# On-Orbit Results for Canada's Sapphire Optical Payload

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**Abstract**

*Sapphire is the first operational Space Situational Awareness (SSA) satellite mission flown by Canada's Department of National Defence (DND). On February 25, 2013 Sapphire was successfully launched into a sun synchronous orbit at ~786 km altitude. The commissioning phase was a success and the Sapphire system is entering its operational phase. Canada and the United States signed an SSA Memorandum of Understanding on May 4, 2012. Under the agreement, data from DND's Sapphire satellite will be contributed to the U.S. Space Surveillance Network (SSN), enhancing the ability of both countries to detect and avoid the collision of critical space platforms with orbital debris. The Sapphire system will soon be collecting SSA data that will be shared with the SSN. This SSA partnership will strengthen the long standing defence relationship between the US and Canada and provide diversity in space based sensors at a time of fiscal constraint.*

*The Sapphire satellite optical imaging payload was designed and built by COM DEV based around a small (13.7 cm) Three Mirror Anastigmat (TMA) telescope similar in design to the Space Based Visible sensor on the US Mid-Course Space Experiment satellite. This paper provides an overview of the design and operational performance of the Sapphire instrument, comparing the actual performance to the requirements. Based on lessons learned on this program we discuss potential improvements that would be feasible in a second generation Sapphire payload including the potential for using this sensor as a hosted payload in other applications.*

## Introduction

For decades DND's two large Baker-Nunn telescopes contributed valuable trajectory data on resident space objects (RSOs) to the SSN until they were decommissioned in 1992. The Sapphire mission represents a major renewal of DND's commitment to provide a value added contribution to the SSN. Sapphire enhances Canada's ability to detect and track satellites and space debris in an era where critical space based communications and navigation infrastructure is increasingly vulnerable to collisions with both passive and active space hazards [1].

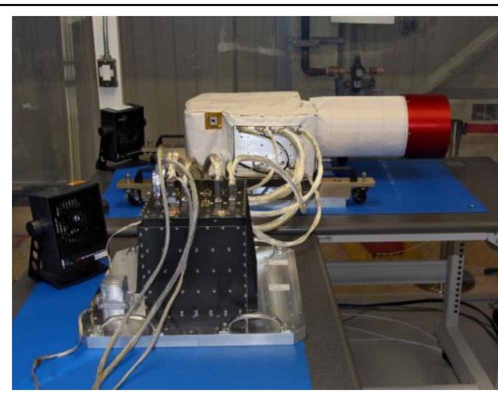

**Fig. 1** Sapphire Optical Payload. Photo Credit: David Florida Laboratory, Canadian Space Agency

The Sapphire satellite was developed by prime contractor MacDonald, Dettwiler and Associates Ltd. (MDA). COM DEV was selected by MDA to provide the Sapphire optical payload [2]. MDA, as the mission prime, has successfully completed the commissioning phase of the system and it is now undergoing a data validation and operations phase led by DND which is expected to provide more than 375 daily updates on the position of RSOs from its low earth orbit. As can be seen in Fig. 1, the payload consists of the Optical Imaging Subsystem (OIS) and the Data Handling and Control Subsystem (DHCS). Designed for a LEO lifetime of 5 years, the imager is comprised of a baffled TMA similar to the Space-Based Visible (SBV) sensor [3], feeding dual-redundant back-illuminated frame-transfer CCDs, each capable of low-noise imaging in a 1.4 x 1.4° field. The readout electronics, and data handling and control system are also dual redundant with no cross-strapping. The DCHS can correct the images that have been captured and compress the image data before it is transmitted to a ground station for additional processing.

The Sapphire payload mass is 28.5 kg, and is comprised of 18.8 kg for the telescope, 8.1 kg for the electronics and 1.6 kg for the harnessing. The average power consumption is 14 W, with periodic increases to 20 W to support internal modes of operation. The image output data rate from the payload is 10 Mbps.

The Sapphire mission payload leverages COM DEV's extensive heritage designing and building optical systems for space including a series of successful space imagers (James Webb Space Telescope Fine Guidance Sensor; CALTRAC™ star tracker; Far Ultraviolet Spectroscopic Explorer Fine Error Sensor). Leveraging this heritage, Canada's first dedicated surveillance of space optical payload was an affordable option in a time of increasing government fiscal restraint.

