Toward Microsatellite Based Space Situational Awareness

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Abstract

The NEOSSat microsatellite is a dual mission space telescope which will perform asteroid detection and Space Situational Awareness (SSA) experiments on deep space satellites. NEOSSat was launched on 25 February 2013 into a 786 km dawn-dusk sun synchronous orbit and is currently undergoing satellite commissioning. The microsatellite consists of a 15cm aperture optical telescope, GPS receiver, high performance attitude control system, and stray light rejection baffle designed to suppress sunlight while pointing at solar elongations of 45 degrees along the ecliptic. The SSA experimental mission, referred to as HEOSS (High Earth Orbit Space Surveillance), will perform SSA experiments to characterize satellites and debris in deep space orbits primarily in GEO. The HEOSS mission objectives are to evaluate the utility of microsatellites to perform space-track catalog maintenance observations of resident space objects and to perform optical SSA experiments which are difficult to perform from the ground. NEOSSat offers the ability to conduct observations of satellites at high phase angles which can potentially extend the trackable portion of space in which deep space objects' orbits can be monitored. This paper identifies some of the initial lessons learned during the initial checkout phase of the satellite prior to the primary SSA experiments to be conducted in 2013.

1. Introduction

On 25 February 2013 the NEOSSat (Near Earth Orbit Surveillance Satellite) was launched into a 786 km, dawn-dusk sun-synchronous orbit aboard an Indian PSLV rocket. NEOSSat is a dual mission research microsatellite carrying a visual-band telescope to search for potentially hazardous near Earth asteroids and to track man-made deep space satellites and debris. The microsatellite was constructed by Microsat Systems Canada Incorporated (MSCI) of Mississauga, Ontario and was delivered to a Canadian Space Agency (CSA) and Defence R&D Canada (DRDC) Joint Program Office in the fall of 2012. The microsatellite shares design lineage with the MOST microsatellite [1] an astronomy microsatellite launched by Canada in 2003. NEOSSat was launched along with the Canadian Armed Forces' Sapphire satellite [2]. Sapphire is a small satellite dedicated to the operational tracking of space debris and will contribute its observations to the United States Space Surveillance Network (SSN).

Fig.1. Left: The NEOSSat microsatellite artistic impression (Image Credit: University of Calgary). Right: NEOSSat being prepared for thermal environmental testing at the David Florida Laboratory in Ottawa, Ontario. The telescope baffle (beveled cylinder) is visible on the right. (Image Credit: Janice Lang, DRDC Ottawa).

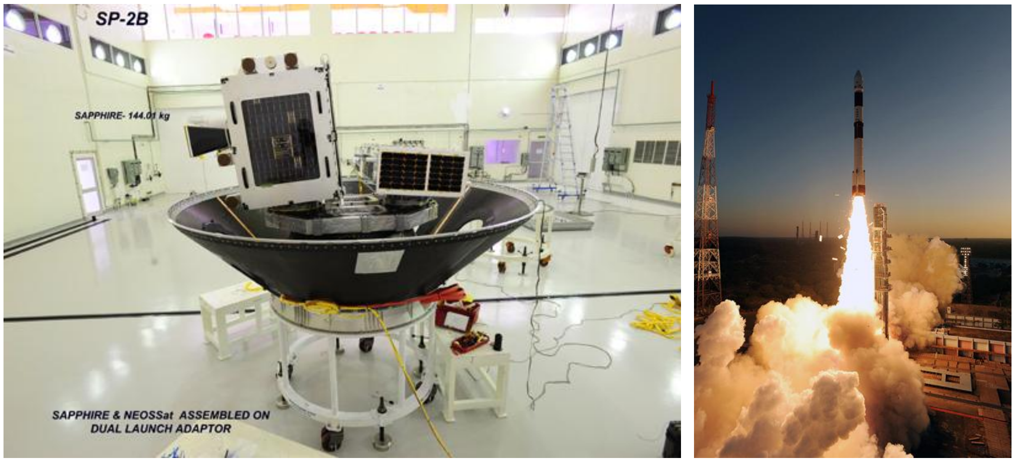

Fig.2. (Left) The Sapphire satellite (indicated) and NEOSSat (smaller satellite to Sapphire's right) mated to the PSLV dual launch adapter. (Right): PSLV C20 launch (Image Credits: ISRO).

