Measurement of the photometric and spectral BRDF of small Canadian satellites in a controlled environment

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ABSTRACT

Measuring a satellite's bidirectional reflection distribution function (BRDF) before and after launch can yield significant information relevant to the exploitation of remote photometric and spectrometric observations for Space Situational Awareness (SSA). There are three Canadian technology demonstration space missions, consisting of four small spacecraft representing three very different small satellite designs, which are scheduled to be launched between 2012 and 2013. These are the NEOSSat, CanX-4/CanX-5, and M3MSat spacecraft and all of these space missions have been partially funded by Defence R&D Canada (DRDC). They will each provide an opportunity to collect BRDF measurements from this class of satellites in a controlled laboratory environment before their launch and to then compare these data to remote observations.

Given that the measurement of a spacecraft's BRDF had never been attempted in Canada, it was deemed critical to develop and test a characterization procedure before gaining access to a real spacecraft. Accordingly, the first characterization experiment was conducted using an engineering model (EM) of the CanX-1 nanosatellite. All of the experimental objectives were successfully achieved and the experiment paved the way for the characterization of the NEOSSat microsatellite that is expected to be launched in early 2012. This paper will describe the spacecraft characterization methodology that was adopted for the CanX-1 EM and will present selected results from the experiments. The paper will conclude with a brief description of the NEOSSat characterization experiment.

1. INTRODUCTION

Space Situational Awareness (SSA), the ability to know what is in space and having the command and control capacity to act on this knowledge, is an essential capability required by those organizations tasked with the protection of the space systems that are deemed critical to Canada's national infrastructure. Not only must Canadian decision makers be aware of what is in orbit around the Earth but they must also be capable to clearly and unequivocally differentiate between environmental and man-made interference with Canadian space systems. This objective poses an interesting challenge that inherently calls for new tools and techniques in the area of space surveillance. One of these relatively new techniques is the use of reflectance spectroscopy for the characterization of artificial space objects, such as active satellites and space debris, in Earth orbit. The use of astronomical reflectance spectroscopy to characterize artificial space objects is a relatively new field that is still evolving. Of those, only the Formosat-3 spacecraft were spectrally characterized in a controlled environment before their launch [1].

The ability to compare in-situ spectrometric measurements of spacecraft before launch with measurements collected once these satellites are in orbit should allow researchers to address fundamental questions regarding the military utility of spectrometric measurements for SSA purposes. With this in mind, a collaborative effort between the Royal Military College of Canada (RMC) and Defence R&D Canada (DRDC) has been initiated and is aimed at further advancing the use of reflectance spectroscopy in the context of surveillance of space. The intended improvement will be achieved through the development of new methods of interpreting remote spectrometric measurements. The main activity supporting this goal will be the comparison of spectrometric measurements of the NEOSSat spacecraft before and after its launch. The novelties of this experiment include the development of a new ground characterization procedure as well as the availability of the NEOSSat attitude data throughout the remote observation period. It is anticipated that the information gained from these two improvements will allow experimenters to directly compare ground-truth and remote measurement.

Given that DRDC and RMC have never conducted a spectrometric and photometric characterization of spacecraft, it was deemed critical to gain experience with this procedure. As a result, an experiment was devised in which an engineering model (EM) of the CanX-1 nanosatellite would be characterized. This would allow a thorough validation of the experimental procedure to ensure time would not be wasted during the characterization of NEOSSat. This paper describes these experiments and present selected results.

The paper will begin with a short description of the CanX-1 EM and then proceed with a detailed summary of the experimental procedure that was adopted. Next, selected results of the CanX-1 EM characterization will be presented and discussed. Problems that were identified during the course of the CanX-1 EM characterization experiment and afterwards during the analysis of the data will be addressed and be followed by a discussion of how these will be corrected for the NEOSSat ground characterization trial. Finally, the paper will conclude with a few thoughts on the overall exercise of the ground characterization of spacecraft in a controlled environment.

2. EXPERIMENT AIM

The aim of the spectrometric characterization of the CanX-1 EM in a controlled laboratory environment was to develop test procedures and data analysis methods in order to gain a better understanding of the requirements for the characterization of real spacecraft before their launch. Given that access to a spacecraft undergoing its final testing will be quite limited, it is critical to have a tested and validated experiment plan to ensure that the opportunity is not wasted. As such, the development of a proven experimental procedure was deemed critical in order to gain access to the NEOSSat spacecraft.

Three objectives were established in order to satisfy the stated aim of the experiment. The first objective was to establish a spectrometric characterization procedure that could be employed for the aforementioned missions. Although the procedures would be developed with the CanX-1 EM and, as such, would have to be adapted on a case by case basis to the satellites being characterized, the core components of the methodology will likely remain the same.

