The DRDC Ottawa Space Surveillance Observatory

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ABSTRACT

DRDC Ottawa recently developed a small optical sensor to serve as an R&D tool for Surveillance of Space (SofS); the sensor is referred to as the DRDC Ottawa Space Surveillance Observatory (SSO). This paper will describe the SSO, its philosophy and architecture, the automated data reduction software system, and initial testing performance. In addition, this paper will describe how the SSO is supporting the Canadian Surveillance of Space Project's Concept Demonstrator, the NEOSSat space-based SofS microsatellite, and DRDC's future R&D directions.

The SSO is regularly observing in star stare mode (SSM), and is automatically producing metric and photometric data for deep-space resident space objects; track-rate mode (TRM) has also been implemented. Observations of GPS satellites demonstrate that the system can regularly produce metric data with an accuracy of better than 3.5" in SSM, and ~1" in TRM. The sensor, located at a decidedly non-optimal site, is sensitive to objects having intrinsic magnitudes down to about 13 in SSM, and below 14 in TRM.

1. INTRODUCTION

Defence Research and Development Canada (DRDC) has recently developed an unclassified R&D surveillance of space (SofS) system that is based on a small optical sensor built using the RAVEN [1] philosophy; the sensor system is referred to as the DRDC Space Surveillance Observatory (SSO). The SSO uses lessons learned while developing the Concept Demonstrator (CD) system [2][3][4] on behalf of the Canadian Forces (CF) Surveillance of Space Project (SofSP). The CD is a system of three geographically separated small optical sensors that are operated remotely and autonomously from a central location at DRDC-Ottawa. The scope of the CD was initially quite ambitious, and the development encountered difficulties that resulted in a review of the architecture and an opportunity to remedy identified hardware and software issues. The SSO has been developed to alleviate these issues, and as such acts explicitly as a prototype for the updated CD system. While discussion of the updated CD is beyond the scope of this paper, many of the features discussed here will undoubtedly be featured in the update based upon the successful implementation in the SSO.

The SSO is a core enabling technology that is being leveraged across DRDC's SofSP R&D activities. For example, DRDC is procuring a microsatellite to perform space-based SofS (a project that has recently advanced to the detailed design phase and which will be available for launch in late 2009). The SSO is being used to help develop the data reduction and exploitation pipeline, to develop and test observation strategies, and to obtain RSO brightness data that will be used to better schedule the space-based observations. The SSO was also built with the specific intent that it be flexible enough to perform a variety of SofS R&D functions, including search, track-rate mode observing, and broad-band photometry; these capabilities will play a key role in DRDC's future SofS R&D, and data obtained with the SSO has already been used to help define the future directions and possibilities.

The SSO system – both hardware and software – are described in Section 2. The performance of the SSO, particularly the metric accuracy, will be discussed in Section 3. The role of the SSO in the various DRDC activities will be discussed in Section 4, and will highlight the enabling role that even a relatively modest sensor can play in moving forward an R&D agenda. The paper will end with a summary in Section 5.

2. SYSTEM DESCRIPTION

The main requirements for the DRDC SSO were simple – it needed to be able to detect and track deep-space RSOs, and it needed to do so reliably, autonomously, remotely, and inexpensively. Further, it needed to be based on the hardware in use in the SofSP CD, with adjustments made to overcome the issues outlined in Sec. 2.1; as such, the design was not from a clean sheet, but was able to leverage lessons learned from past experience.

The philosophy that guided the development of the SSO was that complexity should be minimized, even at the expense of possibly desirable features, as long as the minimum required functionality was retained. This philosophy led to two major design decisions. First, COTS hardware and software use was maximized, primarily in the telescope and telescope control software. Second, the various functions performed by the system were compartmentalized, and interconnections between the various functional units were streamlined to the minimal set.

To illustrate this second point it is useful to separate the functions of the system into the three top-level activities it must perform. First, given a set of observation requests (e.g. a SSN request tasking list) an observation schedule must be established. Second, the sensor must execute the scheduled observations. Third, the resulting image data must be reduced to obtain the satellite metrics and/or photometry required by the operational or R&D user. The three functions are independent and require only a minimum of interaction – the schedule must be passed to the telescope control software in some format that the software can act upon, and the image data must be passed on to the data reduction software. Other interactions, such as identifying failed observations and re-scheduling them for further observations, are not included in the current scope of the system.

