Space Object Radiometric Modeling for Hardbody Optical Signature Database Generation

Bernie Klem and Dave Swann
United States Air Force
Arnold Engineering Development Center
Advanced Missile Signature Center
Arnold AFB, TN

Abstract

Recent advances in spacecraft health monitoring have resulted in successful applications of photometry and light curve analysis to quantify measurable changes to the spacecraft by passive means. Subtle changes in degradation of spacecraft material properties, reorientation of central body attitude, and slight misalignment of major signature producing components (extended solar panels) are often detected under nonoptimized viewing conditions. It is beneficial to the observer/analyst to understand the fundamental optical signature variability associated with these detection and identification processes.

This paper captures the fundamental observable variations of representative convex surfaces that may exist in the surround for which the subtle change processes need to be detected. The key surface parameters include shape, orientation, altitude, surface - sensor - light source scenario, and material reflection characteristics. Specifically, this paper summarizes radiant intensity patterns as a function of prioritized key parameters as generated from moderate to high-fidelity simulations. The intent is to provide the analyst with an information-based capability to select the observation - sensing scenario that has an increased likelihood of successfully monitoring changes to the spacecraft.

The focus of the paper is to present a graphical database summary of typical meter-size convex surfaces that include a right circular cylinder, a right circular conical frustum, a right circular cone, and a thin circular disk. These objects are modeled in their major in-plane and out-of-plane orientations with respect to the sun and the earth, while situated at a low earth orbit (LEO) and a geostationary earth orbit (GEO) altitude location. Results are presented for broad visible spectral band observations as the sensor performs a complete "walk around" of the objects in the solar and solar-perpendicular planes to capture the diffuse and specular reflection signature characteristics resulting from both the direct sun and the earth albedo. Results are also presented for the cases where the space objects experience complete tumbling motion in these planes while being observed from a fixed sensor location. A partial database has already been generated demonstrating the complexity of the earth albedo diffuse and specular glint patterns for LEO altitude surfaces.

Continuous engagement with conference participants in the poster session is anticipated to provide a discussion agenda for expansion of the presented topics to include such areas as (1) simultaneous multiple color sensing, (2) introducing high-fidelity spectral material property simulation capability to the database, and (3) developing infrared observable features into the sensing and status identification algorithms.

Introduction

This presentation summarizes recent activity in monitoring spacecraft health status using passive remote optical nonimaging techniques. The motivation and objectives for this area of research are captured in Fig. 1. Since there is significant activity by a large number of researchers to identify changes in a spacecraft's operating health and configuration, optical techniques often focus on observing nontraditional signature patterns and interpreting the measurement results in terms of the existence of anomalous changes such as solar panel misalignments, antenna misdeployments, and unexpected central body reorientations. To support the analysis of interpretations it is important for the analyst to have a basic understanding of the fundamental signature characterization patterns that can result from observations of the simplest of spacecraft object shapes. With understanding and an application of the baseline signature feature characteristics, one is able to provide correct and improved assessment of the various anomalous event changes that can occur.

To support this effort, signature modeling tools, partially validated by using selected sets of measurements data, have been exercised to characterize specific space object optical signature patterns and generate a baseline signatures database for them. Selected results from that database generation are presented herein.

- **Motivation**
  - **There is significant activity in passive remote optical observations for monitoring spacecraft health status using nonresolved imaging**
  - **Complex optical signature patterns can result even when viewing simplistic convex geometry surfaces**
  - **These patterns can obscure differences in signature features resulting from anomalous events, e.g., solar panel misalignments, antenna misdeployments, unexplained body reorientations**
  - **Algorithm development often uses multiviewing aspect observations**

- **Objectives**
  - **Characterize and understand fundamental/baseline signature features in conjunction with exploiting the status of anomalous events**
  - **Use space surveillance community signature modeling tools to characterize spacecraft optical signatures**
  - **Describe selected results from AEDC/AMSC contributions to optical signature and feature database generation**

Fig. 1. Motivation and Objectives for Research Activity

Process and Definitions

Generation of the optical signature database for characterizing space objects required detailed planning to incorporate all of the meaningful parameters and their key values efficiently. Fig. 2 shows the key parameters, their values used in the database results presented to date, and a sketch of the coordinate system/geometry for the sensing scenario.