## On-Orbit Performance

COM DEV has analyzed 14-bit image data provided by MDA and has performed an initial evaluation of the on-orbit performance of the Sapphire optical payload. The mission payload is working well on-orbit, meeting its specifications, with on-orbit performance in line with pre-launch expectations. The instrument is providing sharp, low-noise low-distortion images at a pixel scale of 5 arseconds. The imaging performance requirement is to contain 85% of the target energy in a 3 x 3 pixel region (15 arcsec sq). Fig. 2 shows that the Sapphire spacecraft attitude control system is working well, adding negligible blurring from pointing drift over 4 second frames. There is no evidence of jitter or contamination degrading the image quality or throughput. Multiple images of the same field are co-aligned to <1 pixel. The system was designed to detect objects from 6$^{th}$ to 15$^{th}$ magnitude and locate them on the sky to within a 1-sigma accuracy of 6 arcseconds. The optical payload is required to detect a 15$^{th}$ magnitude object moving across the field at 4 arsec/s with signal to noise ratio of 6.5:1. The sharpness of the imaging that is being achieved means that the system can actually detect objects 2.5 times fainter than required at the same positional accuracy (16$^{th}$ magnitude).

Fig. 3 is a raw image histogram measured using dual correlated subtraction with full width at half maximum (FWHM) of ~3 counts or 25 electrons. The asymmetry in the plot is mainly due to starlight. We were able to identify only 862 isolated hot pixels above a 10 count threshold (<0.01% of all pixels).

A star-pattern match was performed to measure the image field distortion. An 8-bit low resolution version of the Sapphire image data was sent to online image analysis tool Astrometry.net to determine the target field coordinates for this exercise. Table 1 shows the results with best fit field size and resolution as per the telescope design.

**Table 1** Image coordinates provided by Astrometry.net

| | |
|---|---|
| Center (RA, Dec): (deg J2000) | (193.157, -5.420) |
| Center (RA, hms): (J2000) | 12h 52m 37.691s |
| Center (Dec, dms): (J2000) | -05° 25' 12.552" |
| Size: | 1.42 x 1.42 deg |
| Radius: | 1.005 deg |
| Pixel scale: | 4.99 arcsec/pixel |
| Orientation: | Up is 0.438 degrees E of N |

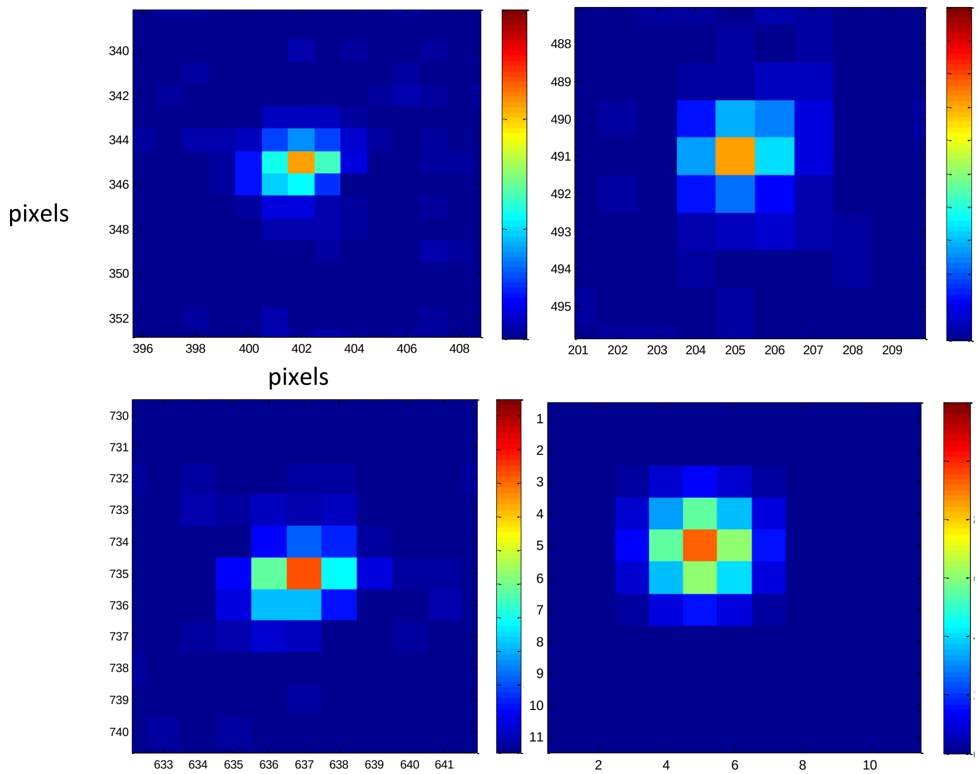


**Fig. 2** Pixel-centred star images at 0.1 seconds (upper left) and 4 seconds (upper right) integration, and 8 images at 4 seconds integration co-added (bottom left); simulated image at required resolution (bottom right)

