Spectrometric characterization of geostationary satellites

Major Donald Bédard*, Gregg A. Wade
Royal Military College of Canada
** Guest investigator, Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics*

Dmitry Monin
Herzberg Institute of Astrophysics

Robert (Lauchie) Scott
Defence R&D Canada Ottawa

ABSTRACT

Much scientific work remains before spectrometric characterization of artificial space objects can be used reliably in an operational context. In particular, a detailed study of the dependence of spectral reflectance on a varying Sun-object-sensor geometry has yet to be described. A thorough understanding of this last problem is considered critical if reflectance spectroscopy is to be used to characterize active low Earth orbiting spacecraft, in which the Sun-object-sensor geometry varies considerably over the course of a few seconds, or to study space debris that have uncontrolled and varying attitude.

It is with the above issue in mind that an observational experiment was conducted at the Dominion Astrophysical Observatory (DAO) using the 1.8-metre Plaskett telescope and its Cassegrain spectrograph. The objective of this experiment was to gather time-resolved spectrometric measurements of active geostationary satellites over extended periods of time per night. This class of satellites was selected because their attitude is controlled and can be estimated to a high level of confidence. We present red/blue color ratios derived from these measurements that shows that the shape of the spectral flux varies significantly with changing Sun-object-sensor geometry and that the rate and amount of change of the spectral flux varies between spacecraft. The lessons learned from this experiment show that reflectance spectroscopy applied to space surveillance is a complex technique that must be used with specific caveats and under certain conditions.

1. INTRODUCTION

In the past decade, two independent teams conducted experiments to collect spectrometric measurements of artificial space objects, or more precisely of spacecraft and space debris, in order to gain knowledge of their surface properties. Detailed knowledge of what an object is made of, or at least which types of materials are detected at its surface, can then be used to convert apparent magnitudes of objects into a physical size. This information is considered critical to improve the characterization of the debris environment in the various Earth orbital regimes.

The first team, led by Abercromby (née Jorgensen), has collected spectrometric measurements of various spent rocket bodies, dead satellites as well as operational ones in various orbits over a 10 year period [1, 2, 3]. Each of these observational experiments sought to derive spectral reflectance curves between 400 and 900 nm for various classes of artificial space objects. In short the experiment consisted in collecting spectrometric measurements of an object over two different time periods. During the first, a measurement at one grating setting was collected to obtain a spectral reflectance from approximately 400 nm to 700 nm. At a different time, typically one night later, a second measurement at a different grating setting was collected to obtain the measurement over the remainder of the band pass, in this case from 600 to 900 nm. Exposure times were adapted such that an acceptable signal to noise ratio (SNR) could be obtained. Exposure times ranged from 60 to 90 seconds for objects in or near the geosynchronous orbital regimes. During the data reduction and processing stage, the two measurements would be first normalized at 600 nm and then combined to produce a single measurement having a wavelength range from 400 to 900 nm. Using this experimental method, Abercromby *et al.* were able to show that identification of material types was possible [2]. However, all of the measurements taken, with the exception of those of a US Inertial Upper Stage rocket body (SCN 19970), showed an unexplained increase in reflectance in the wavelength range above 700 nm (dubbed a "reddening effect"). Although attempts were made to solve this problem, none of the results pointed to the actual physical process that caused this effect.

The second team, led by Schildknecht, used the 1-meter European Space Agency Space Debris Telescope (ESASDT) between November 2008 and May 2009 to collect spectrometric measurements of mostly space debris [4]. The experimental procedure that was followed in order to collect measurements between 450 and 900 nm was similar to that of the first team. More precisely, a series of measurements were made at the blue part of the spectrum followed by a sequence in the red part. The measurements were then normalized at a common wavelength and combined to produce one measurement spanning a range from approximately 400 to 900 nm. Exposures for the measurements were 4 minutes each. The observations of the MSG-2 satellites showed that the spectral measurement varied with phase angle but an in-depth analysis of this variation was not provided. The authors reported that measurements of space debris could not lead to the characterization of material types found on the surface of the object due to the large variation in the spectral reflectance for a given object. The authors of this study did not comment on observing the reddening effect that was consistently observed by the first team.