The NEOSSat microsatellite project was kicked off in August 2005 as a partnership between The Canadian Space Agency, Defence R&D Canada with MSCI as the prime contractor. The satellite weighs 74 kg and is approximately 1.4 x 0.8 x 0.4 meters in size. NEOSSat uses reaction wheels and magnetorquers to reorient itself in space. Fine attitude estimation uses a star tracker which shares the same telescope as the science instrument. The satellite uses S-band radio to downlink data and telemetry. NEOSSat's telescope is a 15cm Maksutov Cassegrain design based on the MOST microsatellite telescope [1] and was modified for imaging stellar fields. NEOSSat features a stray light rejection baffle designed to permit the asteroid science team to image 45 degrees away from the sun while searching for faint asteroids. The NEOSSat microsatellite project cost the Government of Canada approximately $25m Canadian dollars and has a 2 year goal for operational life.

The Near Earth Space Surveillance (NESS) mission will search for potentially hazardous Earth orbit crossing asteroids which could collide with the Earth. The NESS mission will use NEOSSat's telescope to search for Aten and Atira class asteroids with solar elongations greater than 45 degrees in the ecliptic plane. The objects which NESS is searching for are fainter than magnitude 19, posing a detection challenge for any small aperture telescope. The NESS Science team is located at the University of Calgary and has an international contingent of asteroid science participants within Canada and the United States.

The High Earth Orbit Space Surveillance (HEOSS) mission will conduct Space Situational Awareness (SSA) experiments primarily by tracking deep space satellites in geostationary orbit. The HEOSS mission objectives are to: 1) perform an assessment of the suitability of a microsatellite to perform the space-track mission role 2) perform SSA experiments which are not possible from the ground and 3) validate the business model between the Canadian Space Agency and the Department of National Defence to determine the suitability of the Joint Project Office (JPO) model as a means to perform space missions. The HEOSS Science team is located at DRDC Ottawa (Ottawa, Ontario), The Royal Military College of Canada (Kingston, ON), and has affiliated science team members from the NATO Space Situational Awareness community.

There are several advantages to placing a small satellite platform in low Earth orbit to perform the space track role. A Low Earth Orbit (LEO) satellite observer's motion permits visibility to most deep space orbits (see figure 3). The day-night cycle, experienced by ground based telescopes, and weather interruptions by rain, clouds and wind are removed as operational limitations. A LEO satellite also has visibility to geosynchronous orbits (GEO) which are not observable by ground based sensors as the GEO orbital period is locked with the Earth's rotational motion. This causes many geostationary objects to be unobservable by a single ground based observer. In space, an orbiting observer has a wider, planetary grasp of Earth orbiting objects as the entire geosynchronous belt sweeps through the sensors visibility once per day.. Atmospheric attenuation effects (air mass) is also eliminated as sensitivity limitation and permits positional measurement of objects over a larger range of sky at any given time.

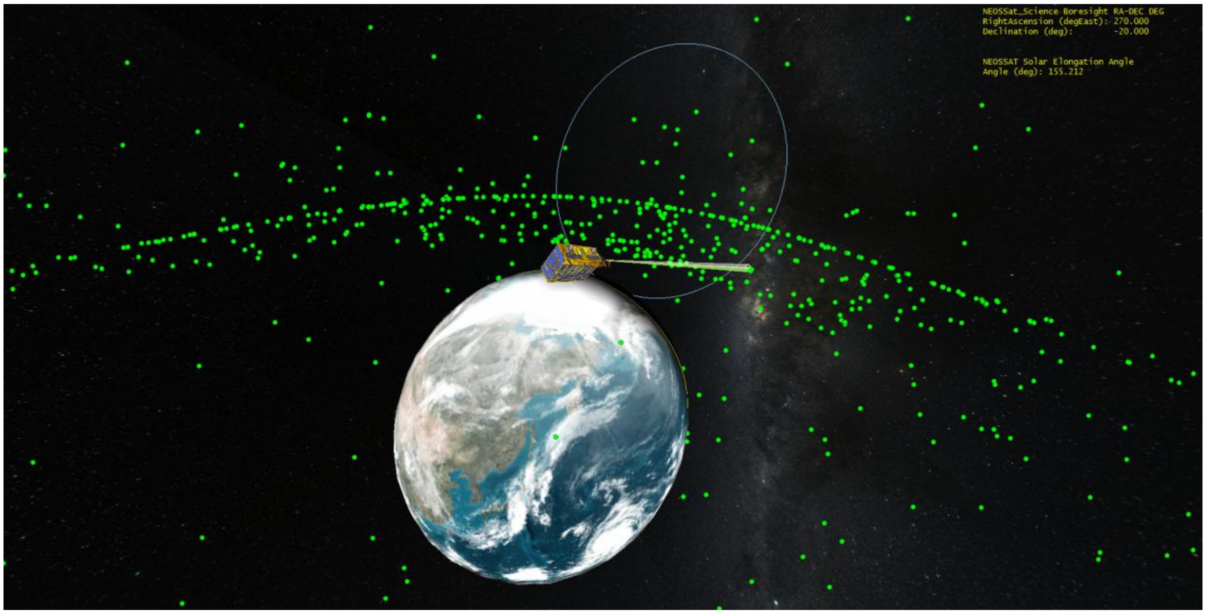

Fig.3. NEOSSat (center) deep space surveillance geometry with deep space satellites shown in green.