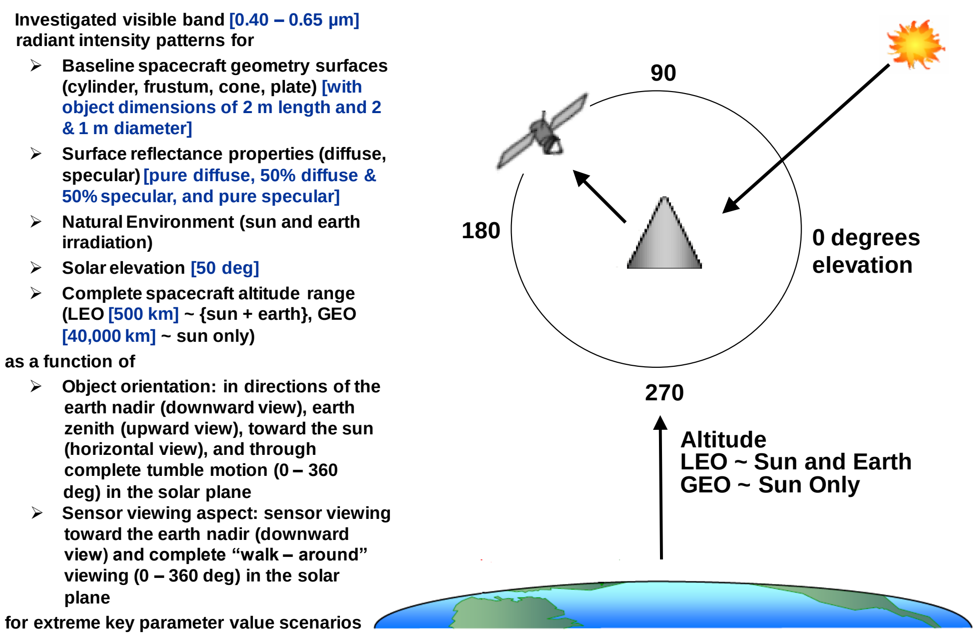

Fig. 2. Process and Parameters Used To Generate Signature Database

The key components to be considered consist of the spacecraft baseline surface geometries, the surface material reflectance properties, the components of the natural environment, the solar elevation, and the spacecraft altitude. The objects are assumed to be aligned at various orientations and viewed by the sensor doing a complete "walk around" in, and perpendicular to, the solar plane, or the object undergoes tumbling motion in those planes while being observed by a sensor at a specific location. An elevation of 0 deg is defined to be in the direction of the sun with the nadir and zenith observation angles defined accordingly.

To a reasonable approximation, it is sufficient for current purposes to assume that signature components accounting for both direct sunlight and earth albedo reflection represent the spacecraft intensity at low earth orbital (LEO) altitudes, whereas the sunlight reflection component alone is representative of the spacecraft intensity when located at geostationary earth orbital (GEO) altitudes.

Presentation Results Summary

Selected results generated for the activity described above are summarized in Fig. 3. Object orientation and/or motion are indicated along with the sensor viewing conditions, object shape, and object material characteristics. Where identified, the entries in the table correspond to charts presented in the pages that follow, whereas blank entries signify signature runs that have recently been, or are currently, being generated for later publication.

Fig. 3 also provides a summary of some of the key findings related to the relative contributions that direct sunlight and reflected earth albedo make to the signature pattern.

Object Orientation	Sensor View	Cone	Frustum	Cylinder	Plate
Nadir Pointing	0 – 360 deg	50/50	50/50		
Zenith Pointing	0 – 360 deg	50/50 100/0 0/100	50/50		
Horizontal Toward Sun	0 – 360 deg	50/50	50/50		
Normal To Sun	0 - 360 deg				
Tumble In Sun Plane	Nadir			50/50	50/50

Findings

For either complete "walk around" viewing or "tumble" motion in solar plane:

- **At GEO (~ sun total), solar-dominated spacecraft signature pattern is complex, but predictable.**
- **At LEO (~ sun + earth total), low to moderate levels of uniform earth reflection can modify the signature pattern significantly.**
- **Mottled earth background scenes can produce signature patterns that are expected to increase the challenges in monitoring spacecraft health status.**

Fig. 3. Presentation Results Summary

Detailed Results

The complex signature patterns resulting from sunlight and earth albedo reflection off the various convex surfaces are illustrated in the figures that follow. Fig. 4a presents the visible band radiant intensity as the sensor views the nadir pointing cone in the solar plane for a sun elevation of 50 deg. The four contributors to signature are the diffuse and specular sun and the diffuse and the specular earth albedo for the conical surface assumed to be covered with material representing a 50% diffuse/50% specular reflector. The earth albedo is seen to generally contribute less than the sun for most viewing angles. The sharp spiking at specific angles represents the solar glint (specular) which is several orders of magnitude greater than the diffuse signature. A sensor would record the total intensity from all components as is presented in Fig. 4b. By presenting the signatures in this format, the analyst receives information that depicts the relative importance of object altitude on the signature pattern. For those viewing aspects at which the sunlight is not received as reflected from the object (zero intensity), earth albedo does provide some level of intensity as a contribution to observability. Although the simulations have been run using a uniform earth albedo value, a mottled earth scene is expected to introduce additional complexity to the signature pattern with some potentially higher frequency variations.

