MODELING THE EFFECTS OF SOLAR CELL DISTRIBUTION ON OPTICAL CROSS SECTION FOR SOLAR PANEL SIMULATION

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Abstract

The Air Force Research Laboratory (AFRL) Time-domain Analysis Simulation for Advanced Tracking (TASAT) was used to explore the variation of Optical Cross Section (OCS) with glint angle for a solar panel with different solar cell distribution statistics. Simulations were conducted using a 3D model of a solar panel with various solar cell tip and tilt distribution statistics. Modeling a solar panel as a single sheet of "solar cell" material is not appropriate for OCS glint studies. However, modeling each individual solar cell on the panel, the tips and tilts of which come from a distribution of specified statistics (distribution type, mean, and standard deviation), accurately captures the solar panel OCS with glint angle. The objective of the simulations was to vary the glint measurement angle about the maximum glint position of the solar panel and observe the variations in OCS with angle for a bi-static illumination condition. OCS was calculated relative to the simulated scattering of a Spectralon® material in the glint orientation. Results show the importance of solar cell distribution statistics in modeling the OCS observed for a solar panel.

Keywords: optical cross section, solar cell tip and tilt, modeling and simulation, Spectralon®

2 Introduction

There are many objects orbiting the Earth, ranging in size from small debris that could pose a potential hazard to other critical assets in space to large satellites and objects such as the International Space Station. It is important to understand and characterize the optical signatures of each of these space objects for Space Situational Awareness (SSA), or the ability to detect and track space objects and determine their capability or intent. This optical signature information aids in the understanding of the space environment as a whole. But in order to understand these optical signatures, a means to accurately measure, model, and simulate the space objects is necessary. As many objects orbiting the Earth have solar panels on their surface, it is of particular interest to understand and characterize optical signatures of solar panels.

Understanding the optical signatures of single material objects such as solar cell is relatively straight-forward. If the material and size are known, material properties such as Bidrectional Reflection Distribution Function (BRDF) can be measured, a model of the object can be manufactured and characterized in a far-field optical measurement facility to determine the Optical Cross Section (OCS), and the optical signature can be modeled with a code such as Time-domain Analysis Simulation for Advanced Tracking (TASAT), a legacy Air Force Research Laboratory

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14. ABSTRACT

The Air Force Research Laboratory (AFRL) Time-domain Analysis Simulation for Advanced Tracking (TASAT) was used to explore the variation of Optical Cross Section (OCS) with glint angle for a solar panel with different solar cell distribution statistics. Simulations were conducted using a 3D model of a solar panel with various solar cell tip and tilt distribution statistics. Modeling a solar panel as a single sheet of ?solar cell? material is not appropriate for OCS glint studies. However, modeling each individual solar cell on the panel, the tips and tilts of which come from a distribution of specified statistics (distribution type, mean, and standard deviation), accurately captures the solar panel OCS with glint angle. The objective of the simulations was to vary the glint measurement angle about the maximum glint position of the solar panel and observe the variations in OCS with angle for a bi-static illumination condition. OCS was calculated relative to the simulated scattering of a Spectralon? material in the glint orientation. Results show the importance of solar cell distribution statistics in modeling the OCS observed for a solar panel.

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(AFRL) satellite simulation code used throughout the satellite modeling community. The appropriate radiometry can be simulated and compared to measurements, resulting in a better optical characterization of the solar panel.

Optical signature experiments performed with solar panels suggest that the far-field glint from a solar panel is unique to that panel and therefore is the panel's signature. Each solar cell has its own complex reflection signature with variations in polarization, wavelength, and intensity as a function of incident and reflection angle. When many solar cells are assembled into a solar panel with small random variations in tilt angle, the result is a very complex panel glint signature that is much larger than would be expected from a single cell. Because each solar cell is attached by human hands, each panel has a different signature and should be modeled differently. This makes the modeling of solar panels very difficult. The data presented in the paper will show comparisons between far-field optical measurements and TASAT simulations with and without random tip-tilt effects applied to individual solar cells.