The remainder of this section describes the sensor component (i.e. the telescope hardware and control software) and the data reduction software; the scheduling software will not be discussed further here.

2.1 SENSOR DESCRIPTION

As mentioned in the introduction, specific design choices for the SSO were made based on experience with the CD [4]. Some specific shortcomings in the CD included:

- The domes could only be opened to observe a portion of the sky at a time. Either the region above about 35 degrees elevation (which includes Molniya orbit objects), or the region below about 40 degees elevation (which includes the geosynchronous belt objects) could be observed in a given dome configuration, but not both. Further, a manual adjustment to the dome shutter was required to move form one mode to another, a severe limitation for a remotely operated sensor.
- The domes did not reliably close on command, risking precipitation damage to equipment.
- The CCD cameras had large and uneven background levels, and the parallel cable connectors limited the download speeds and throughput of the system.
- The original mounts were no longer available, and the control software developed for the CD was not compatible with the new mounts. Thus, any major failures would put the sensor out of commission for a prolonged period of time.
- The cloud and weather sensors were never fully operational, and thus operations required operator oversight.
- The environmental enclosures for the electronic systems were ad-hoc and had poor protection capabilities, putting equipment at risk due to environmental fluctuations.
- The sensor control software attempted to control the sensors from DRDC Ottawa and was subject to network outages, causing multiple failures in the observations.

As a result of these, and other, lessons, the hardware components and control software were chosen based on simplicity of operation and on proven capabilities, while the control architecture moved from a centralized, remote system to one based on local control. The SSO sensor hardware and control software are almost exclusively Commercial Off The Shelf, with minimal (< 100 lines) custom code required. The hardware and software components are listed in Table 1.

The sensor is controlled using TheSky6™ from Software Bisque. The night's schedule is created as an Orchestrate™ script by a scheduling computer located at a central sensor operations centre and is passed via ftp to the in-dome computer. The SSO then executes the scheduled observations autonomously – no further interaction with the sensor operations centre is required. Note that the decision to commit the system to observing on a given night still rests with an operator in order to maintain sensor safety and health.

The system can observe in both Star Stare Mode (SSM) and Track Rate Mode (TRM), with exposure times typically between 2 and 5 seconds. Once an image has been obtained, it is saved on the local computer and then automatically pushed via ftp to a data reduction server (note that the sensor will continue to execute its observations and locally store the image data, even if the ftp connection is severed). The data reduction subsystem is described below.

Figure 1: The DRDC SSO as seen from outside. The dome is pictured in its fully open position, with the mast that holds the wireless link antenna, the weather sensor, and the GPS antenna.

Figure 2: The DRDC SSO as seen from inside. The mount, optical tube, and CCD camera are in the center, while the environmental enclosure containing the computer and networking equipment is in the lower right.

Table 1: SSO sensor hardware components

Function	Component
Dome	10’6” Ashdome REB with electrically lowered screen
Dome Controller	ACE Smartdome
Optics	Celestron 14” optical telescope (f/11)
CCD Camera	Alta E-42 2048x2048 pixel camera, 13 micron pitch
Focuser	Optec TCF-S temperature compensating focuser
Filters	Optec IFW filter wheel with BVRI+clear filters (Bessel spec)
Sky Monitor	Boltwood Cloud Sensor
Environmental Enclosure	ITS Enclosures Icestation IS562626
Mount	Paramount ME Version II with MKS4000 controller
Telescope Control Software	TheSky6™ (using Orchestrate scripts)
CCD Control Software	CCDSoft™ ver 5

2.2 DATA REDUCTION SOFTWARE

The data reduction system is designed to work autonomously and regularly checks the ftp download site for new images files; since the system is simply checking a directory for FITS images, it is largely sensor-agnostic – any image file with the appropriate format will be accepted and processed, regardless of the source of the file.

The main purpose of the data reduction system is to identify the signatures of RSOs within the image and produce corresponding metric and photometric information on the RSOs. The process is divided into three main parts: 1) identification of possible RSOs, 2) determination of metric and photometric information in image-plane coordinates (e.g. pixels, counts), and 3) false alarm reduction and conversion of the image-plane coordinates to some physically meaningful units (e.g. equatorial coordinates, astronomical magnitudes).