The key rationale for the implementation of a microsatellite solution for SSA is to address the disadvantages of space based platforms. The disadvantages of placing a sensor in orbit are the normal space system challenges of expense, development time and service life. While expense can be mitigated by smaller platforms, development time can be reduced, as well as large infrastructure for development is not required (a clean lab environment is often all that is needed). Service life becomes a cost-benefit tradeoff as many microsatellites are constructed without redundant systems.

Other factors are not uniquely addressable by the microspace approach which constrains a space system's utility.
The space environment causes unique detection issues which must be mitigated by data processing (discussed in §3). The satellite resource also tends to have periodic rather than continuous communications with their ground infrastructure. This causes the space system's utility to be less responsive when few ground stations are utilized. Also, in contrast to a ground based SSA telescope, equipment maintenance, repair and technology refresh is uneconomic or impossible for most satellites.

These complex, system-level, benefits and constraints are the reason which Defence R&D Canada sponsored the HEOSS technology demonstration mission. While space based tracking of satellites has been demonstrated in the past [3][4], the use of a microsatellite platform for such a mission role has not been undertaken. The key output from the HEOSS mission is to determine the net utility of the microsatellite with an eye toward satisfying the Canadian Armed Forces' future needs in space.

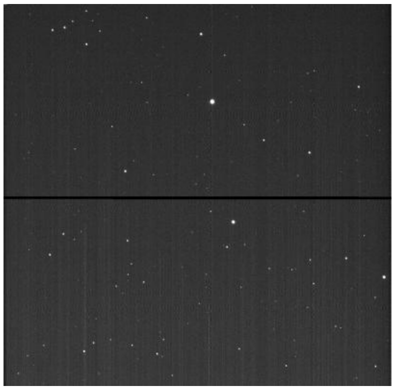

Fig.4. NEOSSat engineering test image near south celestial pole

The placement of a space-based SSA sensor in LEO introduces unique tasking and image processing complexities in order to perform the mission. In this paper we describe the NEOSSat mission architecture (§2), the HEOSS SSA experimental data processing system (§3), a brief overview of the HEOSS experimental plan (§4) precision ephemeris findings as measured in orbit (§5) and particle flux detection measurements of the natural LEO environment (§6).

2. NEOSSat Mission Architecture

A satellite is only one part of a functioning space system. A ground system, development team, operations team, scientific team and related infrastructure are required to communicate, manage and to perform data processing in a space mission. The primary ground station infrastructure and satellite operations team is located at the CSA in St Hubert, Quebec (SHUB) and the alternate ground station in Saskatoon, Saskatchewan (SASK) (see figure 5). For both NESS and HEOSS missions a Mission Planning System (MPS) which manages satellite tasking and data management is collocated at the CSA to provide a web enabled user interface to the satellite. Once NEOSSat is tasked by the MPS to track space objects, it returns its data via S-band radio to the ground stations in SHUB or SASK. The imagery data is stored on the MPS and delivered to the mission science teams for later processing. A backup ground station was constructed at DRDC Ottawa to support surge data requirements and to act as an alternate tracking, telemetry and control (TT&C) facility. For HEOSS SSA science, a separate image processing system (SQUID 3, see §4) was developed by DRDC to process SSA imagery. The NESS Science team maintains an astronomical image processing system designed to handle long exposure NEOSSat imagery in order to detect the presence of asteroids.