3 Data Collection Methodology and Data Processing

Multispectral optical measurements of space objects can be acquired at an AFRL far-field optical measurement facility. The imaging facility allows the collection of accurately simulated observations of space objects without significant atmospheric effects. Having the ability to do this provides the opportunity to measure the optical signatures of satellites for which it is feasible to relocate to the facility. The data from the optical measurement facility is accurate passive far-field imagery, OCS, and spectra helpful in understanding optical space object signatures.

The use of the term far-field intensity distribution or passive OCS in this paper is analogous to the reflective pattern of a distant object in solar illumination. This definition is based on a discussion of radiant intensity as related to a source as discussed in Reference [1]. In short, when the observing distance is larger than $\frac{L}{\Theta_S}$ where Θ_S is the angular diameter of the sun and L is a characteristic length of the largest smooth surface on the space object, the reflected spatial intensity pattern is circular [1]. This distance (D_{obs}) is called the far-field. Any distance less than D_{obs} is considered the near-field where the reflected spatial intensity pattern is not circular.

$$D_{obs} = \frac{\mathrm{L}}{\Theta_\mathrm{S}}$$

D_{obs} = Observing distance

L = Length of the largest smooth surface on the space object

Θ_S = Angular diameter of the source

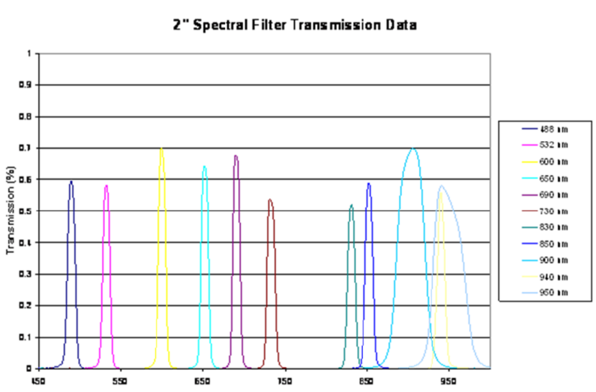
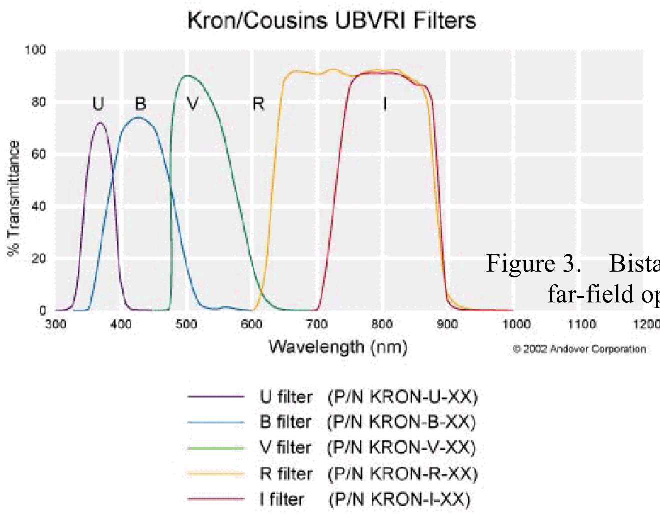


Figure 1. Spectral filter transmission data across the PIXIS waveband.

The next few paragraphs discuss the scientific equipment used at the far-field optical measurement facility as well as the measurement and analysis approach. A digital scientific imaging camera called the PIXIS provides 16-bit data from 400nm − 900nm. Filtered waveband images can be acquired at several different bandwidths with filters that span the Quantum Efficiency (QE) range of the PIXIS. The filters are narrow band filters. The spectral transmission of these filters is shown in Figure **Error! Reference source not found.**. The filter chosen for use in the first data collects of this experiment was the 650nm filter. The quantum efficiency of the PIXIS camera peaks in this waveband.



There are two additional astronomy filters that can be used as well, V-band and I-band filters. The spectral transmission of these two filters is shown in Figure **Error! Reference source not found.**. In addition to the scientific imaging camera, an Analytical Spectral Devices spectroradiometer (ASD) can be used during the data collects as well. The ASD provides continuous spectral information from 350nm − 2500nm. A 6-Degree of Freedom (DOF) robotic arm at the optical facility can be used to pose the space objects. The robotic arm can manipulate a payload of up to 200kg and has a repeatable accuracy within +/−0.5mm.