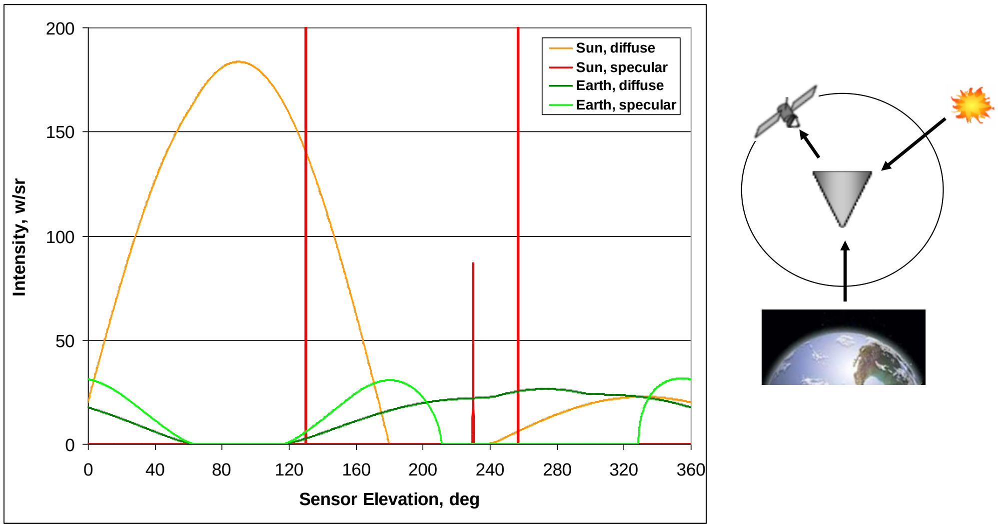

Fig. 4a. Signature Components for a Nadir-Pointing Cone

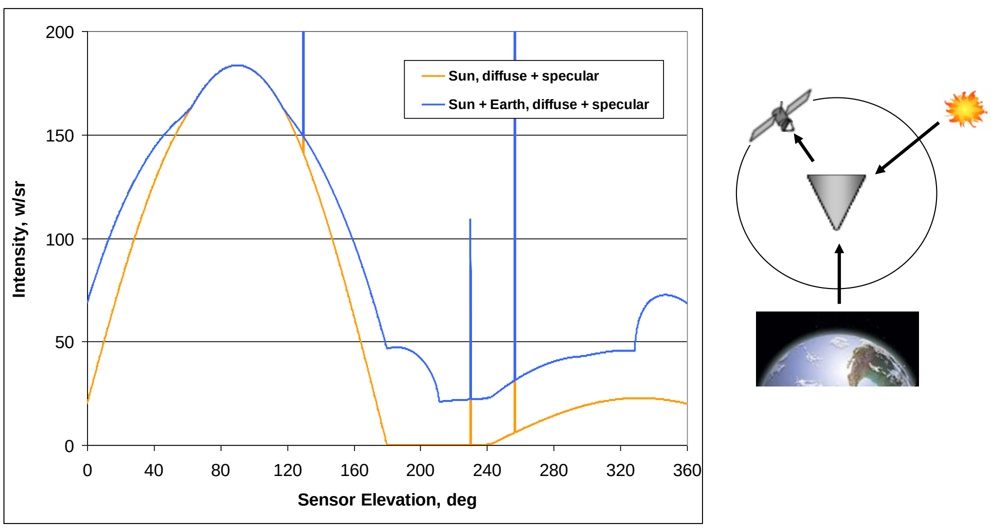

Fig. 4b. Total LEO and GEO Signatures for a Nadir-Pointing Cone

Figs. 5a and 5b present a similar signature pattern for the same conditions as in Figs. 4a and 4b when the conical surface is oriented as pointing to the zenith. This situation results in a significantly different signature pattern than for the nadir case in that the location of the specular glints are noticeably different due to less base reflection of the sun, and the earth albedo contributes in an enhanced manner. The abrupt edges for earth albedo specular reflection are attributed to limitations in the functional model used in the simulation to account for the surface material specularity. Actual earth albedo is expected to show a more subtle increase due to the actual specular glint-broadening lobe of the surface material. Albedo reflection from the conical base contributes significantly to the total signature when the cone underside is viewed by the sensor.