The identification of possible RSO signatures and the determination of image-plane information are performed together, and require little to no a priori information. The steps in the process are:

1. Remove image-plane artefacts (e.g. bad pixels, columns) and large scale background
2. Determine a noise floor and use an 8-connectedness test to identify "objects" above this floor
3. Filter out single pixel events and other non-physical objects.
4. Use image moments to classify objects as either point-like or streak-like
5. If in SSM, fit straight lines to streaks, identify pixel positions of streak end-points, and calculate brightness of the streak
6. If in TRM, find centroids and brightness of both the point sources and the bright streaks

At this point in the processing there is still a fraction of false-alarms (i.e. objects that appear to have the signatures of RSOs, but which are not) that have made it through the processing. For example, in SSM the chance superposition or near-superposition of background stars can appear merged and be classified as a streak. These false alarms are reduced through filters based upon the length and variability of the streak. The variability filter assumes that the brightness variation during a short (approx 3s) exposure should be small, and large variations are due to either the chance superposition of two stars, or by the superposition of a star upon a real streak. In both cases the "streak" is removed from further processing.

The conversion of the image-plane coordinates to useful astronomical values is done using the background stars for reference. In SSM, the COTS PinPoint™ software uses a comparison of pixel positions of the centroids of background stars to the sky positions of stars found in a trusted catalogue (such as the USNO A2.0) to calculate a plate solution, and at the same time computes the conversion between flux counts (photometric zeropoint) and stellar magnitudes. The plate solution is used to transform the end-point coordinates to a sky position that is corrected for annual aberration and is associated with the appropriate shutter open or close time. The resulting data are written to a text file (along with other useful measures) and an appropriately formatted text string is written to another file to be sent to the SSN for analysis (if desired).

In TRM PinPoint™ is used again, except that it is fed the star streak centroids to allow the plate fitting to proceed. In the same way, the star streak counts are fed to PinPoint™ to allow for the conversion to stellar magnitudes. After these conversions are completed by PinPoint™ the rest of the process proceeds as described above.

3. INITIAL RESULTS

The development of the SSO data reduction software was done in a rapid development, test-early-test-often mode, so the testing process was long and consisted of small incremental improvements. It became clear early on that the main issues were (predictably) the quality of the metric data, and the false alarm rate. A lower priority has been the sensitivity and photometric accuracy of the system. The majority of the calibration has been done using SSM data, while TRM was instituted more recently and has not undergone as thorough a testing regime. That said, initial TRM testing has resulted in some conclusions that will be discussed below.

The test results discussed below are based on more than 8000 datapoints obtained over the course of several months. The throughput of the system is quite high, with images being able to be obtained at a rate of <30s/image, the majority of the time being consumed with image transfer and telescope motion. More than 1000 images can be obtained, even on shorter summer nights. The data processing itself generally takes less than 6s/image, limited by the implementation of the software in MatLab™; the processing speed could undoubtedly be improved by coding in C or similar, but since the speed is not a bottleneck the decision was made to sacrifice speed in favour of the ease of coding and debugging.

3.1 METRIC CALIBRATION

GPS satellites are used to gauge the metric accuracy of the SSO. The process is typically to observe a small number of GPS satellites a large number of times (10-100) a night. The metric data produced by the SSO was compared to the GPS reference ephemerides produced by the National Geospatial Intelligence Agency (NGA) [6] and available roughly 48 hours after the observations.

The metric data were subjected to two independent accuracy measurements. The first was conducted internal to DRDC, while XPYC analysts conducted the second as part of their support for the eventual inclusion of the CD into the SSN. While minor differences exist in the two analyses, they are largely compatible and add to our confidence in the quality of our data.

Metric testing has been conducted on both the SSM and the TRM data obtained and processed by the SSO. As expected, the TRM data is, in most regards, superior to the SSM due to the along-track uncertainty in determining the streak end points.

Figure 3 shows two plots of the metric residuals in data obtained using the SSO in SSM; the left hand plot shows the residuals in terms of sky coordinates (RA/Declination) while the right hand plot shows these same residuals in the more informative along-track and cross-track directions. As can be seen, most of the sky coordinate data falls within a circle of radius 6 arcseconds, with a small bias (the bias and sigma are listed in Table 2). Plotting the residuals in the along-track and cross track direction illustrates that the vast majority of the error is in the along-track direction, with the magnitude of the cross track residuals being roughly half that of the along-track residuals. These data support the impression that the along-track end-point determination is currently the limiting factor in SSM.