The second objective was to develop the necessary software tools to process and analyse the various types of collected data sets. It is expected that the spectrometric characterization of the NEOSSat spacecraft will produce several hundred data files. Software tools are not only required to efficiently process the data to assist in the analysis but also to support the characterization experiment themselves. The capability to rapidly process batches of files during the experiments will allow experimenters to retake measurements or collect supporting measurements if interesting and unexpected features are uncovered during the trials.

The third and final objective of the CanX-1 EM characterization experiment was to provide an initial assessment of the utility for SSA of spectrometric characterization of a spacecraft. As a minimum, the following questions were sought to be addressed by this experiment:

- Can information about the surface composition of the spacecraft be inferred or directly determined by studying the spectral content of the reflected light?
- Does the spectral content of the reflected light change with varying incident light angles? If so, how does it change?
- Are the spectral contents of the diffuse and specular reflections different for a given incident light angle?

It was also expected that the answers to these questions would help improve the experimental procedures discussed above.

3. EXPERIMENTAL SUBJECT: CANX-1 EM

The CanX-1 EM, shown at Fig. 1, is an engineering prototype that was developed and built by the University of Toronto Institute for Aerospace Studies - Space Flight Laboratory (UTIAS-SFL) as a precursor to the CanX-1 mission that was launched on 30 June 2003 [2]. With a total mass of less than 1 kg within a 10-centimeter cube, the CanX-1 mission was designed to evaluate various enabling technologies in space including a CMOS horizon sensor and star-tracker, an active 3-axis attitude control system using magnetorquers, and a GPS-based orbit determination system. Unfortunately, contact with the CanX-1 spacecraft was never established and so, sadly, it is now considered space debris.

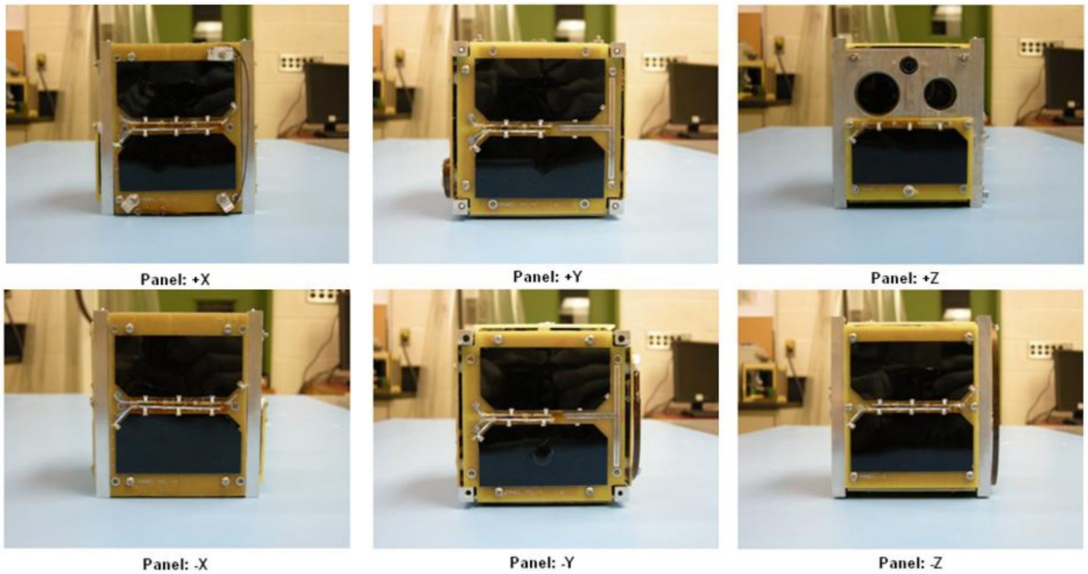


Fig. 1. Images of the six faces of the CanX-1 EM. The nomenclature used to identify the six faces corresponds to that used by the CanX-1 mission team.

The CanX-1 EM was procured by DRDC Ottawa in 2004 as part of an initiative to study the military utility of nanosatellites. With the exception of the missing CMOS sensors on the +Z panel, the exterior of the engineering prototype closely matches that of the CanX-1 spacecraft. Unfortunately, the CanX-1 EM was not stored in a controlled environment and as such contamination and damages resulting from manipulation are clearly visible on the exterior surface. Nonetheless, the utilization of the CanX-1 EM for this experiment satisfied the experimental objectives described above since various manipulation techniques could be tested and evaluated without having to worry about the safety of the experimental subject.