The primary subjects of the experiments described above consisted of space debris, which represent the most difficult experimental subjects that could be selected for such pathfinder experiments. Space debris are typically faint objects, have unknown variable attitudes and are objects for which we have practically no physical information with the exception of the dead satellites. Accordingly, the task of collecting and analyzing spectrometric measurements as well as comparing them to ground truth data collected in a laboratory becomes very arduous. With this in mind, a step backwards was considered necessary in order to gain a better understanding of spectroscopy applied to the observation of artificial space objects. It is from this idea that an experiment focused on gathering optical spectrometric observations of active geostationary spacecraft evolved.

This paper begins with a brief definition of the problem and then presents the experimental aim and procedure. It continues by presenting the first results that were obtained from the spectrometric measurements of geostationary spacecraft. The paper concludes with a discussion of these results and a summary of the future research that will build upon this experiment.

2. DEFINING THE PROBLEM

In 2010, scientists from the Royal Military College of Canada (RMCC) and Defence R&D Canada (DRDC) conducted a spectrometric characterization in a laboratory of the CanX-1 engineering model [5]. This experiment provided an initial data set that the experimenters used to understand the challenges associated with the spectrometric characterization of spacecraft once in space. Among the key lessons that were learned, the most important was the spectral reflectance varied rapidly even with small changes in the light-object-sensor geometry.

Subsequent physics-based modeling and laboratory experiments conducted at RMCC confirmed that for a given material, variations in the spectral reflectance as a function of wavelength occurred when the illumination-object-sensor geometry changed [6]. Spectral reflectance is dependent on a number of factors such as the angle of the incident light, the angle at which the reflection is measured as well as the inherent characteristics of the material from which the reflection is observed. Therefore when observing satellites whose surfaces are composed of a wide array of different materials, the problem in evaluating the spectral signature that is collected is not limited to estimating which material was illuminated and seen by the sensor but also at which angle the incident light impinged on the respective surface components, the physical characteristics of these surfaces, and at which angle the sensor collected the measurements. If the orientation of the object is changing significantly during the measurement, then this factor must also be considered.

Thus, the complexity of using spectroscopy to characterize artificial space objects arises when one considers that a spectrometric measurement necessitates an exposure time of several seconds depending on the size of the sensors used, the orbit of the object and the type of measurement taken (ie, color photometric or spectroscopic). Whereas the sensor integration time is of little concern in a laboratory setting where the source, the subject and the sensor remain fixed, in space it becomes a dominant variable depending on the type of object that is being studied and its orbit. For example, the overall geometry will change very little for an operational geostationary spacecraft during an exposure of 60 seconds. This is not the case for a spacecraft in LEO (Figure 1) or an expended rocket body near the apogee of a GEO transfer orbit. For the latter, although the solar phase angle may change on the same time scale as a geostationary spacecraft, its spin rate would make it such that the geometry changes drastically over the course of a few seconds.

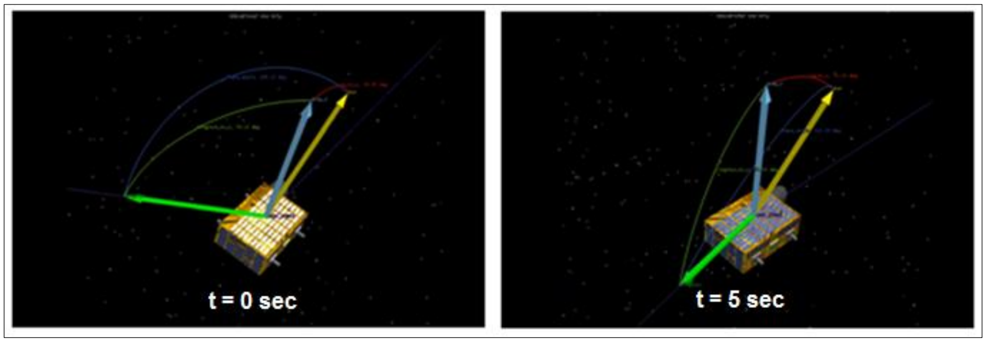

Figure 1. For a satellite in LEO, the Sun-object-sensor geometry changes rapidly. The blue vector is the surface normal of the main solar panel, the yellow is the Sun vector and the green is the sensor vector.

In summary, spectroscopy has been used to characterize various types of artificial space objects but no study has addressed in detail how variations in the Sun-object-sensor affect spectrometric measurements over the entire range of observational geometries that the object can encounter. The following experiment was elaborated as an initial effort to address this question.