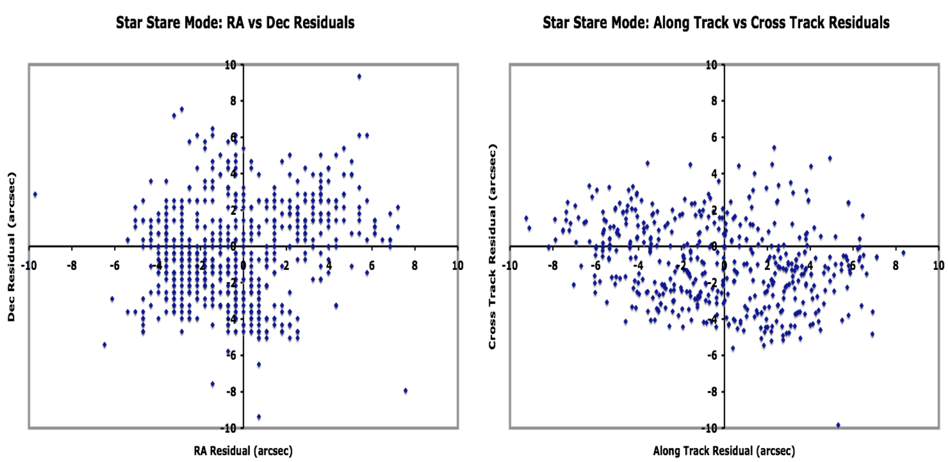

Figure 3:The metric residuals for a series of GPS satellites observed in SSM. The left-hand panel shows the residuals in RA and Declination, while the right-hand plot shows the residuals in the Along-track and Cross-track directions. Note the wider distribution of residuals in the along-track direction.

Similar plots for the TRM data are shown in Figure 4. The improvement in metric accuracy is clearly seen in both plots. A small bias in the along-track direction is still seen; the source of this bias is thought to be related to shutter motion across the imaging chip, and will be corrected for in upcoming revisions of the software. As is, however, the data quality is significantly superior to SSM.

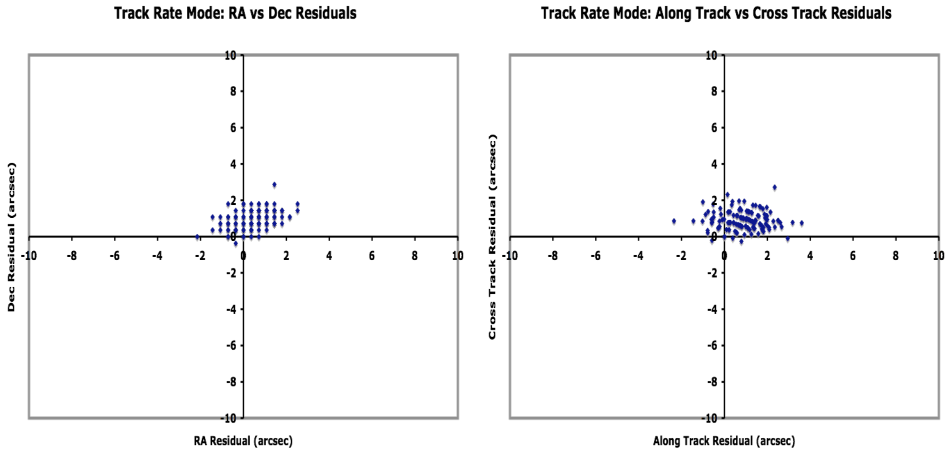

Figure 4: As for Figure 3, except for Track Rate Mode. Note the tighter grouping of residuals and the wider distribution in the along-track direction.

Table 2 : Metric residuals for automated SSM and TRM data

Mode	Measure	Average	Standard Deviation
SSM	RA residuals	-0.41	3.41
	Dec Residuals	-0.37	3.75
	Along-track Residuals	-0.37	4.56
	Cross Track Residuals	-0.83	2.22
TRM	RA Residuals	0.46	0.96
	Dec residuals	0.96	0.49
	Along-track Residuals	0.89	0.89
	Cross Track Residuals	0.97	0.50

3.2 FALSE ALARM RATE

In the context of the processing software a "false alarm" is an image object that has been classified as a RSO, but which is not related to a RSO. Examples of cause of such features are chance superposition of multiple stars, cosmic-ray hits, and un-corrected artefacts on the CCD chip. In practice, the chief cause in SSM is superposition of stars, while in TRM it appears to be related to cosmic ray hits.