4. EXPERIMENTAL SET-UP AND PROCEDURE

The overarching reason for characterizing a spacecraft in a controlled environment is to compare these measurements against those obtained with a telescope once the satellite is in orbit. Accordingly, the experimental set-up was configured to reproduce, as well as possible, the expected illumination-object-sensor geometries to ensure that both types of measurements could be directly compared. The most critical consideration driving this comparison is that for most artificial space objects observed, reflectance spectroscopy requires an integration period ranging from 10 seconds for the very bright targets to 60 seconds for the relatively dimmer ones. As a comparison, spectral reflectance measurements taken in a controlled environment typically require an integration time of a few milliseconds in order to obtain a sufficient signal-to-noise ratio (SNR). Over the course of this integration period in the laboratory, the object, from which the reflections are measured, remains stationary with respect to the illumination source and the sensor. This is not the case for an artificial space object.

With the above in mind, the setup had to allow the experimenters to measure all three types of reflections (i.e. specular, directional diffuse, uniform diffuse) in different phase angles. The desired outcome would be to use the measurements collected in the controlled environment in order to emulate remote spectrometric data. Fig. 2 illustrates the setup that was implemented for this experiment.

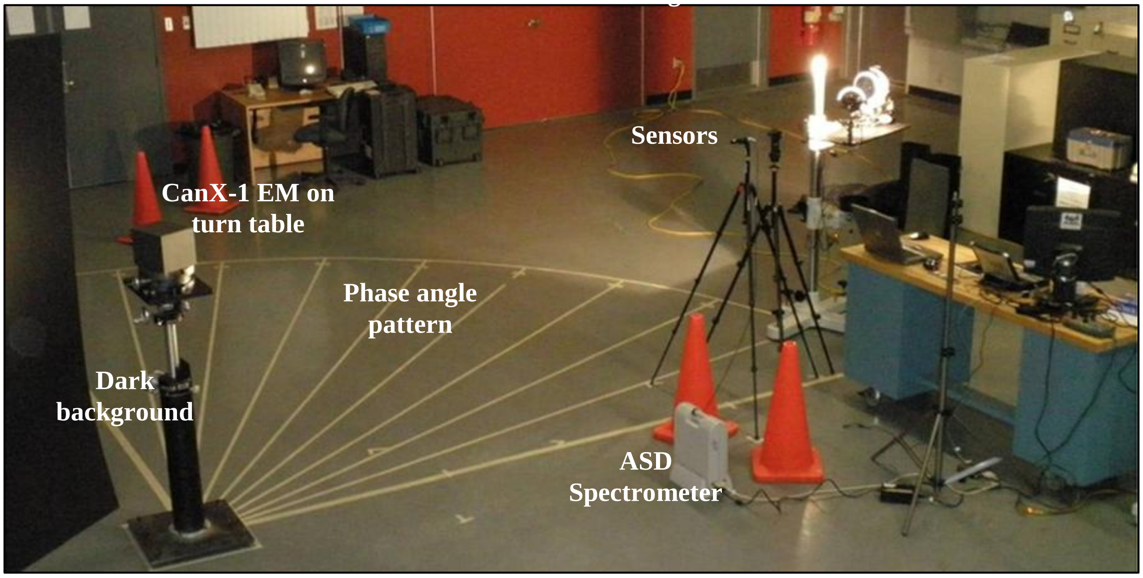


Fig. 2. Picture of the set-up used for the CanX-1 EM characterization experiment.

The light source consisted of a 250W halogen lamp placed at the focal point of a 15-cm parabolic mirror. The illumination angular cone produced by this light on the satellite was a little under 2 degrees. The collimated light beam is slightly bigger than the satellite and did not illuminate much of the environment. A black panel was placed at an inclined position behind the CanX-1 EM to minimize any background reflections to the sensors. The light source was attached on a portable mount that was moved during the experiment to positions that provided the desired phase angles, namely from 10^{o} to 90^{o} in increments of 10^{o} as shown by the tape marking on the floor.

Two sensors were used to gather the photometric and spectrometric measurements during the experiment. The spectrometer that was used was the same model employed by Abercromby (née Jorgensen) during her various material characterization experiments, namely the FieldSpec®Pro, which covers the spectral band from 350nm to 2500 nm [3]. The sensor was equipped with a small objective lens having a field of view of 8 degrees, and was placed at a distance such that the field of view (FOV) would be completely filled by the CanX-1 EM and practically nothing else. The spectrometer remained at the 0^{o} position throughout the experiment. The spectrometer was configured such that each spectral reflectance measurement consisted of an average of 100 separate measurements each having an integration time of 17 msec. The sensor that was used for the broadband (unfiltered) photometric measurements was a Nikon D-700 camera with a 25 Mpixel CCD equipped with a 70/210mm zoom that was uniquely used at the smallest FOV (210mm of focal length).

