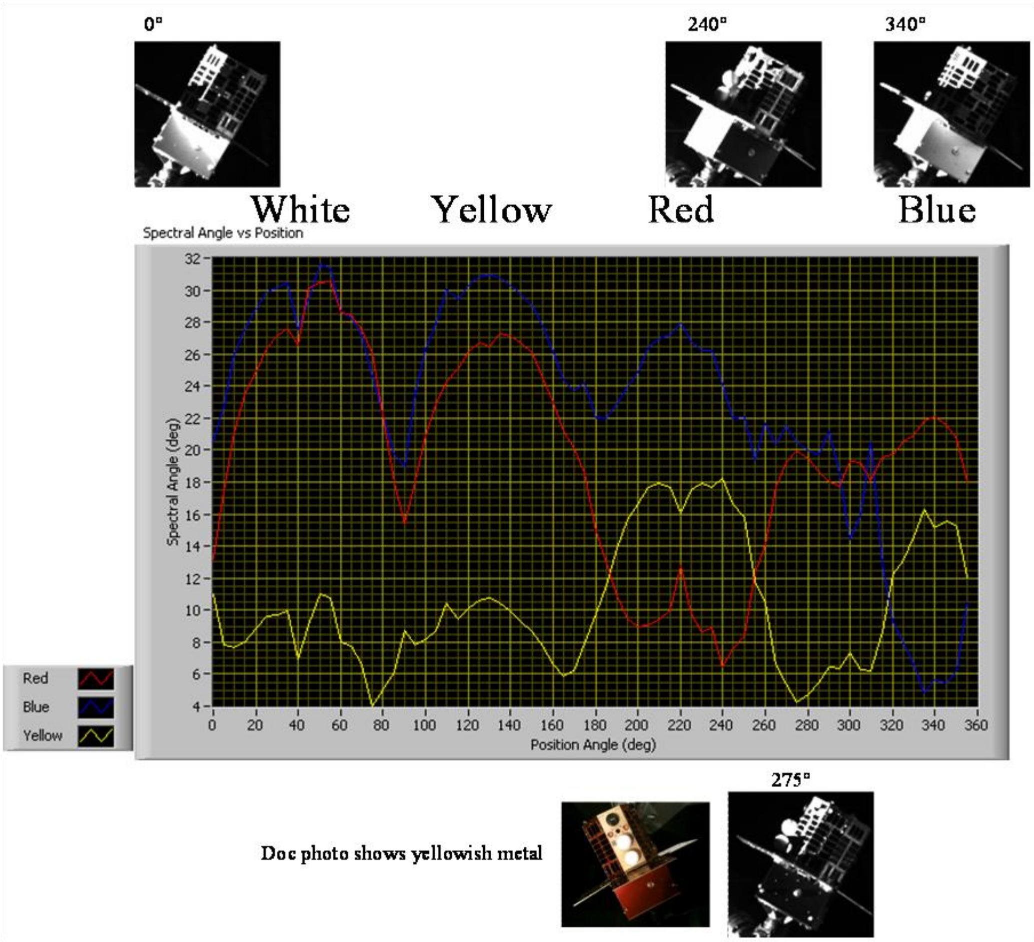

Figure 10: Spectral angle dot product results (red, blue, and yellow BRDF vectors dotted with OCS V, I, and 650nm filter vector) as a function of spin azimuth for position 2.2

CONCLUSIONS

A successful ground-truth characterization experiment was performed on the Oculus-ASR satellite. Optical signatures of the satellite were acquired which were then used to build the 3D predictive satellite models. Based on the accurate imagery and glint and off-glint ground truth datacollected, the predictive models were validated and improvements were made to the simulation and materials database in order to improve simulated and ground truth optical satellite signature agreement.

It is concluded that determination of which colored panel of the Oculus-ASR is most visible from on-orbit spectral data is plausible upon analysis of ground truth data. Pose determination can then be estimated based on the most prominent colored panel visible. However, the current satellite material choices and the chosen wavebands that data was acquired in were not optimum. One change that may improve spectral signature collection and pose determination would be to change the panel colors from red, yellow, and blue, to red, green, and blue. The spectral difference between these colors is greater than the first set of colors. Also, using more diffuse materials such as a diffuse colored paint may provide larger signals at non-specular geometries. The choice of wavebands to acquire data in was not optimum. RGB 50nm FWHM filters would work best with the recommended panel color change. Additionally, a polarizer may remove much of the first surface reflection which will increase the difference in spectral signal among wavebands.

The objectives of the Oculus-ASR mission stated in the introduction were successfully completed. A ground-truth characterization of the spacecraft was performed to aid in the understanding of space object signatures for SSA. Based on the ground-truth characterization data, successful construction and validation of predictive computer models was accomplished. And an investigation in pose determination from on-orbit spectral returns was performed.

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PCB Piezotronics
Raytheon Missile Systems
SAIC
Spectrolab
Systems Integration Plus Incorporated
TiNi Aerospace
Tyco Electronics
Wind River

Works Cited/Referenced:

1) King, Hohnstadt, Fierstine. *Pre-launch Optical Characteristics of the Oculus-ASR Nanosatellite for Attitude and Shape Recognition Experiments*. 2011 SmallSat Conference