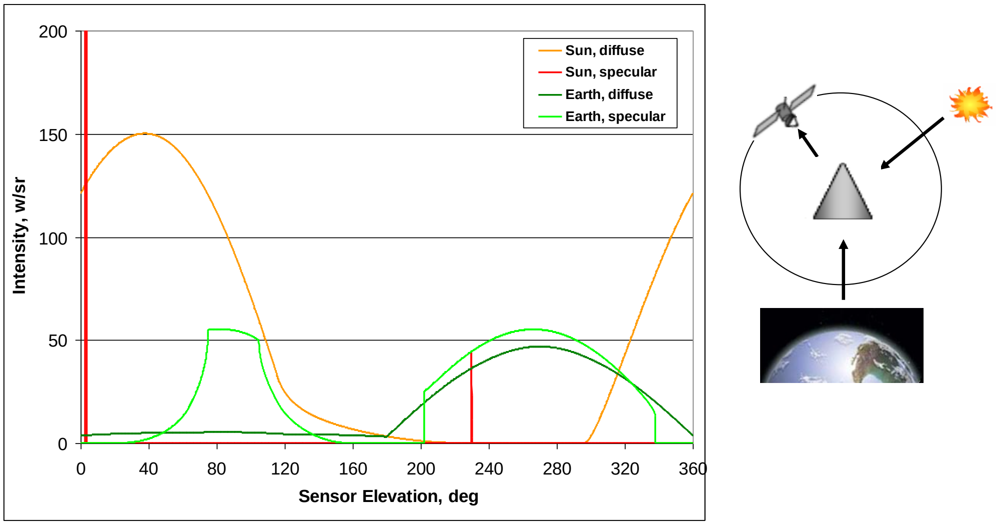

Fig. 5a. Signature Components for a Zenith-Pointing Cone

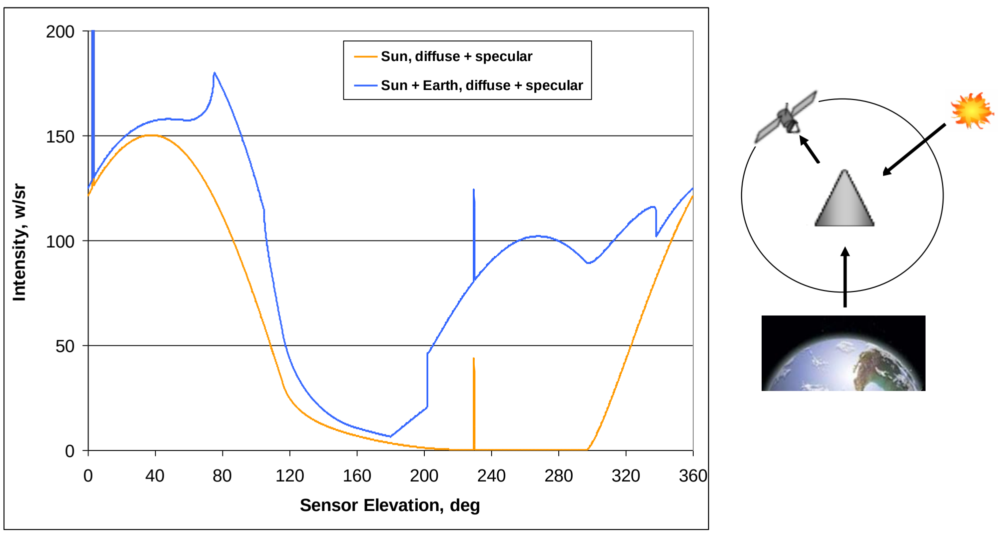

Fig. 5b. Total LEO and GEO Signatures for a Zenith-Pointing Cone

The signature pattern changes again significantly when the cone is oriented horizontally in the general direction of the sun. Figs. 6a and 6b show the intensity patterns for this orientation of the conical surface. At this point it should be evident to the analyst that the "walk around" signature pattern is not specifically unique; rather, it is very strongly dependent on the length-to-diameter ratio of the object, its orientation, and the position of the sun. Results show that these patterns can be modeled reliably and that the related absolute intensities are predictable for these fundamental convex surface geometries. These patterns contribute to establishment of a fundamental database or training set of observable features. When observations are made of surfaces containing additional reflecting surfaces in the way of solar panel protrusions, onboard sensor caps/covers, or space antenna components, the observed signature pattern is expected to depart from the fundamental signature database values, thus providing the observer with observational data that correlate with the signature pattern excess or modification.