Figure 2. Transmission graph of the Kron/Cousins V- and I-band spectral filters.

The measurement approach relies on the fact that a couple of requirements are met. First, the space object must be in the far-field as described by the definition above. When the object is imaged in the far-field, accurate optical signatures can be measured. Second, accurate far-field measurements rely on a reference material in the scene with the space object at all times. Atmospheric variations and absorption lines that would become troublesome in the analysis fall out of the measurement when images can be normalized to a known reference image under the same lighting conditions. Solar passive space object surface radiance can vary largely, so a reference material that exhibits the same brightness independent of illumination and surface orientation is ideal. The reference should also be spectrally flat over the entire measurement wavelength range. Spectralon is a good diffuse reference for these types of measurements, though it has a limited range of acceptance angles and exhibits enhanced backscatter in a monostatic geometry. The backscatter is not a concern in this experiment as the only geometry used is a bistatic geometry with a 90° Solar Phase Angle (SPA), as depicted in Figure **Error! Reference source not found.**.

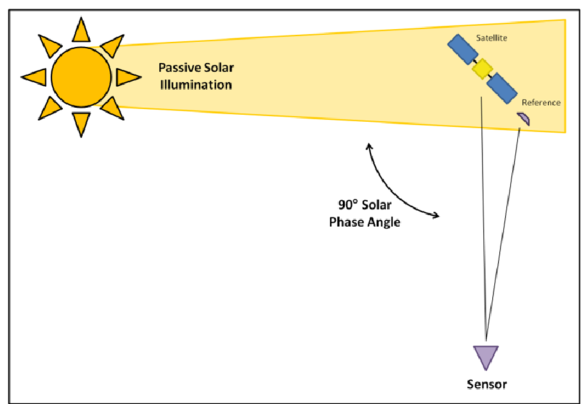


Figure 3. Bistatic illumination geometry for the far-field optical measurement facility.

Once the reference is chosen, it is imaged in the scene with the space object at all times. The space object data is normalized to this reference and the result is scaled to OCS which is in units of $[m^2]$. The Spectralon surface brightness with units of $\left[\frac{W}{m^2\, sr\, \mu m}\right]$ is related to the irradiance with units of $\left[\frac{W}{m^2\, \mu m}\right]$ by a factor of $\frac{1}{\pi}$. Normalizing by the irradiance minimizes the atmospheric effects and could remove lens Field of View (FOV) and vignetting effects, as well as mitigate issues with non-uniform illumination of the space object. This way, the far-field imagery, spectrum, and any simulation data can be compared directly.

4 Far Field Imaging Results

In order to generate the OCS data needed to compare to a tip-tilt model, a solar panel with visible random tip-tilted solar cells was placed in the measurement facility and rotated about the vertical axis. The PIXIS camera was used to obtain low noise, resolved measurements of the solar panel for up to twelve wavebands in the spectral range from 400nm-900nm. PIXIS image data was collected through the glint angle in 0.1° increments as shown in Figure 4. For this data collection, the glint angle had been pre-determined (defined as zero degrees) and allows the angular glint distribution to be mapped out through small angular rotations. A piece of reference Spectralon® material was placed in the image, and was used in post-processing to perform the OCS calculation. Spectralon has been shown to be a very good representation of a Lambertian surface for angles not exceeding roughly 60 degrees from normal. An example of this image with the calculated OCS is shown in Figure 5. The images in Figure 4 are only to show variations in the reflected pattern when the solar panel is rotated about the vertical axis. The 2-D character of the glint pattern can be seen in Figure 6. This image is a picture of the near field reflection of the solar panel off a wall in the imaging facility.The pattern in this image is intended to illustrate the issues with using localized panel or solar cell measurements to infer the far field reflection pattern of the solar cell array.