3. EXPERIMENTAL AIM AND REQUIREMENTS

The aim of this experiment was to study how the spectral reflectance from artificial space objects varied with changing Sun-object-sensor geometry as they moved along their orbital trajectory. The experiment sought to address the following questions:

1. What are the scales of the changes in spectral reflectance and on what timescales do they occur?

2. Are the color variations similar for all satellites?

3. Can the color variations themselves be used to characterize the objects?

The experiment was elaborated in order to monitor color variations of an observed artificial space object over the duration of an evening. To reduce the number of parameters that could influence the outcome of the results, two principal requirements were established at the onset of the experiment.

The first requirement was that the observations would be limited to artificial space objects whose Sun-object-sensor geometry changed very little during a 60 to 90 second period, which represented the expected exposure time for one spectrometric measurement of sufficient SNR. This limited the range of objects down to operational geostationary spacecraft. More specifically, communication satellites in geostationary orbits have buses with their antennas pointed towards nadir while their solar panels are tracking the Sun. Thus, it was assumed that any variation in the spectral reflectance can be more easily interpreted by using commercial-off-the-shelf software such as the Satellite Tool Kit's (STK™) Vector Geometry tool to assess which part of the spacecraft were illuminated and seen by the sensor.

The use of geostationary satellites also provided the added benefits of facilitating the collection of spectrometric measurements in that it was much easier to maintain the object on the spectrograph's field of view. Finally, given their apparent stationary position in the night sky with respect to the observer, the use of geostationary satellites also facilitated the reduction, processing and interpretation of the data since all measurements, for a given spacecraft, were taken at equal air masses.

The second requirement of this experiment was to limit spectrometric observations to a spectral region that could be acquired in a single exposure. It is critical to note that the main driver of this experiment was to measure color changes, or variations in the flux in different wavelength regions. Consequently, confidence in the results would be much greater if these could be measured in a single frame instead of two taken at different instrument settings, at different times and hence at different Sun-object-observer geometries as well as potentially different atmospheric conditions. Considering the characteristics of the detector that would be employed and the results of reflectance modelling and laboratory experiments at RMCC [6], a measurement wavelength range between 420 and 750 nm was selected.

4. EXPERIMENTAL SET-UP AND PROCEDURE

The spectrometric observations were conducted using the National Research Council's 1.8m Plaskett telescope located at the Dominion Astrophysical Observatory (DAO) in Victoria (Canada). The telescope is equipped with a Cassegrain spectrograph [7]. The 21(3/2)1 configuration that was selected for this experiment provided a grating of 150g/mm, a blaze of 5000 Ȧ and a dispersion of 120 Ȧ/mm. This configuration provided the widest possible wavelength range for a given grating angle.

Since the objects of interest were all at an elevation of approximately 33^{o} and because the telescope is not equipped with an atmospheric dispersion corrector, a 30 x 18 arcsecond slit was used for this experiment. The slit was covered with a slightly-tilted thin glass plate that reflected about 5% of the incoming light to the guiding camera. The measurements were captured with a UV-coated SITe-2 CCD (1752 x 532 pixels, 15 micron square pixel) with a nominal operating temperature of -110^{o} C. More information on the telescope, the Cassegrain spectrograph and the CCD detector can be found on the DAO main web site [8].

Twenty-two nights of observations were scheduled over two periods. The first period occurred from 20 to 30 March 2012 while the second was scheduled between 13 and 24 August 2012. Of the 22 scheduled nights of observation, there were eight nights that yielded approximately 3500 spectrometric measurements of geostationary satellites.

The STK™ software was used for observation planning or more precisely to determine the visibility of spacecraft, as well as their respective Sun-object-sensor geometry. Three types of data were collected during the observation campaign. The first consisted in collecting sets of bias and flat field frames required for the data reduction process. Second, observations of spectrophotometric standards as well as solar analogue stars (ie, spectral type G2V stars) at various air masses were gathered in order to retrieve the intrinsic reflectance of the observed spacecraft. Finally, the third type of data that was collected was the spectrometric measurements of the geostationary satellites. Table 1 provides a list of the geostationary satellites that were observed as part of this experiment.

Table 1. Geostationary satellites that were observed between 16 and 24 August 2012.