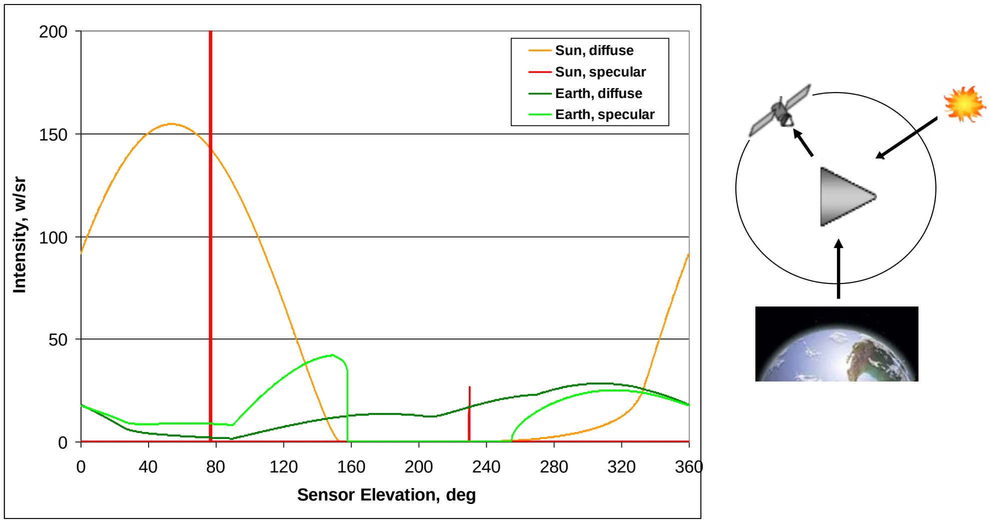

Fig. 6a. Signature Components for a Horizontal-Pointing Cone

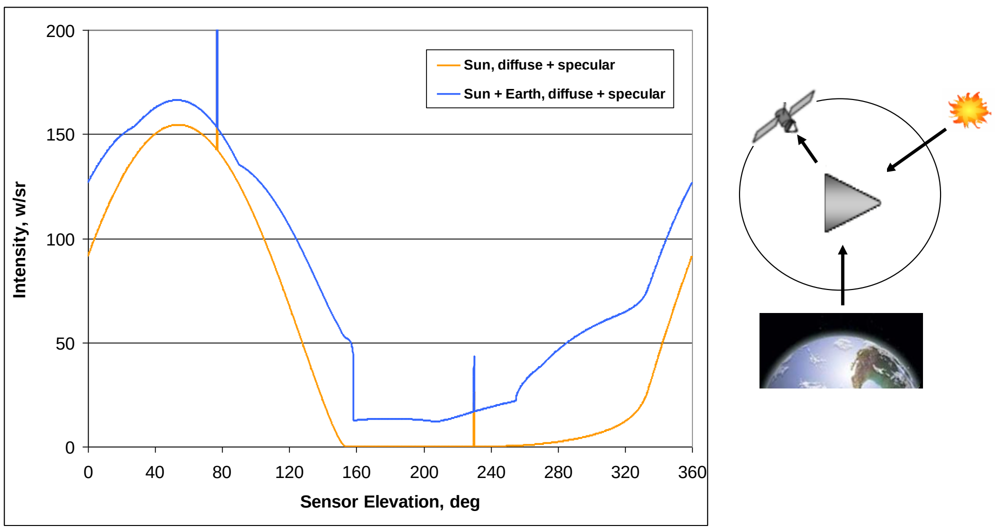

Fig. 6b. Total LEO and GEO Signatures for a Horizontal-Pointing Cone

The above cases have been repeated by substitution of the conical surface with a conical frustum. In these examples, the frustum nose is taken to be half the size of the base, thus resulting in signature observable features that capture the additional changing patterns from the two flat surfaces as well as from the less tapered frustum that differs from the cone. The reader is invited to note these differences by comparing the signature patterns presented in Figs. 7a, 7b, 8a, 8b, 9a, and 9b with their counterparts in Figs. 4 through 6. Inferences can be made from such comparisons that signature patterns of the type generated can be useful in contributing to detecting changes in spacecraft surface geometry and dimensions.