The CanX-1 EM was placed on a turn table that allowed it to be rotated at any angle with respect to the spectrometer between 0^{o} and 360^{o} in increments of 1^{o}. The satellite was positioned such that the 0^{o}, 90^{o}, 180^{o} and 270^{o} marks on the table corresponded to the spectrometer at normal position with respect to each of the four satellite panels.

5. EXPERIMENTAL PROCEDURE

The selected method to obtain spectrometric data of the CanX-1 EM was the collection of reflectance factor, , which was defined by Nicodemus *et al*. as "*the ratio of the radiant flux reflected from a sample surface to that which would be reflected into the same reflected-beam geometry by a lossless perfectly diffuse standard surface irradiated in exactly the same way as the sample.* [4]" Mathematically, this definition is expressed as follows:

$$R\ \ \theta_i,\phi_i,\theta_r,\phi_r,\omega_i,\omega_r\ \ = \frac{d\Phi_r}{d\Phi_{r,id}} = \frac{\pi}{\Omega_i\Omega_r}\cdot \quad _{\omega_r}\ \ _{\omega_i}\ \ f_r\ \ \theta_i,\phi_i,\theta_r,\phi_r\ \ \cdot d\Omega_i\cdot d\Omega_r,$$

where $d\Phi_r$ is the radiant flux reflected by the surface of the CanX-1 EM, $d\Phi_{r,id}$ is the radiant flux reflected by an ideal lossless surface reflected into the same reflected-beam geometry, Ω_i is the projected solid angle of the incident light on the surface, Ω_r is the projected solid angle of the sensor onto the surface, $f_r\ \ \theta_i,\phi_i,\theta_r,\phi_r$ is the bidirectional reflectance function (BRDF). It is critical to note at this point, that the reflectance factor consists of the ratio of two measurements taken under identical view illumination and sensor geometry [4]. Fig.3 provides a flow chart of the experimental process that was followed to collect measurements.

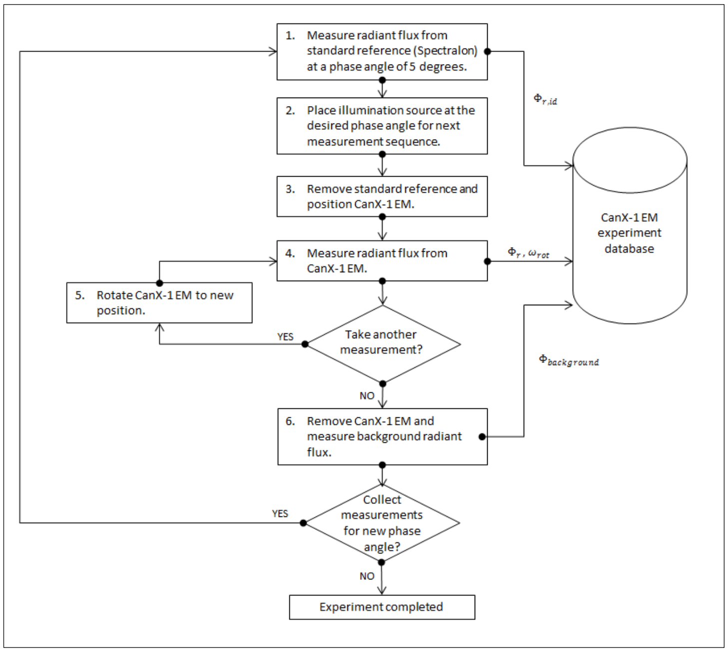


Fig.3. Flow chart of the CanX-1 EM characterization experiment.

During the execution of the experiment, all lights in the room were turned off. For every set of measurements taken for a given phase angle, one measurement of the white reference (Spectralon) was taken and would be used to compute the spectral reflectance factor from the satellite. The white reference was placed on the turn-table in a position such that the spectrometer and the Nikon camera would be at an angle of 0^o with respect to the surface normal. Once this was completed, the satellite was placed on the table. In order to keep the duration of the experiment to 3 days, the number of measurements taken had to be limited. Hence, the experimenters collected measurements in regions where the reflections were strong enough to be measured. More precisely, since the greater portion of the surface was covered in solar cells, the reflection tended to be highly specular with practically no diffuse components. Hence, the specular reflection was detected and measured and then other measurements on either side (i.e. at larger and smaller angles) were taken in increments of 1^o until the signals were barely detectable. An example of the spectrometric and photometric measurements that were obtained are presented in Fig. 4 and 5 respectively.