Spacecraft	Satellite Catalogue #	Air mass	Bus	Lauched	Observation: Day # of 2012
Anik F1	26624	1.875	BSS-702 (with concentrator arrays)	Nov 2000	233, 234
Anik F1R	28868	1.876	Eurostar-3000S	Aug 2005	233, 234
Anik F3	31102	1.780	Eurostar-3000S	Aug 2007	236
Ciel 2	33453	1.782	Spacebus 4000C4	Dec 2008	229, 231, 236
GOES 15	36411	1.799	BSS-601	Mar 2010	229, 230, 234, 235
Viasat 1	37843	1.799	LS-1300 (expanded)	Oct 2011	230, 231
Wildblue 1	29643	1.829	LS-1300	Dec 2008	229

Raw spectrometric measurements were pre-processed (ie, Bias removal, flat field correction, cosmic hits removal and spectra reduction) using the Image Reduction and Analysis Facility (IRAF) developed by the National Optical Astronomy Observatories (NOAO). Due to the high number of spectrometric measurements that were acquired, final processing of the data was done with MATLAB scripts developed internally at RMCC. In brief, each reduced spectrometric measurement was multiplied by filter band pass functions approximately corresponding to the Bessel BVR filters (Figure 2). The filtered products were then integrated to compute the total flux in each band from which color ratios were produced.

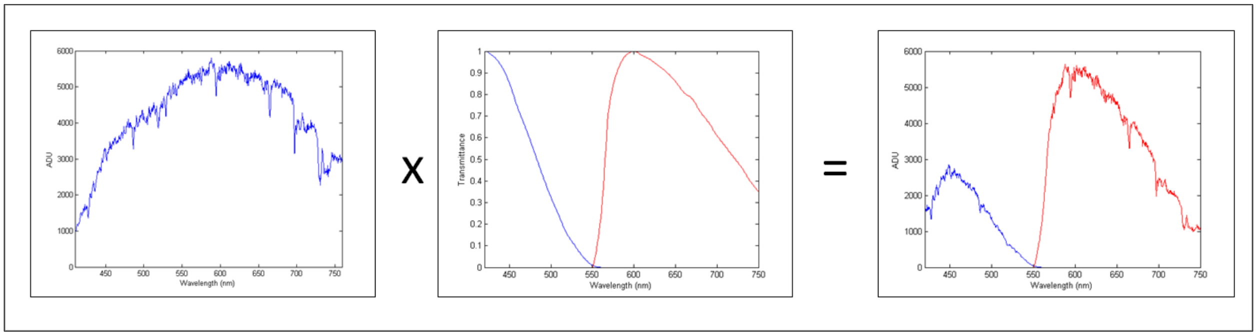

Figure 2. Each reduced spectrometric measurement was initially multiplied by color filters. In this example the blue and red filters are applied to the measurement.

Finally, each spectrometric measurement was integrated over the entire observed spectral range to produce a single photometric count value which served to produce a photometric light curve. This complimentary data product was used verify that the light curve of the observed geostationary spacecraft matched with the canonical light curves published for its specific bus design and to ensure that any variation in color was not due the presence of clouds.

With the final data products in hand, namely the color ratios, the following exercises were conducted:

- Color ratio plots as a function of time were produced for all observed satellite. These plots were used to study if and how the color ratios evolved over the course of each night.

- Color ratios plots of the same satellite observed on multiple nights were compared to determine if color variations were repeated. Repeatability of patterns would indicate that this technique could be used to characterize objects and would also serve to provide higher confidence in the data collected during this specific experiment.

- Color ratios plots of various spacecraft were compared to study if distinction between the satellites could be made using this type of information. In particular, for two spacecraft having a separation of a few arcminutes, it was assumed that measurements could be compared directly to each other without having to remove the effects of the atmosphere on the measurements. For spacecraft having a separation of several arcminutes, then use the spectrophotometric standards as well as solar analogue stars, corrected to the appropriate air mass, was deemed necessary to remove atmospheric effects such that there would be completely certainty that only the intrinsic reflectance would be compared.

Given the short amount of time between the final observation campaign and this conference, the paper will only presents results that pertained to the first two objectives as well as a comparison of two geostationary satellites separated by a few arcminutes. A subsequent paper will be submitted at a later date with a reporting of all results and thorough analysis.