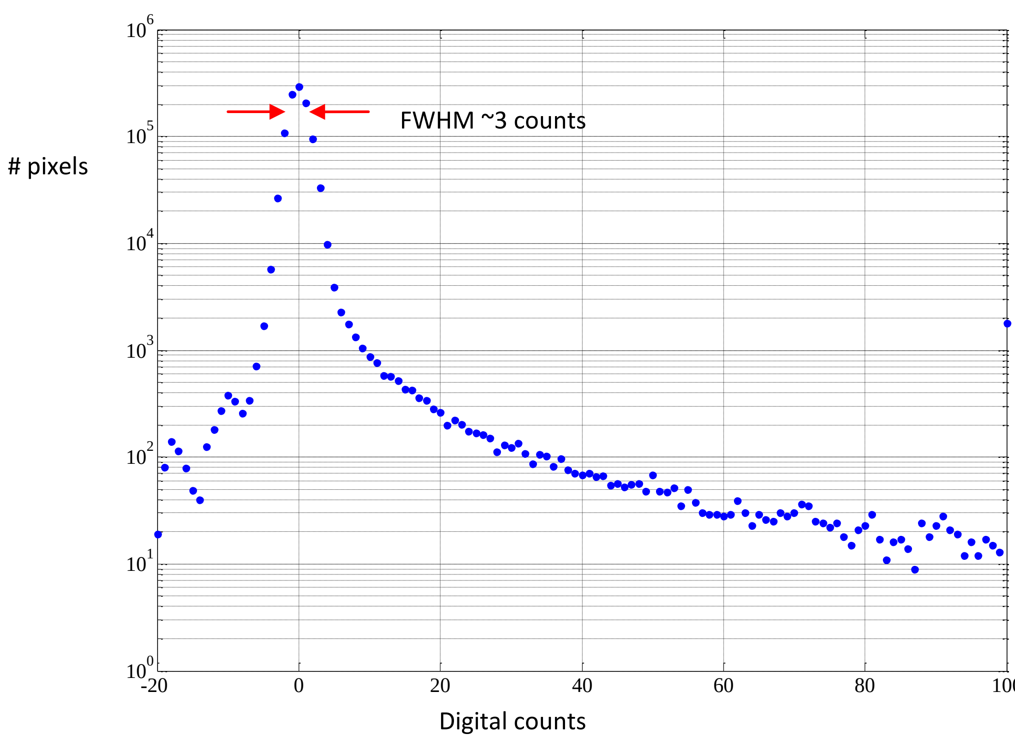


**Fig. 3** Average image histogram (8 co-added 4 second frames).

We extracted a section of the Guide Star Catalogue-II[1] corresponding to the same field, aligned with the centre of the image, and applied the rotation and pixel scaling provided by Astrometry.net. Fig. 4 shows the extremes of the field distortion comparing the Guide Stars with measured visible photographic magnitudes ($F_{pg}$) to the undistorted raw image (no distortion calibration applied). Maximum distortion, seen in the bottom left corner of the image, is about 20 arcseconds, similar to pre-launch measurements. Most of the image lies ≤5 arcseconds (≤ 1 pixel) from a linear mapping. All of the known sources to magnitude 15 are identified, and most of the sources out to $F_{pg}$=16 are unambiguously detected with good SNR. Small variations in detectability are expected because the instrument's colour response is not exactly the same as the $F_{pg}$ filter definition.