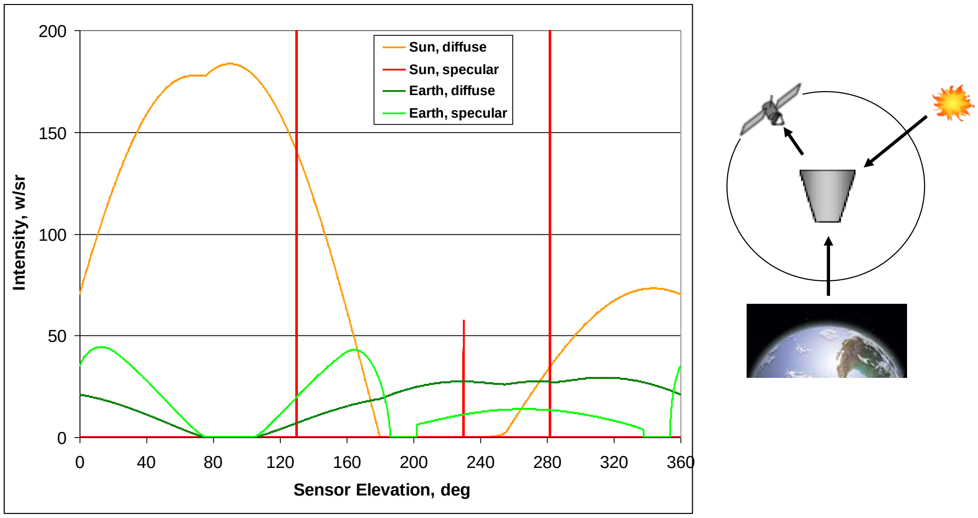

Fig. 7a. Signature Components for a Nadir-Pointing Frustum

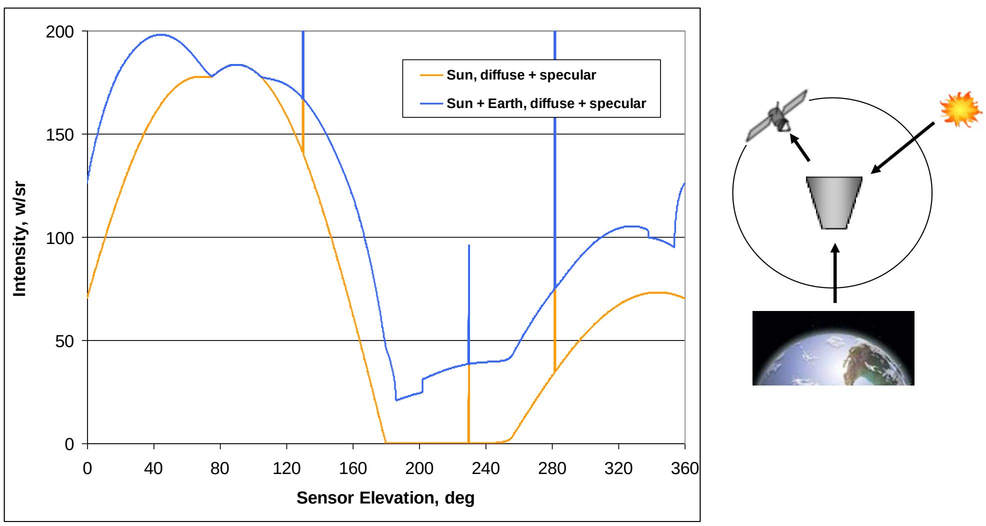

Fig. 7b. Total LEO and GEO Signatures for a Nadir-Pointing Frustum

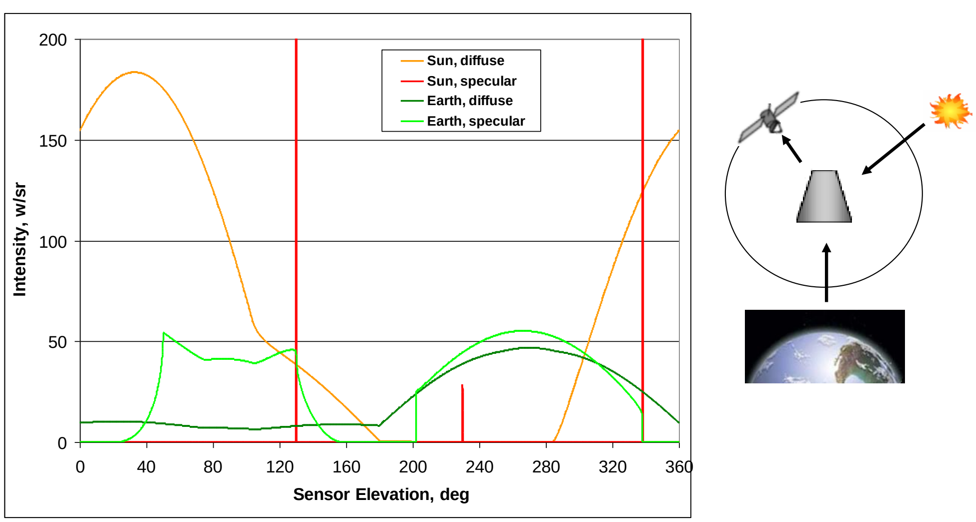

Fig. 8a. Signature Components for a Zenith-Pointing Frustum

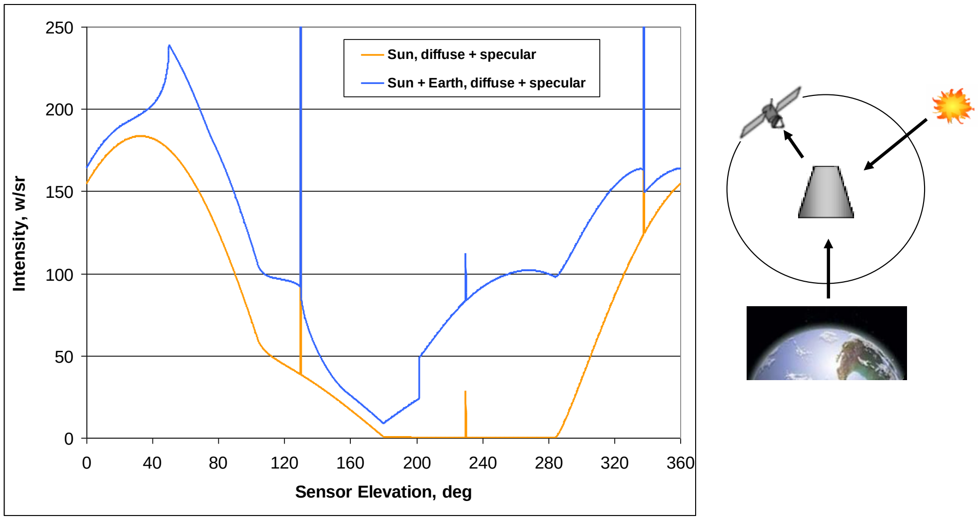

Fig. 8b. Total LEO and GEO Signatures for a Zenith-Pointing Frustum

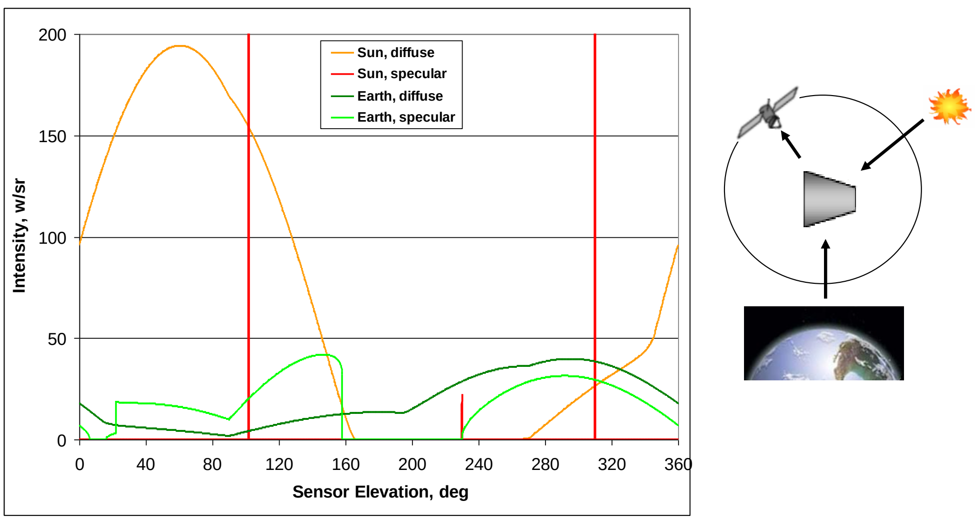

Fig. 9a. Signature Components for a Horizontal-Pointing Frustum

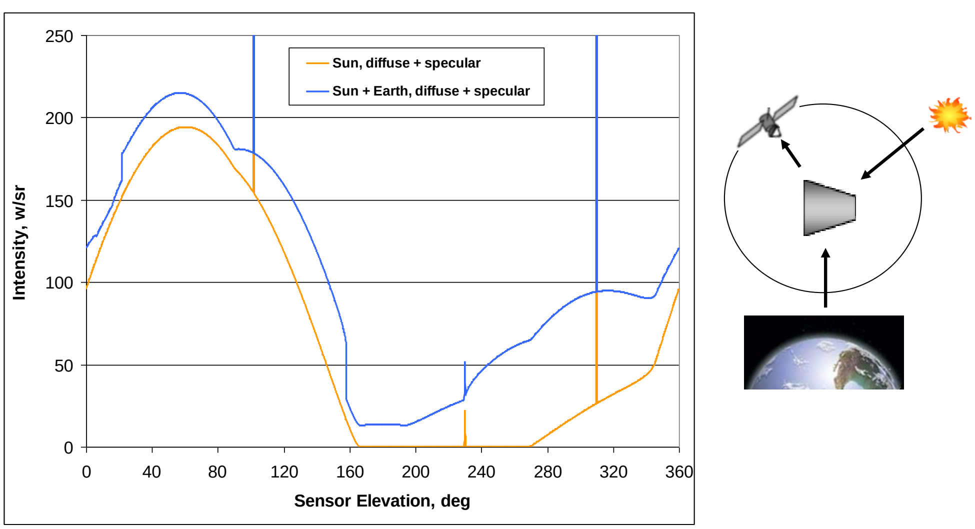

Fig. 9b. Total LEO and GEO Signatures for a Horizontal-Pointing Frustum

It is instructive to review the signature pattern resulting from the situation in which the object tumbles in the solar plane while the sensor remains in a fixed viewing position. This is illustrated in Fig. 10 for a cylindrical surface being viewed from above in the nadir direction. For this case, the total LEO and GEO intensity