5. RED/BLUE COLOR RATIOS FROM SPECTROMETRIC MEASUREMENTS

The red/blue color ratios for the Ciel 2, GOES 15, Viasat 1 and Anik F3 geostationary spacecraft are presented in Figures 1 to 4 respectively. These figures illustrate ratios of measured fluxes in the red to the blue portion of the spectrum as a function of time. They provide a good measure of how the spectral reflectance varies over the course of a night. A high ratio indicates that the red content of the measured reflected light is more significant than the blue content. A decrease in this ratio indicates that the blue content of the light as increased with respect to the red. With the exception of Anik F3 (Figure 6), all figures show at least two nights of measurements. In all cases, the distribution pattern of red/blue color ratios as a function of time is repeated, and hence gives confidence in the quality of the measurements.

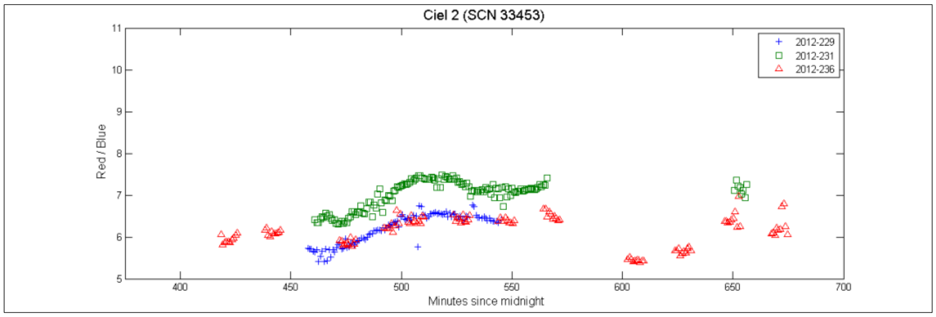

Figure 3. Ratios of Red to Blue flux of the Ciel 2 spacecraft as a function of time. The ratios were calculated from measurements collected on three different nights of observations.

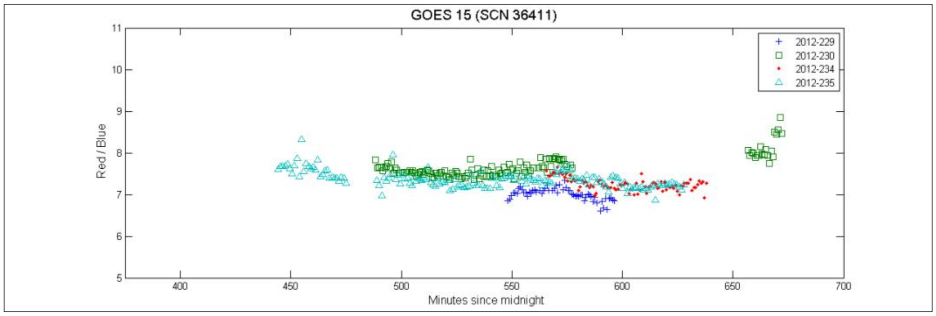

Figure 4. Ratios of Red to Blue flux of the GOES 15 spacecraft as a function of time. The ratios were calculated from measurements collected on three different nights of observations.

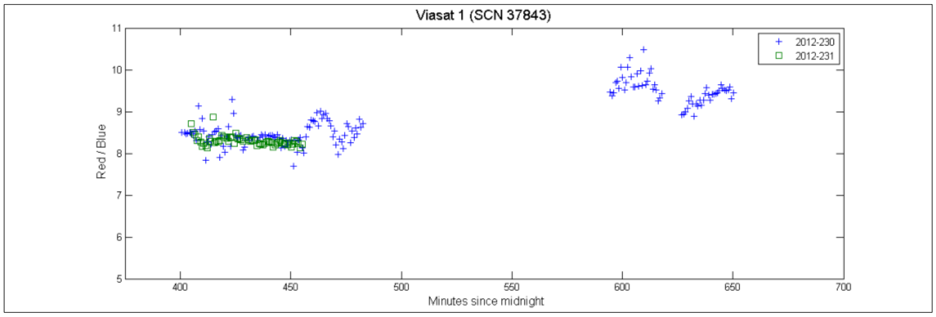

Figure 5. Ratios of Red to Blue flux of the Viasat 1 spacecraft as a function of time. The ratios were calculated from measurements collected on three different nights of observations.