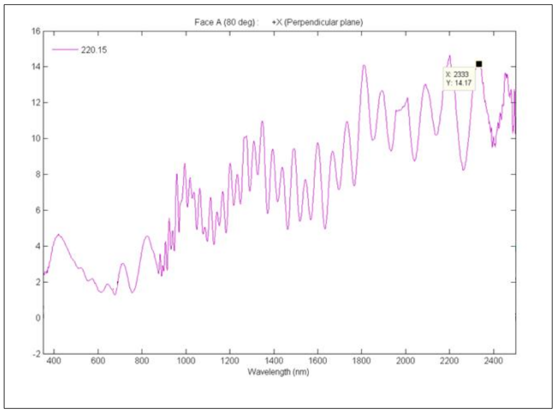


Fig. 4. The reflectance factor as a function of wavelength. An interference pattern, only observed in the specular components of the reflection, is clearly seen above 900 nm. This is a result of multi-layer film interference caused by the 13 layers of semi-conductors that comprise the CanX-1 EM triple junction photovoltaic cell.

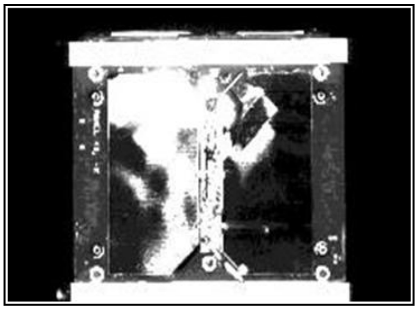


Fig. 5. An example broadband image of the CanX-1 EM.

6. DATA ANALYSIS

There are no plans at the moment to obtain remote spectrometric data of the CanX-1 spacecraft. Nonetheless, the analysis of the spectrometric data collected during the CanX-1 EM characterization was performed to improve the experimental procedure ahead of the NEOSSat trial. Having a database of the ground truth data also allows for further spectral comparisons should data be obtained later on. This was also done to make an initial assessment of the utility for SSA of spectrometric characterization of a spacecraft.

The first order of business was to confirm that the surface composition of the spacecraft could be inferred or directly determined by studying the spectral content of the reflected light. Although the experimenters had no spectral reflectance database for materials typically found on the surfaces of spacecraft for comparison, it was very obvious from cursory visual interpretation that there was information in the measured signal. The variation in the intensity of the measurements confirmed that the CanX-1 EM is mostly a specular reflector and that this specific characteristic is due to the fact that five out of six faces are almost entirely covered by photovoltaic cell. Outside of the region of specularity the signal was barely measureable.

During the in-depth data analysis of the spectrometric measurements (discussed below) it was confirmed that the measured specular reflections clearly contained information about the materials that were on the surface of the spacecraft and that in this specific case, the detected signals were mainly dominated by those reflected from the Emcore triple-junction (TJ) photovoltaic cells found on the surface of the spacecraft. This was further verified by the results of modelling work independently carried out at RMC and DRDC Valcartier. Unfortunately, the presence of other materials on the surface of the CanX-1 EM, such as aluminum 6061, could not be identified in any of the spectrometric measurements obtained of the five faces covered in solar cells.

The fact that reflectance spectroscopy could be used to characterize and possibly identify specific materials is unsurprising as this technique has been extensively used for asteroid characterization since at least the seventies and has been experimented with for spacecraft characterization since the late nineties. However, the surprising result is that the spectral response of the spacecraft changed as a function of the light-spacecraft-sensor geometry. More precisely, there was an apparent shift of some spectral features as the satellite was rotated to a given phase angle position. This variation is clearly noticeable in Fig. 6 where at least three features, initially centered at approximately 660, 720 and 790 nm for the satellite rotation angle of 208 degrees, are displaced towards shorter wavelength as the satellite is rotated to a geometry that results in a stronger reflected component. Equally interesting is an apparent narrowing of the feature as the signal gains in strength.