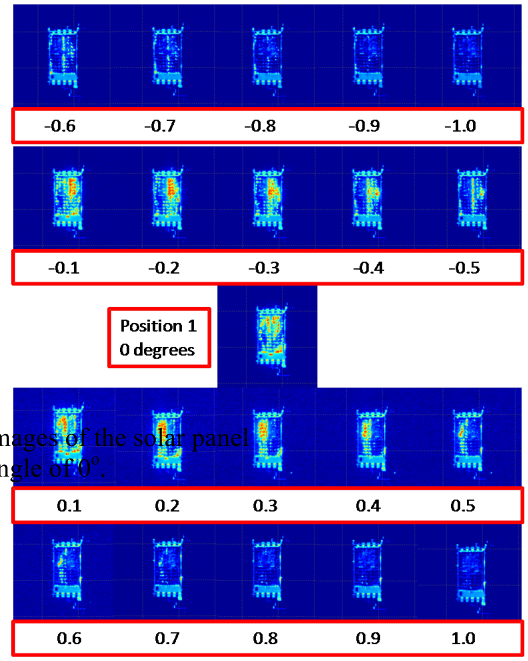


Figure 4. Pixis images of the solar panel through the glint angle of 0°.

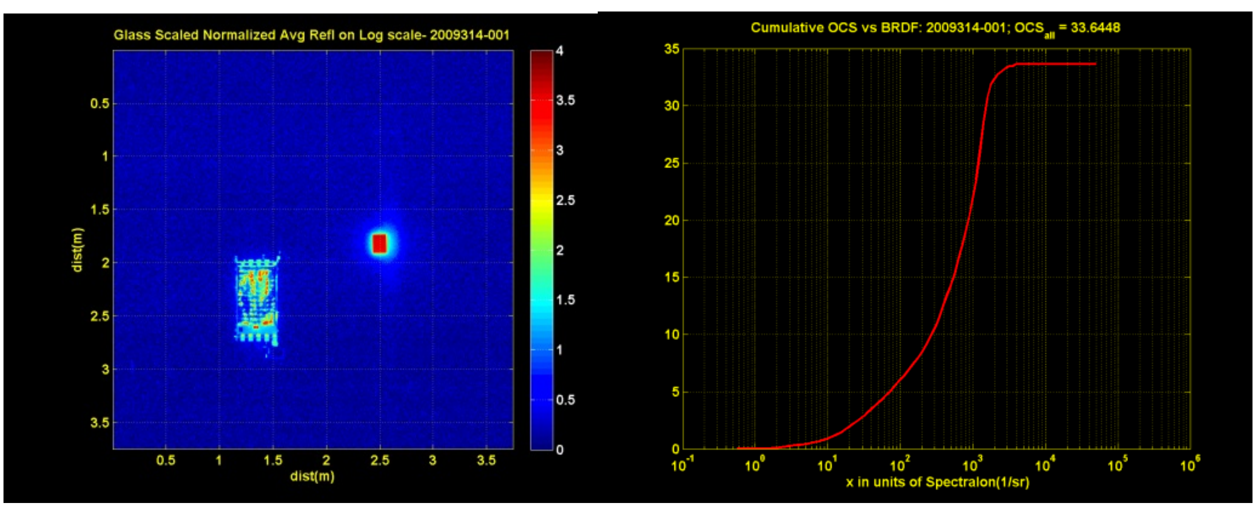


Figure 5. Pixis image of solar panel with Spectralon® reference (left), and calculated OCS relative to Spectralon® (right)

Figure 6. Solar panel reflection off a flat surface. This figure illustrates the complex 2-D pattern of individual tip-tilts from solar cells.

5 Modeling and Simulation Comparison

The solar panel was first modeled as perfectly flat individual solar cells made of solar cell material. The solar panel was created as a CAD model and simulated with the imaging facility parameters with TASAT. TASAT uses a BRDF to apply scattering effects for the chosen material. TASAT produces a unit irradiance image that is directly comparable to a scaled PIXIS image. Figure 7 shows the initial comparison of the scaled PIXIS image to the TASAT simulation of a single "sheet" of solar cell material, in an off-glint position. Clearly the far field comparison shows major differences in the OCS calculation (off by a factor of almost 7). Also, and as expected, the simulation catches none of the fine detail of the solar cell tip-tilt reflection pattern.