patterns demonstrate an interesting yet quantifiable result. For the GEO case, the detailed signature pattern consisting of the apparent constant intensity level is a direct result of the cylinder length (2 m) being equal to its diameter (2 m). Runs made with lengths increasing to 3 and 4 m show significant departure from this constant intensity level. The relatively sharp "saw blade" pattern for LEO altitudes results from the approximate methods used to calculate the specular and diffuse earth albedo signature components.

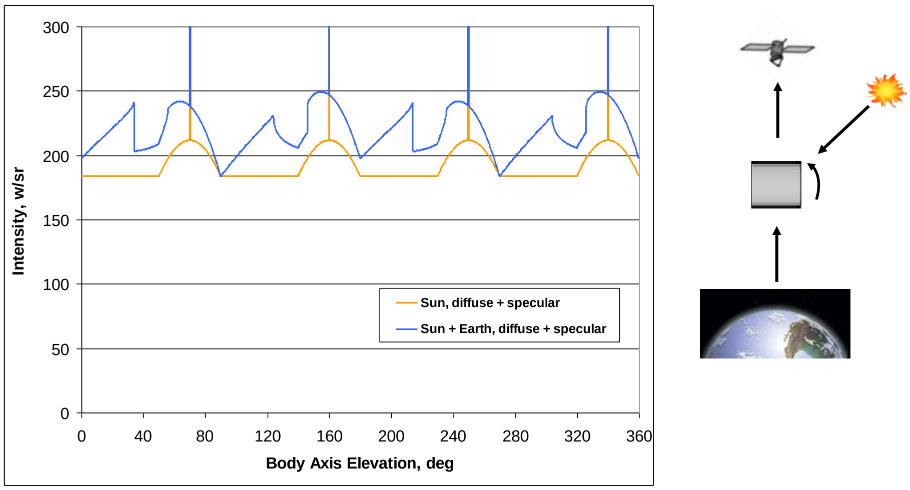

Fig. 10. Total LEO and GEO Signatures for Nadir View of a Tumbling Cylinder

When the tumbling cylinder is replaced with a tumbling circular plate 2 m in diameter, the intensity pattern changes drastically. This is illustrated in Fig. 11 which shows that the nadir viewing plate signatures match the cylinder end plate values, but there is only half the number of specular solar glints per tumble period.