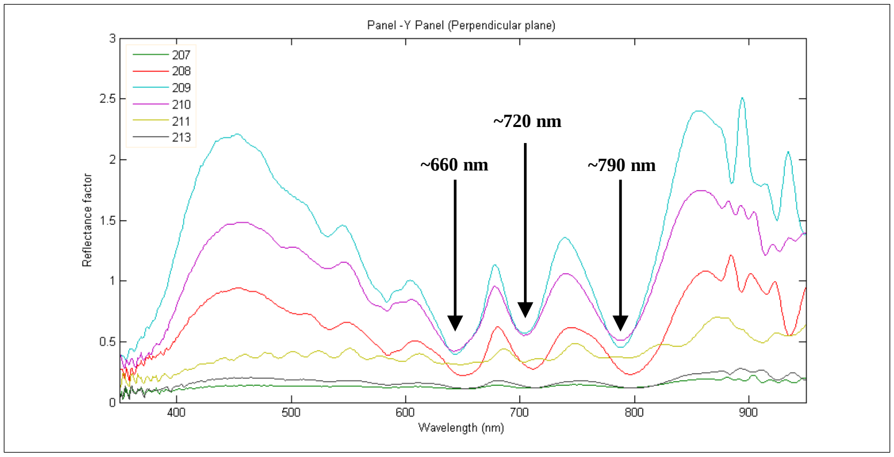


Fig. 6. Spectra of the -Y panel (perpendicular plane) taken at an illumination phase angle of 60°. The specular component was measured at a satellite angle of 209° while the 207° and 213° represent the angles at which no practical signal was detected.

Subsequent solar cell reflectance numerical modeling conducted at RMC confirmed that most, if not all, of the solar cell's major reflectance features were caused by multi-layer film interference. A typical triple-junction cell consists of a double anti-reflection layer deposited over a photovoltaic cell, itself consisting of between 13 and 16 layers of various semi-conductor materials. From the modeling, it appears that wide absorption features below 900 nm, such as seen in Fig. 6, are a result of the two anti-reflection layers which are relatively thin. The same modelling experiment also shows that the interference patterns that were typically observed at wavelengths above 900 nm (see Fig. 4) were a result of the thicker layers of semi-conductor materials found deeper within the photovoltaic cell.

The next part of the analysis consisted of comparing, for all six faces of the CanX-1 EM, the spectra of each face oriented first in a horizontal and then in a vertical manner for the same illumination geometry. This was done to determine whether reflectance spectroscopy could be used not only to differentiate between panels but also the orientation of these panels. The results were inconclusive. The spectra of most of the faces in the vertical and horizontal position showed that the surface panels appeared approximately the same with the exception of the intensity of the collected signal. The only exception to this statement was for the measurements of the +Z panel (containing the cutouts for the CMOS cameras), which is a very different panel.

The left diagram of Fig. 7 shows that measured reflections from the +Z panel showed no trace of solar cell spectral characteristics when this face was positioned such that the photovoltaic cell was in a horizontal position (such as shown in Fig. 1). In this configuration, the specular lobe was broader and this was attributed to the fact that half of this face is composed of a relatively smooth aluminum 6061 surface. The absence of any solar cell spectra in the detected signal was attributed to the fact that the cell was not positioned perfectly flat onto the surface of the +Z panel and as a result, it did not reflect the light in the direction of the sensor. On the other hand, when the CanX-1 EM was placed in a manner such that the photovoltaic cell was now vertical, the signal was once again dominated by the Emcore TJ cell as shown in the right diagram of Fig. 7.

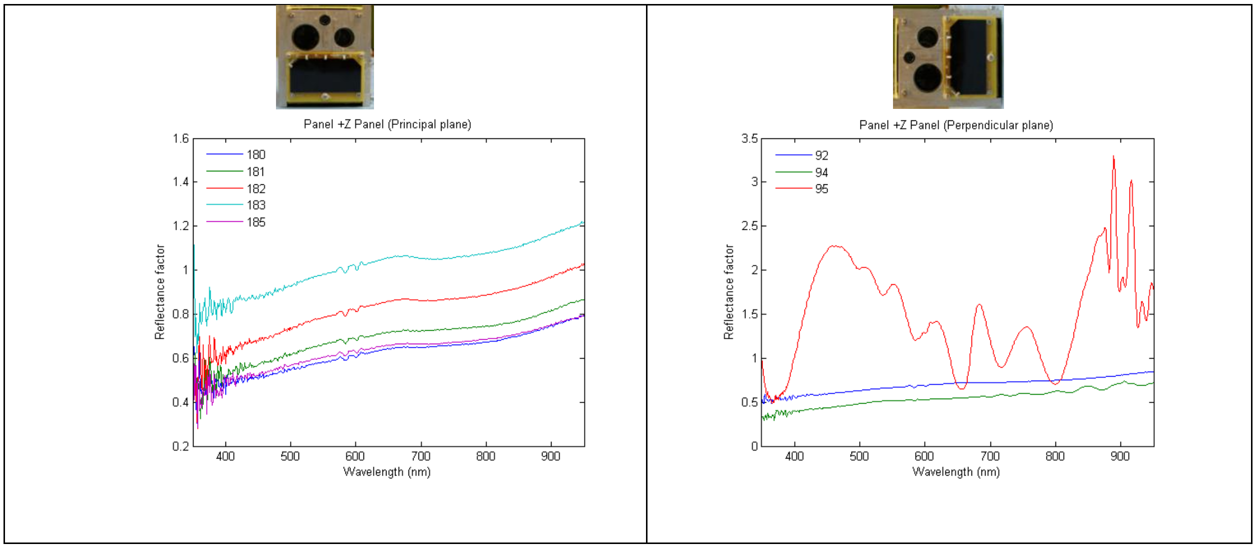


Fig. 7: Comparison of principal and perpendicular plane of the +Z panel taken with a 5 degrees illumination phase angle. The left image shows weak diffuse reflectance from the Aluminum 6061 surface, while the right image shows reflectance from the solar cells at 95 degrees.