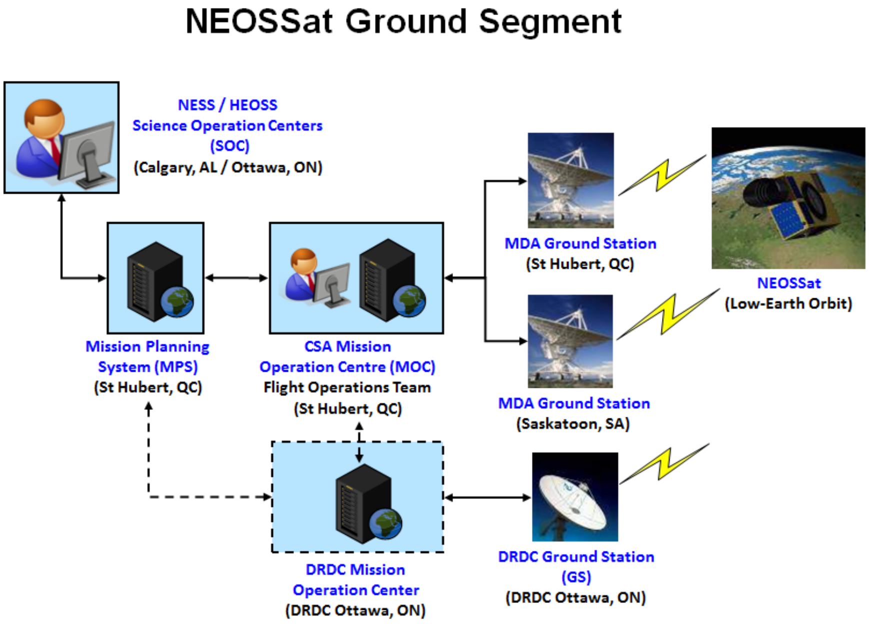

Fig.5. System architecture for the NEOSSat Mission

3. SSA Data Processing

The primary data acquisition mode for NEOSSat is track-rate-mode (TRM) which slews the NEOSSat telescope in a manner following the relative motion of the target resident space object (RSO). Alternatively, sidereal stare (inertially fixed) imagery can also be acquired. HEOSS employs an automated image processing system to generate metric and SSA data products from both NEOSSat's imaging modes. The system, the third generation SSA image analysis software developed at DRDC is dubbed Semi-QUick Image Detection (SQUID3) and runs on two workstations, one for image analysis, while the other archives imagery and SSA products in a database. SQUID3 receives NEOSSat imagery directly from the Mission Planning System as it becomes available. The primary data products from SQUID3 are time, metric position (right ascension and declination) and photometric magnitude data of the detected deep space objects.

SQUID3's uses an image stacking algorithm to processes sequences of 5 to 10 images. The stacking algorithm was developed for two reasons: to increase detectability of faint RSOs and to reject cosmic rays as false positives. The stacking algorithm must compensate for position drift of the RSO in successive images. This drift comes from the imprecise pointing of the telescope, which is measured by the astrometry of the image's star field, and from the RSO's motion not being perfectly tracked by the telescope's slew rates. The RSO motion is approximated very accurately with the RSO's supplied TLE, but less accurately with the slewing capabilities of NEOSSat. The size of the drift errors is calculated for each image at the precise exposure time. The images are then shifted by a compensating number of pixels (usually between zero and ten for geostationary RSOs) so that the stacked RSO signal is additive. Figure 6 (left) shows the stacking of five simulated images of a geostationary satellite (Nimiq-1) without drift compensation. By applying relative motion drift compensation the RSO signature becomes additive (see figure 6 right), despite not having any a-priori knowledge of the RSO location in each image. By compensating for the relative motion between NEOSSat and the RSO the stacking algorithm is able to increase the signal to noise ratio of the RSO in an N image sequence by a factor of $\sqrt{N}$ compared to each individual image [5].

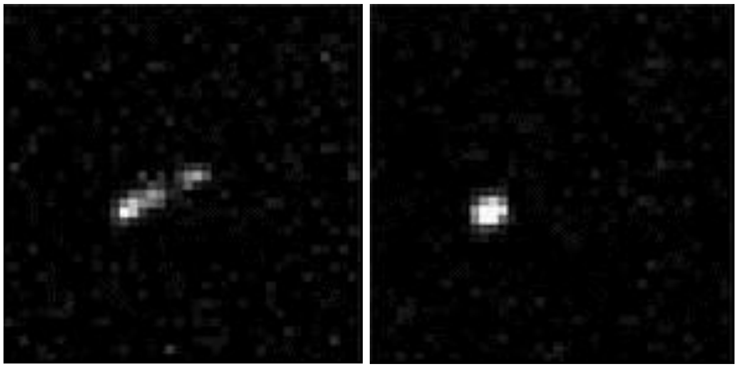

Fig.6. Sequence of 5 track rate mode images stacked directly (left) and with drift compensation (right).

The stacking process also provides a method of rejecting false positive signals produced by the numerous energetic particle strikes inherent in space imagery (see §6). As particle strikes appear in random locations in each image, SQUID3 enforces a constraint that for each signal detected in the stack, a fraction of that signal must be present in the same location in each image. This constraint ensures that particle strikes are systematically rejected.

SQUID3 can also process sidereal stare imagery, but must do so individually. For sidereal stare images a matched filter is fed the predicted RSO motion across the detector FOV. The matched filter detects any RSO streaks matching this orientation.

Once an RSO is identified, its position is recorded and corrected for annual and orbital aberration. It is then correlated against the latest Two Line Element (TLE) catalog from Space-Track.org. Metric data products are then produced and evaluated by the science team.