As noted previously, the streak and endpoint identification and definition portion of the software – despite filtering on shape and minimum number of pixels – yield a certain fraction of false alarms. Two more filters – one based on variability within the streak, the second based on a minimum length criteria – are also required. The variability filter is based upon a comparison of the maximum and minimum brightness of a streak to the noise that is expected to be associated with a streak having the corresponding mean brightness. While the tolerance has not been optimized, the filter removes a large fraction of false alarms.

The minimum-length criterion rejects any identified streaks that are shorter than would be expected for a RSO travelling at a minimum angular rate across the sky (this minimum angular rate is currently 15"/s). This criterion breaks the "no *a priori* information" intent of the software, in that the minimum detectable angular rate is somewhat ad hoc (and excludes objects such as Molniya satellites near apogee), and requires knowledge of the pixel scale in order to convert between pixel and sky units. It is also worth noting that there is an implicit relationship between this data reduction setting and the length of the exposure - the exposure must be long enough that the length of the streak is larger than the majority of the possible false alarms.

The resulting false alarm rate varies between roughly 2-4% of the returned data, depending largely on the background star density. This, plus the issue of multiple RSOs discussed below, required the development of an observation correlation tool that rejects data metric datapoints that fall greater than some distance from the expected position of a known RSO. While not fully integrated at the time of writing, assuming that false alarms are spread evenly across the field of view, it is expected that this correlator will reduce the false alarm rate by more than 90%.

A cause of "false-alarms" that has not been discussed is the appearance of unexpected (or multiple) RSOs within the field of view – as much as 50% of the false alarms can be traced back to these objects. While detection of serendipitous objects is a desirable feature, allowing for more data to be captured for use by the SSN, unless the data are tagged with the correct SSN identifier this data becomes more of a hardship than a boon. This has added extra impetus to the development and integration of the correlation tool.

3.3 SENSITIVITY AND PHOTOMETRY

The bulk of development effort thus far has focused on a) getting the SSO working in an automated manner and b) assessing and improving the metric accuracy of the output data. As a result, relatively little effort has been expended on using the SSO for photometry and on quantifying sensitivity limits. Nonetheless, some information comes from the imagery "for free" and this information will be described here.

Pinpoint™ software using the in-frame stars for reference performs the basic conversion between image counts and magnitudes. The USNO A2.0 star catalogue is used to provide both the star positions and the stellar magnitudes. Pinpoint™ uses R-band magnitudes for this conversion, a reasonable match to the expected (but not yet measured) spectral sensitivity of the SSO. No effort has thus far been made to tie the resulting magnitudes to a well-established standard, such as one based on the Landolt UBVRI system (e.g. [1]), but the USNO A2.0 catalogue is thought to have a RMS error of 0.26 magnitudes [5].

With these caveats, the SSO has an estimated sensitivity down to about 13 in SSM, and below 14 in TRM (both measures for exposures of 3 seconds in length). An example of photometric data obtained with the SSO in SSM is shown in Figure 5. Measurements of two satellites that are seen in the same series of images are shown in this plot; one satellite is undergoing a relatively linear brightness change, while the second is undergoing a rather more complex change; note the stable photometry obtained over the 18-minute observation. While the observations containing the data obtained for this plot were not intended for photometry let alone SSA, it is interesting to note that the RSOs have very similar bus types, and should exhibit similar behaviour. Discussions with the operator of the satellite showing the more erratic change revealed that the one of the solar panels did not deploy correctly, and thus is a possible explanation for the difference in photometric behaviour. This helps underline the utility of even a modest non-imaging sensor to SSA.