Given that all surfaces are practically identical, with the exception of the +Z panel, these results are not surprising. The characterization of spacecraft with exterior body panels that are all different from each other, such as NEOSSat, should help determine whether reflectance spectra can be used to infer some information with respect to the orientation of the spacecraft.

Finally, the measurement procedure that was established for the CanX-1 EM characterization experiment may have allowed the experimenters to fortuitously stumble upon a possible explanation of the reddening effect that is commonly seen in remote spectrometric measurements of artificial space objects [5], [6]. Variations in the magnitude of the detected spectral reflectance as a function of angle had been expected, however the experimenters had not anticipated that the slope and the spectral content, or in other words the overall shape of the reflectance curve, between 350 and 2500 nm would change as the illumination and sensor geometry varied. Although the displacement of presumed absorption bands was rapidly attributed to thin film interference caused by the solar cells, the increase in reflectance beginning in the region of 800 nm in certain illumination-sensor geometries remained unexplained. It was later uncovered that an apparent analogous phenomenon, clearly seen in Fig.8, was commonly observed in spectral reflectance obtained from remote observations of satellites and was referred to as the reddening effect [5], [6]. To date, it had not been, and still is not, reported has having been observed before in a laboratory environment.

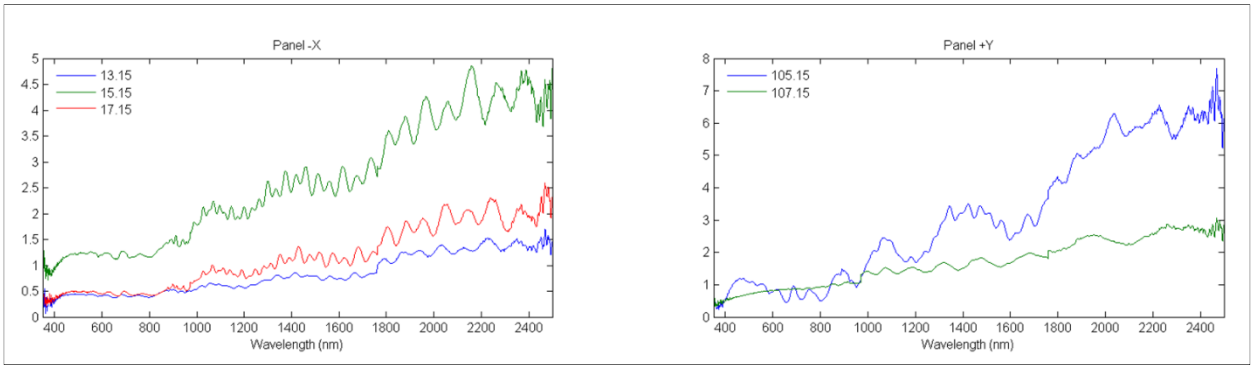


Fig.8. Spectral reflectance measurements of the –X and +Y faces taken at a 30 degree phase angle illumination.

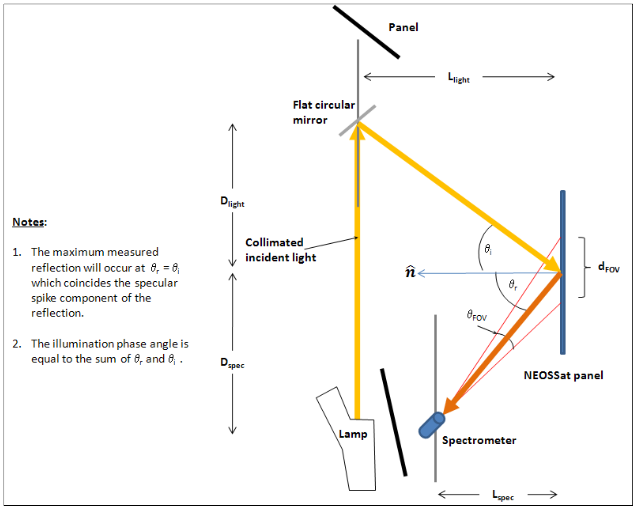
A careful review of the experimental procedure was conducted to determine if there was mishandling of the spectrometer used during the characterization of the CanX-1 EM. Although minor errors were noted, there were none that could have affected the measurements themselves. Following a review of the limited literature available on the subject of spectral reddening for artificial space objects, the question was posed as to whether the reddening effect was a natural consequence unaccounted for in both the ground truth measurement collection and the spectral reflectance model used by Abercromby *et al.* A description of this experiment and its result is presented in another paper by the principal author in these proceeding.