4. HEOSS Experimental Plan

The HEOSS experimental mission is intended to last for 1 year after satellite commissioning. The spacecraft will then be offered to the Canadian Armed Forces for operational usage. The HEOSS mission experimental year is designed to assess the suitability of the microsatellite platform to perform satellite catalog maintenance. This suitability assessment primarily focuses on sensor accuracy, productivity and tasking reliability of the microsatellite platform. As the sensor is relatively small (15cm Maksutov Cassegrain) sensitivity is anticipated to be ~13.5 visual magnitudes. While this can sense the majority of deep space geostationary RSOs, it will be limited to detecting larger objects whereas fainter debris objects will be undetectable.

After the completion of the utility assessment, a series of experiments will then be conducted taking advantage of NEOSSat's orbital vantage point where unique, space based opportunities for optical satellite observation are not commonly available. The NEOSSat microsatellite is limited in terms of sensitivity so detection of fainter objects is more challenging. Table 1 identifies the experiments which are planned during the utility assessment stage of the NEOSSat mission.

Table 1. Selected Space-Based SSA Experiments for the HEOSS mission

Experiment	Objective
Precision metrics on deep space objects from Space (Primary HEOSS Experiment)	Use of a small aperture, visible light telescope to obtain metrics from a microsatellite platform on orbit.
High Area to Mass (HAMR) objects study	Detect and track bright HAMR objects and maintain orbit custody
Space debris spin characterization	Attempt measurement of a decommissioned GEO's spin axis
Space Object Characterization	Obtain LEO-observer modulated light curves of objects
High Phase Angle Measurements	Obtain measurements on GEO objects with a solar exclusion angles up to 45 degrees from the sun.
Non-resolved attitude estimation of NEOSSat from the ground	Use NEOSSat precision ephemeris and attitude information with pre-flight bidirectional reflectance distribution function measurements to validate optical ground based photometric estimates of the attitude of NEOSSat
LEOP of a newly launched GEO	Track and maintain orbit custody on a newly launched GEO satellite

NEOSSat's surface was spectrally characterized [6] and spectral bidirectional reflectance distribution function (BRDF) data collected. This will assist in ground based SSA experiments where the precision position, attitude and geometry are known ahead of time. Ground based optical observations of NEOSSat will occur from small aperture telescopes in Canada to remotely determine the attitude of NEOSSat using light curve techniques. NEOSSat can be used as a calibration object to refine techniques to estimate the orientation of the spacecraft and perform LEO angles-only tracking from the ground.

5. On Orbit Precision Ephemeris Results

As NEOSSat will be used as a metrics sensor, parallax effects must be eliminated as an observational uncertainty. Parallax error can be reduced by making accurate positional measurements of the NEOSSat platform on orbit. NEOSSat uses dual Novotel GPS receivers to reckon its position. This navigational system is performing very well and sub-meter ephemeris positions for the satellite are regularly being obtained. Position measurements from the GPS' receivers' navigation solution are input to AGI's Orbit Determination Tool Kit [7] and an extended Kalman filter process is run. The 3-sigma uncertainty in the satellite position is providing orbital estimates better than required. When new measurement data is input into the orbit estimate, sub-meter precision is achieved. Figure 7 shows the accuracy of the orbital solution. As sub-meter precision of NEOSSat's orbit is regularly achieved it can be used as a cooperative calibration reference for optical ground based tracking.

Periodic data drop events occur on orbit due to poor GPS constellation geometry. This causes a temporary loss of GPS lock which forces the propagation of the last known orbital state forward in time in the absence of new measurement data. During these ~15 minute data outages; the maximum in-track propagated error growth grows to approximately 10 meters. This propagated orbit error is still suitable for performing space-track observations on deep space satellites as the incurred metric error is less than ~0.05 arcseconds on observations of distant geostationary satellites.