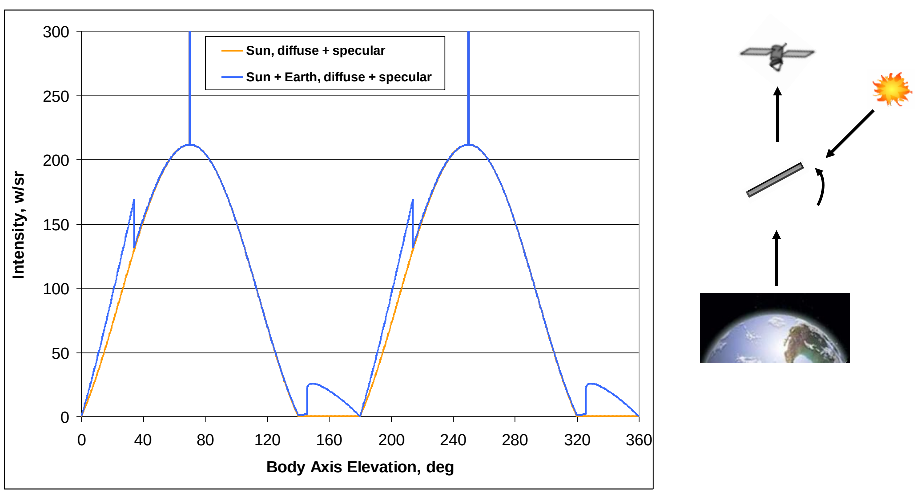

Fig. 11. Total LEO and GEO Signatures for Nadir View of a Tumbling Plate

Fig. 12 presents a limited summary of the effects of material diffusivity and specularity. For this case, the total LEO and GEO signatures for a zenith-pointing pure diffuse and pure specularly reflecting conical surface are illustrated for a complete sensor "walk around" view. Results show that for the diffuse cone, the absence of solar glint is, of course, a major feature. For the specular cone, the signature primary features are the two solar glints as well as a broad range of earth albedo glint at the LEO altitude. At GEO, the only signature components are the two solar glints occurring at the indicated viewing angles. As in the previously displayed charts, these detailed signature patterns are highly dependent on the surface orientation, the sun position, and the object geometry shaping. But again, it is emphasized that all of these results can be modeled and predicted.

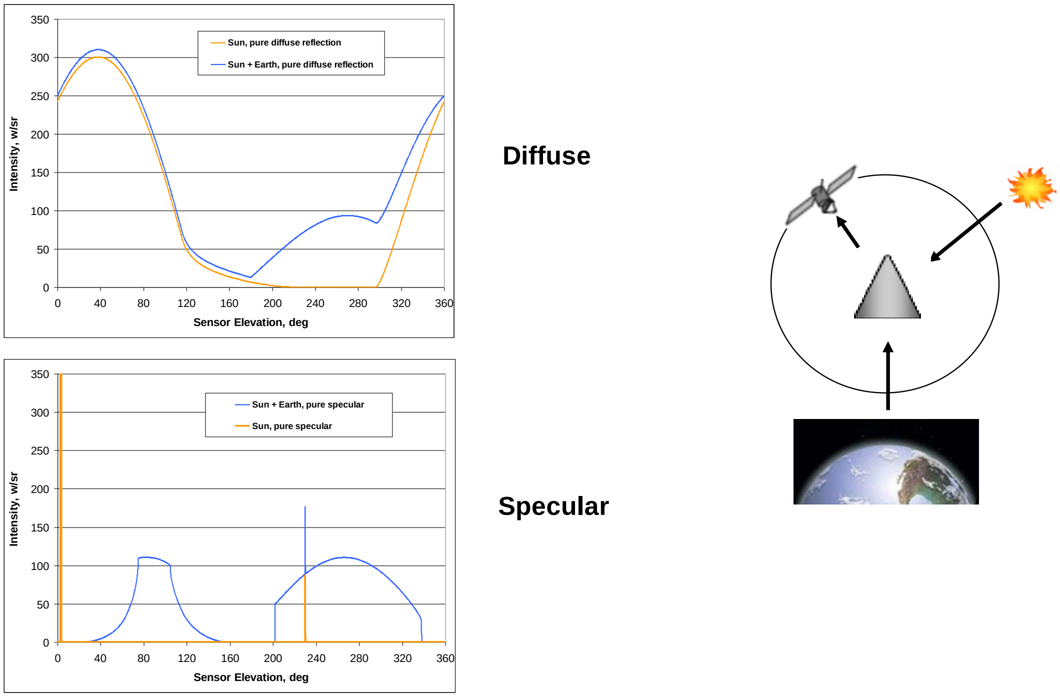

Fig. 12. Total LEO and GEO Signatures for Zenith-Pointing Pure Diffuse and Pure Specular Cones

Summary

This presentation has featured selected results from the generation of optical signatures to support spacecraft health status monitoring. As indicated in Fig. 13, the resulting signature patterns are complex. Yet they are fully predictable for establishing baseline geometry signature patterns to support detection and exploitation of various anomalous events that can affect a spacecraft's general health in conducting its assigned mission. Since observations are usually conducted with detailed consideration for sensor viewing aspect under specified illumination conditions, the databases generated serve as a contributor to developing the multiviewing aspect algorithms needed to successfully achieve the status-monitoring mission. For additional details, the reader is invited to contact the authors using the information provided in Fig. 13.

- **Summary**
  - **Presented selected results from generating spacecraft optical signature database to support health status monitoring**
  - **Found that total environment illumination (sun and earth) can produce complex signature patterns to passive remote sensing systems**
  - **Baseline spacecraft characterizations and target signature patterns are needed to exploit anomalous events occurrences, e.g., solar panel misalignments, antenna misdeployments, unexplained body reorientations, etc.**
  - **Results support algorithm development based on multiviewing aspect observations**

- **Contact Information**
  - **Bernie Klem**
    - **Bernard.Klem@arnold.af.mil**
    - **310.733.7727**
  - **Dave Swann**
    - **Dave.Swann@arnold.af.mil**
    - **931.454.6176**

Fig. 13. Summary and Contact Information