7. GROUND CHARACTERIZATION OF THE NEOSSat SPACECRAFT

The confidence in the experimenters' ability to conduct this experiment efficiently and without harm to the satellite was such that the NEOSSat Joint Project Office along with the prime contractor responsible for the development and build of the spacecraft provided their authorization for the experimenters to proceed with the characterization of the NEOSSat spacecraft.

The aim of the NEOSSat characterization experiment is to perform the photometric and spectrometric characterization of the NEOSSat spacecraft. NEOSSat is expected to be launched in early 2012. This spacecraft will have an approximate mass of 80 kg and dimensions of roughly 79 x 141 x 39 cm. The prime contractor for the NEOSSat spacecraft, Microsat Systems Canada, Inc. (MSCI), has given their approval to allow ground characterization of the spacecraft during the AI&T (Assembly, Integration & Testing) phase at the David Florida Laboratory (DFL).

In essence the NEOSSat spacecraft characterization will be very similar to the CanX-1 EM experiment with one major change. As in the CanX-1 EM case, the NEOSSat spacecraft will be characterized when it is installed on a mass properties table, allowing experimenters to rotate the satellite. The experimental set-up is illustrated in Fig. 9 and represents an improvement over that used during the CanX-1 EM experiment. As shown, for a given incidence angle, spectral reflectance measurements will be collected over a wide range of reflection angles. This setup will allow the experimenters to measure how all of the reflection components vary as a function of phase angle. It will also provide an adequate sampling of spectrometric measurements to allow simulation of remote spectrometric data.



Notes:

1. The maximum measured reflection will occur at $\theta_r = \theta_i$ which coincides the specular spike component of the reflection.
2. The illumination phase angle is equal to the sum of θ_r and θ_i .

Fig. 9. Conceptual experimental set-up of the ground characterization of the NEOSSat spacecraft.

As part of the overall NEOSSat characterization experiment, spectrometric measurements of individual surface materials will also be collected. These measurements, taken in a variety of illumination-sample-sensor geometries, will be used to study spectral mixing in spatially unresolved spectrometric measurements. Furthermore, these data, along with those measurements collected of other sample spacecraft material, will also form the first entry of a database of spectral reflectance.

Finally, the data collected during the NEOSSat characterization experiment will be used as the ground truth against which all remote observations of the NEOSSat spacecraft with ground optical sensors will be compared. It is expected that having full knowledge of the NEOSSat attitude during all remote observations will allow for greater insight during the interpretation of the collected data.

8. CONCLUSION

Over the next three years, there will be at least three opportunities to characterize, in a controlled environment, microsatellites and nanosatellites that are either fully or partially funded by the Government of Canada. The first of these missions will be the NEOSSat spacecraft due to be launched early next year. Given that this type of experiment had never been attempted in Canada, a characterization procedure was elaborated and validated using the CanX-1 EM, a spacecraft prototype which, for all intents and purposes, was nearly identical to the actual CanX-1 satellite that was launched in 2003. Although each characterization procedure will have to be adapted to the specific spacecraft being studied, e.g. to account for the facilities in which the procedure will be conducted and the requirements of the prime contractor responsible for the spacecraft during the AI&T phase, the CanX-1 EM experiment has nonetheless allowed the experiment to establish a solid baseline upon which all other exercise may be planned.

In all, the experiment was considered a success. The first objective was satisfied in that a detailed procedure for the ground characterization of the NEOSSat spacecraft was established. This provided the credibility that was required to approach MSCI, the prime contractor of the NEOSSat spacecraft, to obtain their permission to fit a similar experiment within their very demanding schedule. Next, over 1000 spectral reflectance files were acquired during the experiment that lasted three days. This allowed the experimenter to develop the software tools and techniques that will be needed to efficiently and rapidly process the data during the NEOSSat characterization. This will permit the experimenter to rapidly assess where the attention of the characterization must be focused. The elaboration allowed for a greater understanding of the data as well as the instrument and provided additional insight as to how the data should be collected in future experiment. Finally, the third objective, which consisted of making an initial assessment of the utility for SSA of spectrometric characterization of a spacecraft in a controlled environment, was also satisfied.

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