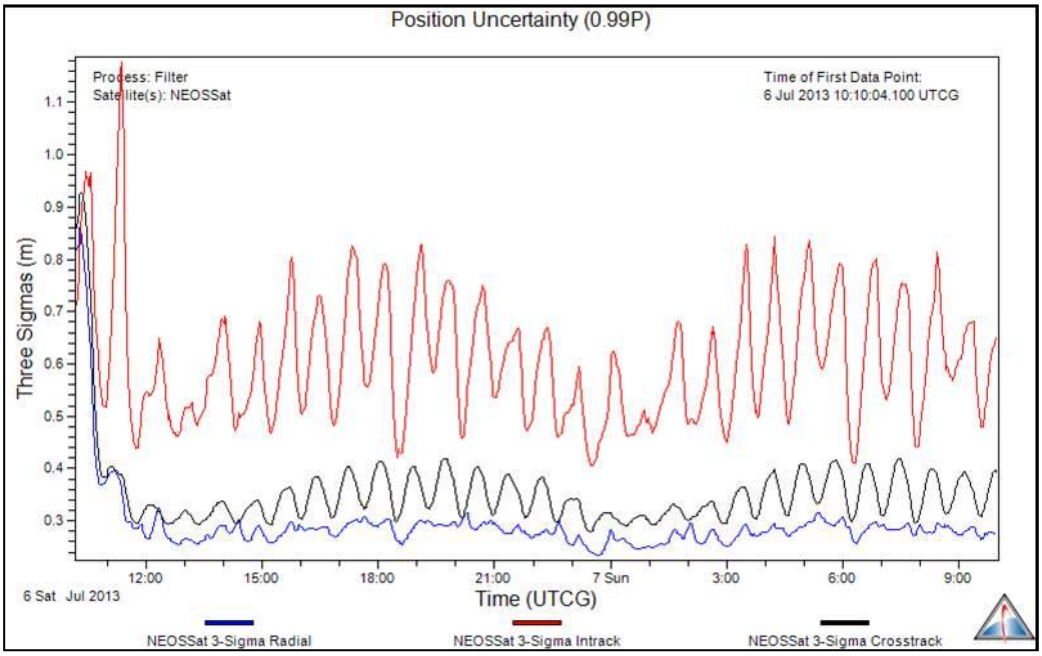

Fig.7. NEOSSat position covariance plot (3-sigma). In-track error is dominant in the microsatellite motion and is shown in red. The pulse effect observed in the covariance is due to the orbital motion of NEOSSat and is due to the GPS receivers observing the GPS constellation at various locations in Earth orbit.

6. Dark Frames and the South Atlantic Anomaly

Satellites using visible-band CCD imagers are regularly bombarded by energetic particles residing in the LEO space weather environment. While these particle strikes can occur anywhere in Earth orbit a considerable portion the energetic particle population is encountered in the region of the South Atlantic Anomaly (SAA) and the polar auroral regions. The SAA is a region of strong geomagnetic field deviation which traps high energy particles (mainly protons) in an elongated region near Brazil.

During instrument testing dark frame images were collected with the telescope shutter closed. These dark frames permit the removal of thermal noise from CCD images and helps to mitigate single pixel noise variations. A considerable population of particle strikes was observed on the imager (see figure 8). These energetic proton strikes manifest themselves as star-like point source objects and occasionally as streaks on the NEOSSat imager.

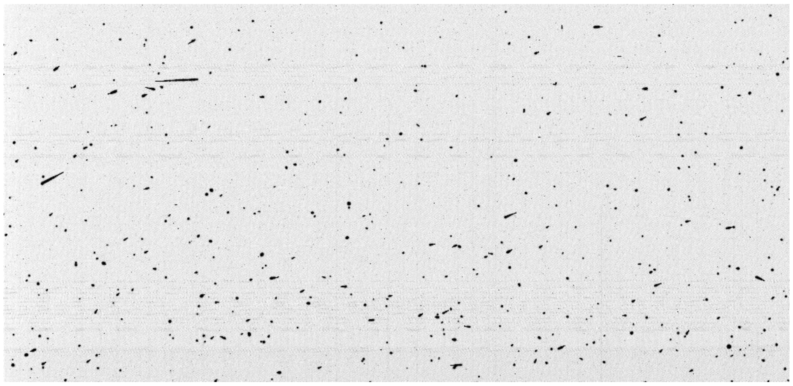

Fig.8. NEOSSat dark calibration frame (negative image shown) collected during a grazing SAA pass. The particle strikes tend to appear mostly as point source objects within the SAA. Steak-like objects occur less often.

An estimate of the natural particle flux density (proton events striking the CCD imager) can be made by obtaining dark frames over several NEOSSat orbits. Three orbits of dark images were collected at a sample rate of one image every three minutes and particles strikes were counted on each frame using the HEOSS image processor. The normalized event strike flux is shown in figure 9. These particle strikes were observed during mildly disturbed geomagnetic conditions where the average planetary Kp[1] was between 4-5. NEOSSat's passage through the SAA is visible as the 2-order of magnitude increase in particle flux (figure 9).

