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A novel approach to modeling spacecraft spectral reflectance

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Abstract

Simulated spectrometric observations of unresolved resident space objects are required for the interpretation of quantities measured by optical telescopes. This allows for their characterization as part of regular space surveillance activity. A peer-reviewed spacecraft reflectance model is necessary to help improve the understanding of characterization measurements. With this objective in mind, a novel approach to model spacecraft spectral reflectance as an overall spectral bidirectional reflectance distribution function (sBRDF) is presented. A spacecraft's overall sBRDF is determined using its triangular-faceted computer-aided design (CAD) model and the empirical sBRDF of its homogeneous materials. The CAD model is used to determine the proportional contribution of each homogeneous material to the overall reflectance. Each empirical sBRDF is contained in look-up tables developed from measurements made over a range of illumination and reflection geometries using simple interpolation and extrapolation techniques. A demonstration of the spacecraft reflectance model is provided through simulation of an optical ground truth characterization using the Canadian Advanced Nanospace eXperiment-1 Engineering Model nanosatellite as the subject. Validation of the reflectance model is achieved through a qualitative comparison of simulated and measured quantities.

Keywords: Space surveillance; Spectrometric characterization; Bidirectional reflectance distribution function

1. Introduction

The need for satellites by modern society is increasing the number of artificial resident space objects (RSOs) in Earth orbit (NASA Orbital Debris Program Office, 2014). The importance of space surveillance, defined as the "routine, operational service of detection, correlation, characterization, and orbit determination of space objects" (del Monte, 2007) is also increasing. This is required to manage these valuable space assets and to identify potential hazards and threats to humans on Earth and in orbit.

It is common for spacecraft, regardless of their orbital regime, to be beyond the diffraction-limitations of ground-based optical telescopes tasked for space surveillance. Typically on the order of 1 m, these telescopes are unable to obtain any useful spatial resolution in images (Luu et al., 2003). An example of an observation made using such a telescope is shown in Fig. 1, which contains four geostationary Earth orbit (GEO) satellites. These appear as spatially-unresolved point sources indistinguishable from one another.

Characterization is the practice of learning more about an object's nature in order to distinguish it from others. Characteristics of RSOs include: orientation, rate of change of orientation, physical shape, and surface material composition. Research into the determination of spacecraft characteristics using unresolved observations has focused on the analysis of light curves obtained by photometry (Luu et al., 2003; Scott et al., 2008; Somers, 2011; Bédard, 2013; Jolley, 2014). A broadband photometric light curve is a plot of the magnitude of spacecraft

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Fig. 1. An image containing Anik-F1, -F1R, -G1, and Echostar 17 (Jolley, 2014).

brightness, essentially a photon count, as a function of time. Photometric variation has been used successfully to determine the spin rate and spin axis of uncontrolled spacecraft (Somers, 2011), as well as to differentiate between co-located satellites in the GEO ring (Scott et al., 2008).

The light gathered by optical space surveillance sensors is reflected sunlight with spectral characteristics modified by the spacecraft's surface materials. Spectrometric variation is a change in spectral energy distribution (SED) as a function of time, orientation, or both, and is indicative of the surface composition of the object. Broadband photometric light curves do not indicate spectrometric variation while color-filtered light curves (products of color photometry) provide insight into the spectral changes occurring within the spacecraft's reflection over time (Bédard, 2013; Jolley, 2014; Bédard et al., 2014). These are produced by filtering the spacecraft-reflected photons over specific wavelength ranges. Unfortunately, while ideal for the surface composition characterization of unresolved objects, measurements of wavelength-resolved spectra are difficult to obtain due to changes in spacecraft illumination and reflection geometry coupled with the limited size of space surveillance-tasked telescopes. This results in poor signal-to-noise ratios for these measurements (Bédard et al., 2011). Regardless, numerous studies have been conducted to determine the utility of reflectance spectra for unresolved spacecraft characterization (Luu et al., 2003; Abercromby et al., 2006; Duggin et al., 2008; Hall, 2010; Chaudhary et al., 2011; Bédard and Lévesque, 2014). While none of these studies have demonstrated a marked level of success by conclusively determining a spacecraft's physical shape or material composition (or both) solely through the use of spectrometric measurements, they have provided some insight into required *a priori* knowledge to differentiate one spacecraft from another.

The optical ground truth characterization of a spacecraft, hereafter referred to as its *ground truth*, is the collection of such *a priori* knowledge including physical dimensions, material composition, and the reflectance properties of these materials (Abercromby et al., 2006). This characterization is obtained in a laboratory and can be photometric or spectrometric in nature (Abercromby et al., 2006; Bédard and Lévesque, 2014). It serves as a basis to which all photometric and spectrometric measurements of the spacecraft in Earth orbit can be compared (Bédard et al., 2011).

The method to obtain a spacecraft's ground truth is to illuminate it with a collimated light source and take measurements using a far-field camera or spectrometer (Bédard and Lévesque, 2014). Performed in a controlled environment, this allows for the closest re-creation of the conditions under which the spacecraft will be illuminated and observed while in Earth orbit. The Canadian Advanced Nanospace eXperiment (CanX)-1 Engineering Model (EM) is a mock-up of the first spacecraft of the first Canadian picosatellite program (Wells et al., 2002). Bédard and Lévesque (2014) conducted an optical ground truth characterization experiment with this spacecraft, measuring its reflectance factor and bidirectional reflectance distribution function for two illumination and reflection geometry scenarios. At the conclusion of this experiment, Bédard et al. (2011) highlighted three challenges that this method presents:

1. Measurements must be made for as many different orientations as possible to reproduce the expected illumination and observation geometries in orbit.
2. Larger spacecraft are more difficult to illuminate uniformly with a collimated light source and observe with a far-field detector.
3. Access to a subject prior to launch can be difficult to obtain, especially for extended periods of time.

The reflectance of a spacecraft is a combination of the reflectance of its composite materials, with contributions proportional to their relative abundance (Luu et al., 2003; Hall, 2010). A method to simulate the ground truth of a spacecraft, thereby avoiding the disadvantages of a laboratory characterization, requires the spacecraft's computer-aided design (CAD) model and homogeneous samples of its composite materials. Application of the material reflectance characteristics to the CAD model results in a simulated spacecraft ground truth (Abercromby et al., 2006). This method avoids the difficulties of the laboratory characterization as small material samples can be manipulated easily, illuminated uniformly with a collimated light source, observed with a far-field sensor, and obtained for analysis with unimpeded access.

Current space-surveillance ability limits surface composition characterization to the interpretation of photometric