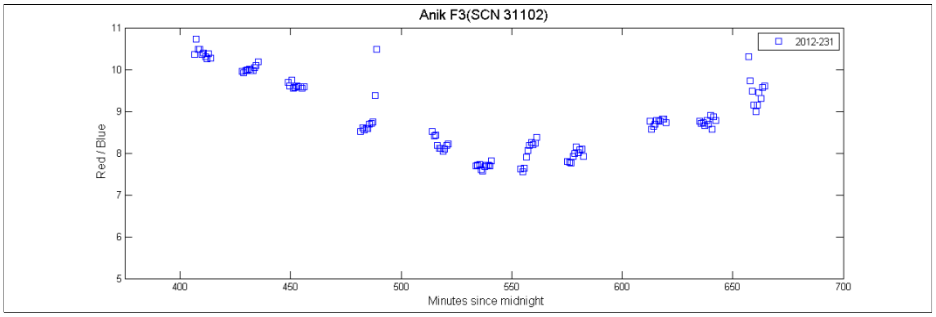

Figure 6. Ratios of Red to Blue flux of the Anik F3 spacecraft as a function of time.

Figures 1 to 4 illustrate quite clearly that the shape of the spectral flux between 420 to 750 nm varies significantly with changes in the Sun-object-sensor geometry. It is interesting to note that the amount and rate of change in the red/blue ratios is different for the four spacecraft. For example, in the case of Anik F3 (Figure 6), the change from red to blue represents a change of approximately 25% in the span of about 128 minutes starting at the 400 minutes mark. However, looking at the similar situation in which the red content diminishes for the Ciel 2 spacecraft (Figure 3, using the 2012-236 data set), the change is approximately 17% over a period of approximately 85 minutes. Although the variation illustrated in Figure 4 for the GOES 15 spacecraft is not as obvious as the two previous satellites, the lower red to blue ratio is still perceptible as well as a much slower decreasing rate as a function of time. This difference is currently believed to be attributable to the fact that all three spacecraft have different design configurations as well as different surface compositions.

As a reminder, the measurements used to produce the results presented above were not processed to remove the effects caused by observing through different air masses. Therefore no definitive conclusion is stated as to why the red/blue ratios are different for each of these spacecraft. However, observations of the Anik F1 and Anik F1R satellites, taken on 20 and 21 August 2012, also showed that these objects have red/blue color ratios that are very different from one another. These satellites are separated in the sky by only a few arcminutes and as a result, it is assumed that a direct comparison of the measured flux from each object can be performed. More precisely, these objects were observed at the same air mass and under the same atmospheric conditions for a given night. The repeatability in the observed pattern of the red/blue color ratios served to increase confidence in the quality of the measurements as well as the observation strategy.

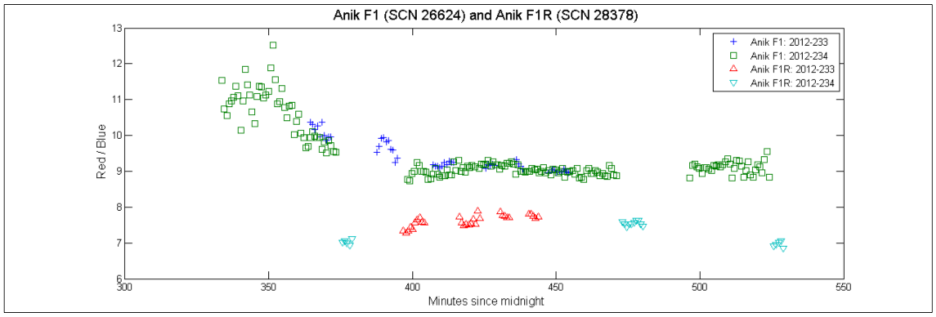

Figure 7. Derived color ratios taken of the Anik F1 and Anik F1R spacecraft. These spacecraft are positioned a few arc-seconds apart thus the observation taken during the same night are taken under identical observing conditions.

As shown in Figure 7, the Anik F1 red/blue color ratio varied between approximately 11 and 9 while that of Anik F1R varied between 7 and 8. Essentially, this signifies that Anik F1 is reflecting less blue light with respect to red than Anik F1R. A potential clue that could explain this difference, at least in part, pertains the different operational age of these satellites. As a reminder from Table 1, Anik F1R was launched almost five years after Anik F1. If space weathering increases the overall surface roughness of materials over time, then the overall decrease in reflectivity in the lower end of the spectrum could be explained by this physical process and would agree well with physics-based reflection models. Many more nights of observations will be required before any general conclusion can be made as to why the range of the ratios is different for each spacecraft. Another lead that will be investigated is to verify whether the reflectivity in the blue portion of the visible spectrum of photovoltaic cells, and other materials commonly found on the surfaces of satellites, diminishes with time spent in space.