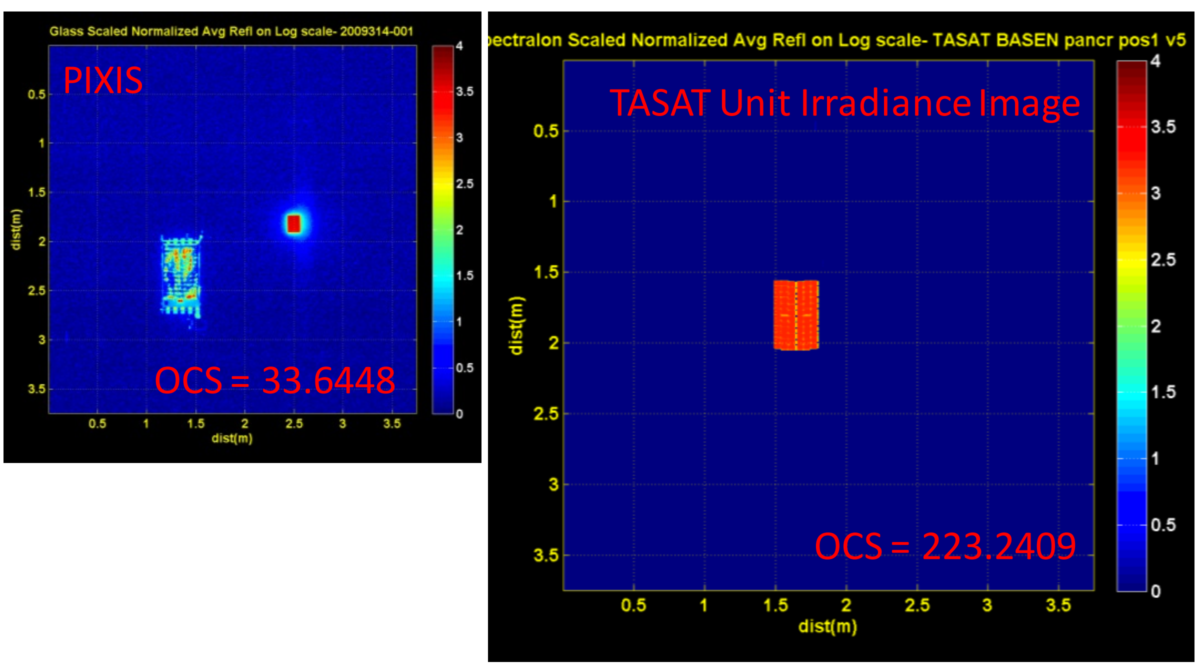
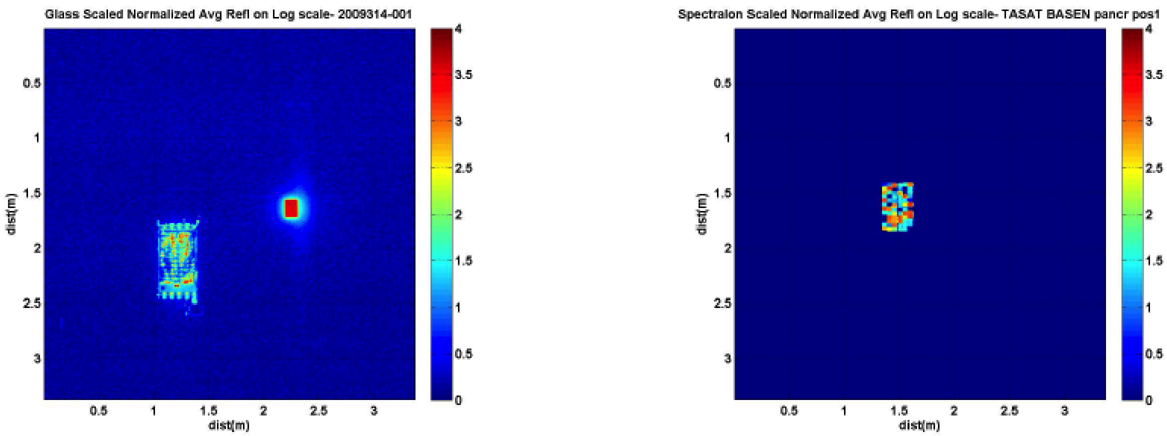