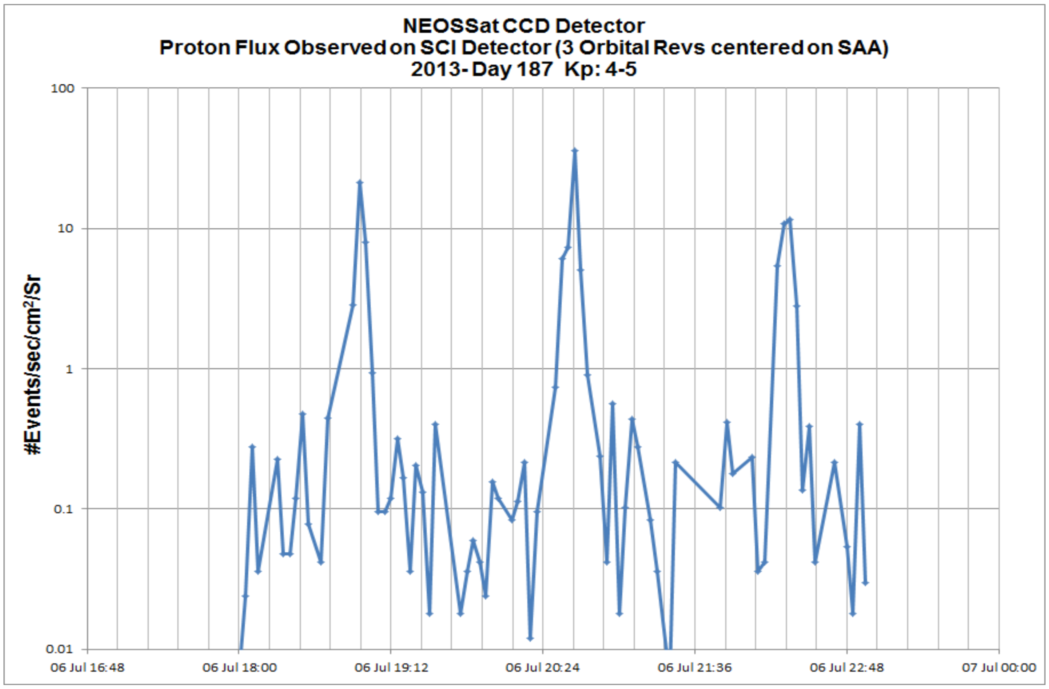

Fig.9. Particle strike flux as observed by the NEOSSat SCI detector. South Atlantic Anomaly entries are visible as spikes in the flux plot.

The amount of energy deposited E_{dep} on the CCD array due to an energetic particle raising a photoelectron on the CCD [8] can be estimated by equation 1.

$$E_{dep} \approx 3.65 \cdot (DN) \cdot g \tag{1}$$

where ***DN*** is the bias-removed counts of the CCD pixels affected by the particle strike event, ***g*** is the gain of the NEOSSat science imager and the constant 3.65 eV is the amount of energy required to raise a photoelectron on a silicon CCD.

Figure 10 shows the amount of energy deposited on the CCD imager during the dark frame test. The highest levels of energy deposition tend to occur during NEOSSat's traversal through the SAA, while other parts of NEOSSat's orbit tend to experience lower energy deposit on the CCD. Prolonged exposure to the LEO radiation environment will eventually increase the dark current generation rate on the NEOSSat CCD. To remedy this, an annealing process (a warming of the CCD chip) will eventually be needed in order relieve particle strike induced dark current build up on the CCD. This is a unique requirement for space based optical sensors and will periodically need to be performed.

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[1] Kp is an indicator of the three hour average geomagnetic disturbance. The scale is between 0 (very quiet conditions) to 9 (extremely disturbed geomagnetic storm conditions).