As a final note on the differences between the red/blue ratio values and how these ratios vary over time, we suggest that this information could be used to solve problems related to cross-tagging of co-located objects in geostationary clusters [9]. Although broadband photometric light curves are currently used to accomplish this task, the combination of both techniques may lead to results that are of higher confidence and obtained more rapidly.

6. DISCUSSION

More spectrometric observations of geostationary satellites will be required before any sort of general assertion can be made as to how the color variations can be used to characterize artificial space objects or to gain detailed information on their surface composition. Notwithstanding, this experiment exposed four critical points regarding the use of astronomical reflectance spectroscopy applied to the context of space surveillance.

This experiment clearly demonstrated that the reflected light as a function of wavelength is dependent on the Sun-object-sensor geometry, which itself changes as a function of time. Consequently, the first conclusion of this experiment is that any spectrometric measurement, or its derived products, must be provided with, in the very least, a date and a time at which the data was collected. This information can then be used to retrieve the Sun-object-sensor geometry that will provide the context for the measurements. If attitude information of the observed artificial space object is known then it should be provided. In the case of an active spacecraft for which the attitude can be obtained or estimated with a high level of confidence, then the date and time will be sufficient to describe the Sun-object-sensor geometry. Without this ancillary information, the utility of the spectrometric measurement is severely reduced.

The second lesson taken from this experiment pertains to the method of combining measurements obtained at different times, and hence different observational geometries, to produce a reflectance measurement over a wider range of wavelengths. Although this method may be acceptable for astronomical subjects, such as stars, it is probably one that should be reconsidered when applied to the characterization of artificial space objects. Given that the spectral reflectance of an object varies with observational geometry, measurements obtained at different times should be combined only if there is good confidence that they were collected in similar circumstances. Since this condition is probably only attainable in limited situations, such as a geostationary spacecraft observed on two successive nights, then this technique should not be employed.

The third conclusion derived from the results is that the initial spectrometric characterization of an artificial space object requires a very high number of measurements. This is especially true if one seeks to use this type of measurement to compare various objects to each other. The results presented in this paper have shown that the spectral reflectance for one spacecraft varies as the Sun-object-sensor changes over time. Therefore, a limited set of spectrometric measurements is not sufficient to properly characterize an artificial space object. On this note, it must be stressed that the measurements presented in this paper were all taken during a period close to the autumnal equinox, or when the center of the Sun is on the same plane as the Earth's equator and the geostationary belt. The authors fully expect to see different red/blue color ratios patterns for the same satellites over the course of the year as the center of the Sun moves away from the Earth's equatorial plane. From the third conclusion it follows that an ideal spectrometric characterization of an object should consist of measurements taken from the complete range of Sun-object-sensor geometries that the object should encounter.

The fourth conclusion is that the sampling rate as well as the exposure time for each measurement must be adapted to the rate of change of the illumination-object-sensor geometry. For instance, in for the case in which the subjects were geostationary satellites with controlled attitude, an exposure time of 45 seconds appears to be sufficient to measures changes in the spectral flux. However, such a sampling strategy would be far from adequate for a spinning object (ie, a rocket body or a dead satellite) with a spin rate of a few revolutions per minute. Hence, a priori knowledge of the object's attitude or in at least the rate of change of this attitude is a strict requirement that must be satisfied before one proceeds to use a spectrometer to characterize the object.

When considering that the exposure time of a spectrometric measurement must adapted to the varying Sun-object-sensor geometry, it becomes necessary to question whether the use of astronomical spectroscopy to characterize faint debris with rapid spin rates is appropriate. More precisely, these faint objects will require exposure time on the order of several minutes in order to obtain acceptable SNR. Based on the results of this experiment as well as those published by Schildknetch *et al*. [4], it appears that spectroscopy is the wrong approach for the characterization of space debris in general. On the other hand, if the use of color ratios can be used eventually to characterize material type, then multi-color photometry (in which fluxes in multiple bands are acquired simultaneously) could prove to be a valuable tool for some types of debris. Accordingly, this approach is currently being investigated jointly by the Department of Physics at the Royal Military College of Canada (RMCC) and the Space Systems Group at Defence R&D Canada Ottawa. The aim of this effort is to employ three small aperture telescopes at RMCC in a coordinated manner.