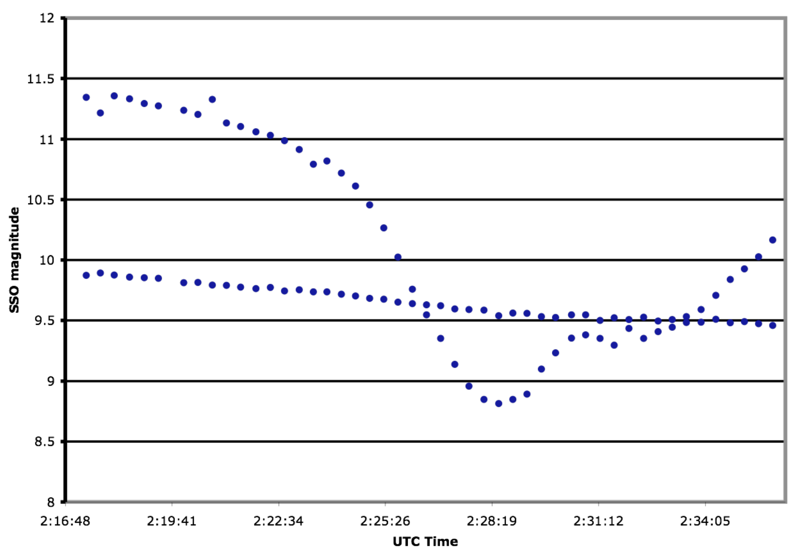

Figure 5: A plot of the brightness of two RSOs observed simultaneously over an 18 minutes timeframe. Note the two very different behaviours exhibited by the RSOs despite similar body shapes and phase angles.

Future work with the SSO will include validating the magnitude estimates by performing all-sky photometry against Landolt standard fields, and by performing UBVRI photometry of select RSOs as part of investigations into non-resolved space-object identification (SOI).

4. ROLE OF SSO IN DRDC PROGRAMS

The SSO will serve three broad programmatic purposes within the DRDC SofS R&D effort. First, it serves as a tool for a range of R&D topics related to SofS including SOI and satellite metrics. Secondly, it serves as a prototype for the SofSP CD system. Finally, the SSO serves as a surrogate sensor for the NEOSSat spacecraft that is being developed jointly between DRDC and the Canadian Space Agency. Each topic will be briefly addressed below.

As DRDC Ottawa's only current sensor, the SSO will predictably serve a central role in DRDC SofS R&D. DRDC efforts have largely focused on the development of the infrastructure (sensor, software, control systems) needed to perform R&D. In the process a significant knowledge-base has been gained, as has a significant amount of archival data. The plans going forward are to initiate projects that focus more on expanding the types of data that are obtained, and on exploiting these data in ways that may be useful to the Canadian Forces and its international partners. Examples of such projects include:

- Orbit determination and updates
- Unresolved SOI and light curve analysis
- Search techniques and methods
- Monitoring of health and status of Canadian Assets
- Limited terminator mode observations for high altitude LEOS.

The NEOSSat spacecraft [7][8] is a microsatellite that will host a 15cm optical telescope and CCD. The purpose of NEOSSat is twofold: to perform SofS on deep-space objects, and to detect and track Aten-class asteroids which have orbits that are primarily within – but cross - Earth's orbit. One of the major objectives for NEOSSat is to demonstrate the ability of these smaller spacecraft to not only be procured for less than a traditional satellite, but also to be operated at a lower cost. To further this aim the operations surrounding NEOSSat – operator interaction, scheduling, and data reduction and analysis – will be automated to the extent practicable. Many of the CONOPS for this mode of operation are being tested using the SSO, with the current emphasis on operator interaction, automated scheduling and automated data reduction. In addition, an early prototype of the NEOSSat scheduler used an estimate of the expected RSO brightness that assumed all RSOs have the same brightness characteristics. The SSO will be used to measure the actual brightness of such deep-space objects as are visible and detectable by the SSO in order to explore methods to more efficiently schedule NEOSSat.

Finally, as discussed in the introduction, the SSO is being used as a prototype for improvements to be rolled out to the SofSP CD. In order to speed development and ease trouble-shooting for the CD improvements, the SSO was developed to both test the hardware locally to DRDC Ottawa, and to serve as the test sensor for testing the operator interface, scheduling and data reduction software, and database system. For this reason the SSO and the CD will have significant similarity, easing development and trouble shooting in the future.

5. SUMMARY

The DRDC SSO is a small optical sensor system that has been developed for remote autonomous operations in support of SofS R&D. The sensor itself is based upon COTS hardware and software, while the scheduling and data reduction systems are custom software developed at DRDC-Ottawa. The primary mission of the SSO is the collection of satellite metric information in support of catalogue maintenance, but photometry easily obtained using the image data is also being routinely extracted.

The SSO obtains data in both Star Stare and Track Rate modes, with limiting sensitivity to deep-space RSOs being roughly magnitude 13 in SSM and better than magnitude 14 in TRM. In terms of metric accuracy the SSO data is good to better than 4" in SSM and to about 1" in TRM. The SSO supports not only the general R&D agenda for DRDC, but also the upgrade for the SofSP CD and the development of ground systems for the NEOSSat SofS microsatellite.

6. REFERENCES

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