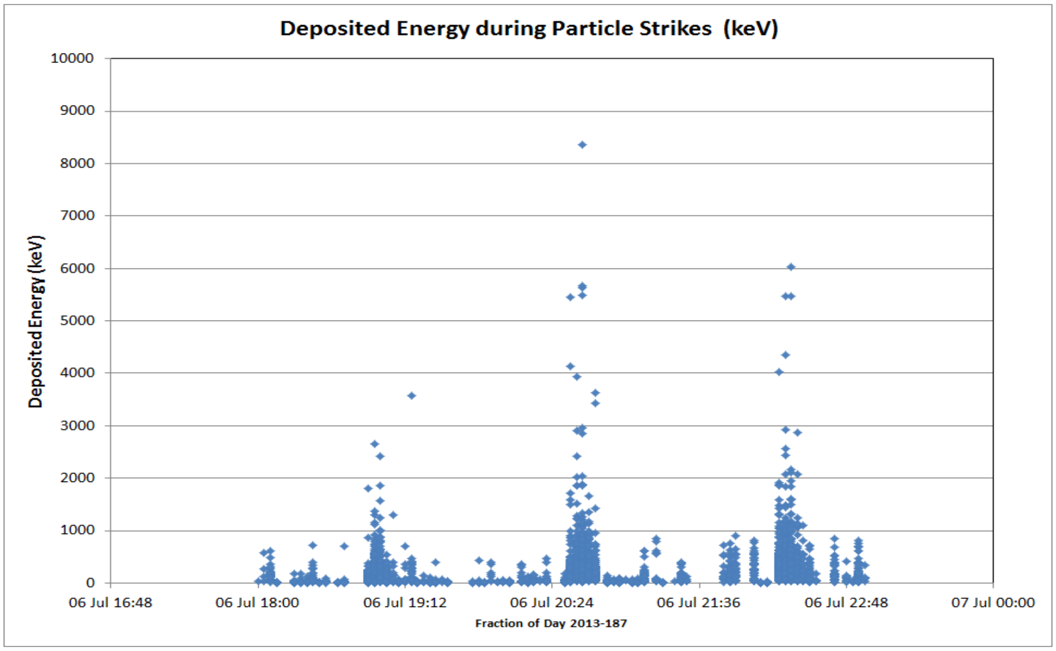

Fig.10. Particle strike energy deposited on the NEOSSat science telescope. South Atlantic Anomaly entries are visible as spikes in the flux plot. The highest energetic particle events occur during the SAA entries.

The number of affected pixels per particle strike is shown in figure 11. The majority of the particle strikes tend to produce round-point like objects on the NEOSSat imager where 8 interconnected pixels or less tend to occur most often on the imager. In track rate mode of operation, this will tend to increase the population of possible false positives as the image processor is seeking round objects in the imagery. Pixel clustering techniques will need to process out these objects in order to ensure accurate metric observations are collected. The use of the stacking method will help eliminate these false positives.

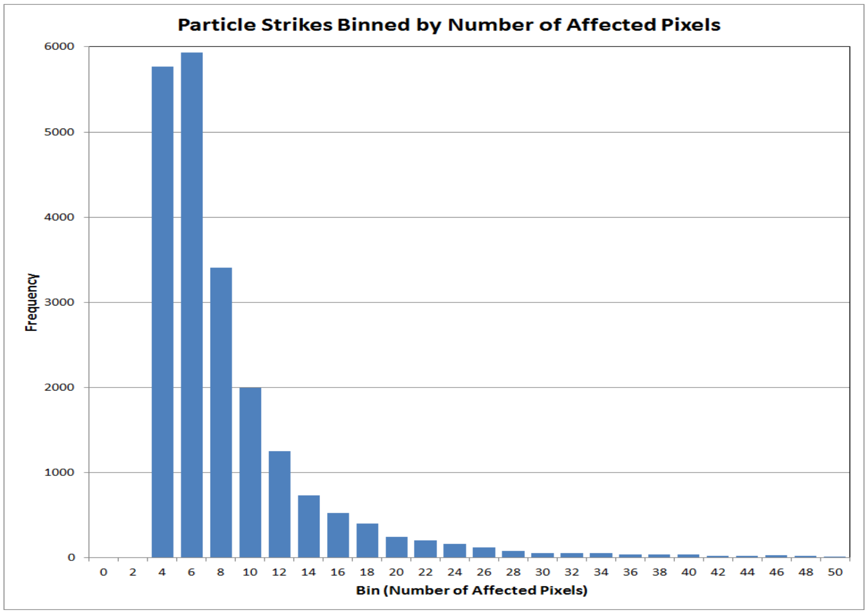

Fig.11. Distribution of the number of affected pixels per particle strike event on the NEOSSat science CCD. Approximately 70% of particles strikes affect 8 or fewer pixels. A threshold of 4 interconnected pixels is used as the threshold of object detection for and causes the sharp cliff in the connected pixel plot on the left.

7. Engineering tests and Commissioning

At this time the NEOSSat microsatellite is undergoing command and data handling (CD&H) refinement to ensure that the attitude control system and instrument is working nominally together. Fine pointing, using the star tracker co-boresighted with the NEOSSat instrument, will produce arcsecond level pointing. The spacecraft will then begin a sequence of first light images to stress test the NEOSSat instrument. Landolt star fields [9] will be imaged to verify the detector's sensitivity, color index corrections and to validate the astrometry of the star fields. Once these basic functionalities are completed, the spacecraft will then be taken through a series of image and slew commands in order to begin basic satellite tracking capability testing.

8. Summary and Future Work

The HEOSS experimental plan will begin after the completion of satellite commissioning. The ability of the microsatellite to perform space track catalog maintenance will then be ascertained. The follow-on experiments in SSA tracking will then occur, with an eye toward responsiveness of the system to changing events on orbit. This will mark a milestone in Canadian Space Situational Awareness and in microsatellite development in Canada.

9. Acknowledgements

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