7. CONCLUSION

We presented the results of an observational experiment that was conducted using the 1.8m Plaskett Telescope located at the Dominion Astrophysical Observatory. The red/blue color ratios derived from spectrometric measurements of geostationary satellites demonstrate quite convincingly that an artificial space objects may have many different spectrometric signatures that are dependent on the Sun-object-sensor geometry, which changes as the object moves along on its orbital trajectory. It is important to remember that this geometry is not limited to the consideration of the phase angle but includes the orientation of the objects and, more importantly, how this orientation evolves over time.

From this single result, we have concluded four key lessons that should be put into practice when using reflectance spectroscopy in the context of space surveillance. First, spectrometric measurements, or products derived from these measurements, should be presented in a manner such that the Sun-object-sensor geometry can be known. If attitude information of the subject is available, then this should be provided, if not, then the date and times of the measurement is a strict minimum requirement. Second, the method of combining two spectrometric measurements taken at different wavelength ranges to produce a single measurement should be completely avoided unless both measurements were taken in exactly the same Sun-object-sensor geometry. The third lesson is that a thorough spectrometric characterization of an object will ideally require measurements to be collected over the complete range of Sun-object-sensor geometries that it could encounter. Finally, the observing strategy, when using spectroscopy for space surveillance purposes, must be adapted to the subject. Due to the nature of the sensor used, it follows that spectroscopy is the wrong tool for the characterization of faint or rapidly spinning debris.

The results of the experiment presented in this paper are positive yet more work remains before artificial space objects can be characterized by their spectrometric profile or more importantly, before we can confidently identify specific material types from such measurements. First and foremost, other methods of processing the data collected during this experiment will be studied to determine whether specific types of material can be identified from the measurements. Second, subsequent observational experiments using the 1.8m Plaskett Telescope will focus on continuing the characterization of the spacecraft studied during this experiment as well as characterizing spacecraft of similar design. As part of this study, we also wish to study the evolution of a spacecraft's spectral reflectance over the course of its operational lifetime. The Anik G1 spacecraft, which is expected to be launched by the end of 2012, has already been identified as the subject of this effort. Finally, simultaneous multicolor photometry of space debris will be explored with using the three small aperture telescopes located at RMCC.

8. REFERENCES

[1] K. Jorgensen, G. Stansbery, J. Africano, K. Hamada, P. Sydney and P. Kervin, "Most Recent Findings from the NASA AMOS Spectral Study (NASS): Squiggly Lines lead to Physical Properties of Orbiting Objects," in *AMOS Technical Conference*, Wailea, Maui, Hawaii, 2002.

[2] K. Jorgensen, J. Okada, J. Africano, D. Hall, M. Guyote, K. Hamada, G. Stansbery, E. Barker and P. Kervin, "Reflectance spectra of human-made space objects," in *AMOS Technical Conference*, Kihei, Maui, Hawaii, 2004.

[3] K. Abercromby, J. Okada, M. Guyote, K. Hamada and E. Barker, "Comparisons of Ground Truth and Remote Spectral Measurements of the FORMOSAT and ANDE Spacecraft," in *AMOS Technical Conference*, Wailea, Maui, Hawaii, 2006.

[4] T. Schildknecht, A. Vannanti, H. Krag and C. Erd, "Reflectance Spectra of Space Debris in GEO," in *AMOS Technical Conference, Wailea, Maui, Hawaii*, 2009.

[5] D. Bédard, M. Lévesque and B. Wallace, "CanX-1 Characterization Experiment," in *AMOS Technical Conference*, Wailea, Maui, Hawaii, 2011.

[6] D. Bédard, "Using a physics-based reflection model to study the reddening effect observed in remote spectrometric measurements of artificial space objects," Wailea, Maui, Hawaii, 2011.

[7] E. H. Richardson, "The Spectrographs of the Dominion Astrophysical Observatory," *Journal of the Royal Astronomical Society of Canada,* vol. 62, p. 313, 1968.

[8] H. I. o. Astrophysics, "The Dominion Astrophysical Observatory (DAO)," [Online]. Available: https://www.astrosci.ca/DAO/. [Accessed 08 09 2012].

[9] R. I. Abott and T. W. Wallace, "Decision Support in Space Situational Awareness," *Lincoln Laboratory Journal*, vol. 16, no. 2, 2007.