Figure 7. Comparison of PIXIS far field image to TASAT simulation of a single "sheet" of solar cell material

Next, a tip-tilt scheme was applied to the individual solar cells on the solar panel model. The solar panel used contains 72 cells arranged in 6 columns of 12 cells. The individual solar cells can be rotated in two directions, vertically (tip) and horizontally (tilt). A Gaussian distribution was assumed for both the tip and the tilt of the cells on the panel. One Gaussian random distribution containing 144 values (72 cells * 2 rotations on each) with a mean of zero and a standard deviation of 0.3 was generated using Matlab. The first half of the numbers in the distribution were set as the individual solar cell tilt values and the second half of the numbers were set as the individual tip values. TASAT simulations were run with the new model and the results are shown in Figure 8. Clearly the addition of the tip-tilt scheme has drastically improved the comparison, both visually and across the collection angles through the glint position. Since each solar cell is attached by human hands on the panel, a random distribution will not match the actual solar cell distribution exactly, though it can get very close, and is a good statistical comparison.



PIXIS normalized average reflectance TASAT normalized average reflectance

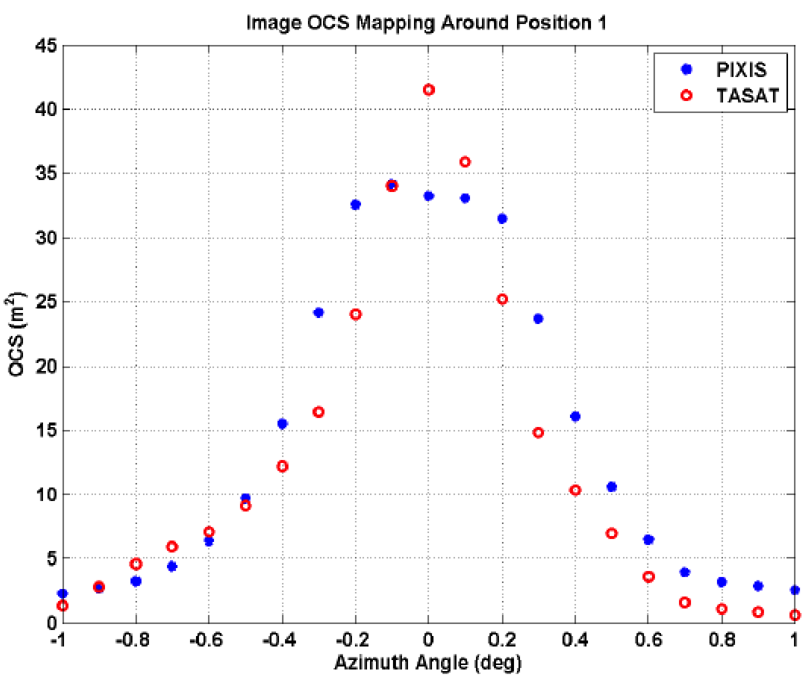


Figure 8. TASAT comparison to PIXIS imagery with a tip-tilt scheme applied to individual solar cells.

6 Conclusions

This paper presented a methodology to statistically model random tip/tilt effects observed on solar panels. Understanding the optical signatures of space objects is important in SSA efforts going forward, and the ability to understand the signatures of complex patterns will definitely help characterization for space object imaging. The PIXIS images from the glint mapping measurements were compared with TASAT images for the same positions. The solar cells were aligned in tip and tilt using a Gaussian distribution representing the glint mapping measurement OCS distribution calculated from the data. Using this approach, the TASAT simulation glint mapping OCS magnitudes were found to have similar statistics (mean and standard deviation) as the measurements, indicating good model agreement statistically.

7 References

[1] L. Mandel and E. Wolf, *Optical Coherence and Quantum Optics*, s.l.: Cambridge University Press, 1995.

[2] King, L., Hohnstadt, P., and Feirstine, K., Pre-launch Optical Characteristics of the Oculus-ASR Nanosatellite for Attitude and Shape Recognition Experiments. AIAA/Utah State University Small Satellite Conference; 2011 August; Utah State University, Utah.