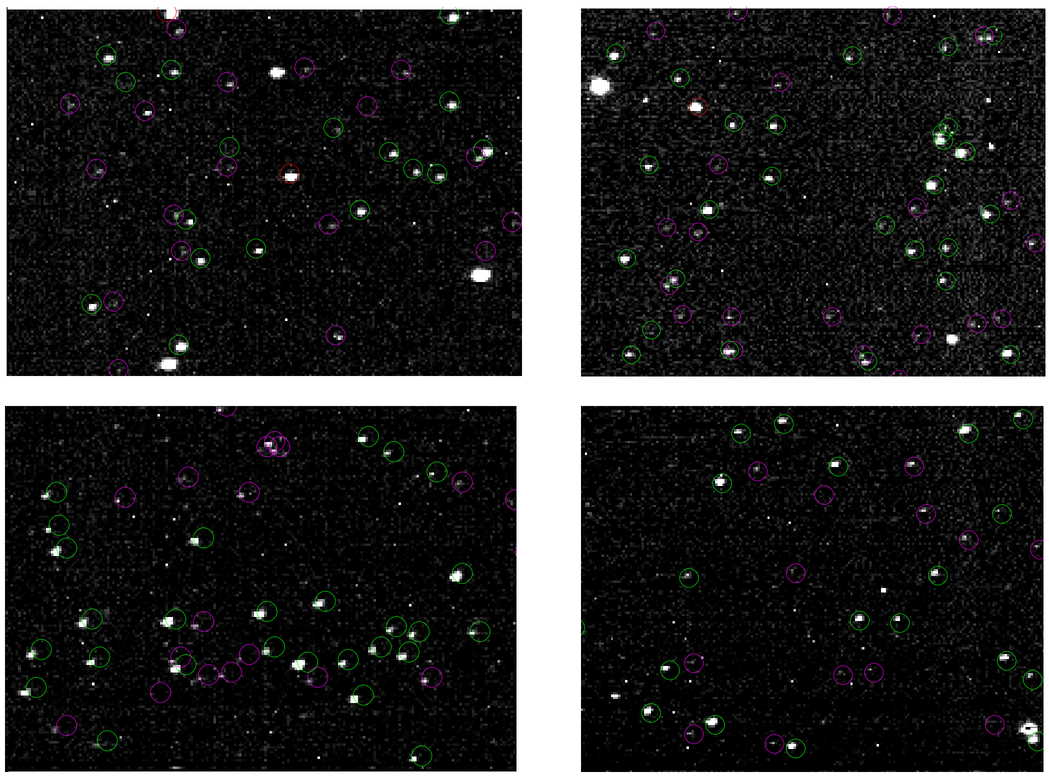

**Fig. 4** Comparison of extreme corners of a Sapphire star field image to Guide Star Catalogue-II sources linearly mapped with known photographic magnitudes. GSC-II sources (circles): $F_{pg}$<12 (Red); $F_{pg}$ 12-15 (Green); $F_{pg}$ 15-16 (Magenta)

This sensitivity can be translated into a target range and size at a fixed sun angle for various target reflectivities, as shown in Table 2. This suggests that the Sapphire optical payload could detect down to ~1 m diameter satellite in GEO orbit, from a GEO platform 180° away (if the earth were not in the way) in a 4-second frame. The positional resolution of the instrument at such extreme range will be on the order of 2-4 km. Even higher sensitivity is achievable at longer integration times if the relative angular motion of the RSO is small (ie. GEO-to-GEO).

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[1]*The Guide Star Catalogue-II is a joint project of the Space Telescope Science Institute and the Osservatorio Astronomico di Torino. Space Telescope Science Institute is operated by the Association of Universities for Research in Astronomy, for the National Aeronautics and Space Administration under contract NAS5-26555. The participation of the Osservatorio Astronomico di Torino is supported by the Italian Council for Research in Astronomy. Additional support is provided by European Southern Observatory, Space Telescope European Coordinating Facility, the International GEMINI project and the European Space Agency Astrophysics Division.*

Fig. 5 shows an example of two fast moving RSOs that were detected serendipitously. Due to the observed angular motion in the 4 second integration data these objects are presumed to be in similar LEO orbits. Fig. 6 shows two slow-moving objects in similar trajectories detected in 4 subsequent frames at 0.1 s integration over a 10 second interval.

**Table 2** RSO diameter in metres for various viewing geometries and RSO magnitude for 90° sun angle (median illumination case). Sapphire detects everything in the highlighted region for a 4 second integration.

| | Reflectivity = 0.8 | | | Reflectivity = 0.17 | | |
|---|---|---|---|---|---|---|
| | Range [km] | | | Range [km] | | |
| RSO Magnitude | 83033 | 54196 | 1471 | 83033 | 54196 | 1471 |
| 18 | 0.23 | 0.15 | 0.004 | 0.49 | 0.32 | 0.009 |
| 17 | 0.36 | 0.23 | 0.006 | 0.78 | 0.51 | 0.014 |
| 16 | 0.57 | 0.37 | 0.010 | 1.24 | 0.81 | 0.022 |
| 15 | 0.90 | 0.59 | 0.016 | 1.96 | 1.28 | 0.035 |
| 14 | 1.43 | 0.94 | 0.025 | 3.11 | 2.03 | 0.055 |

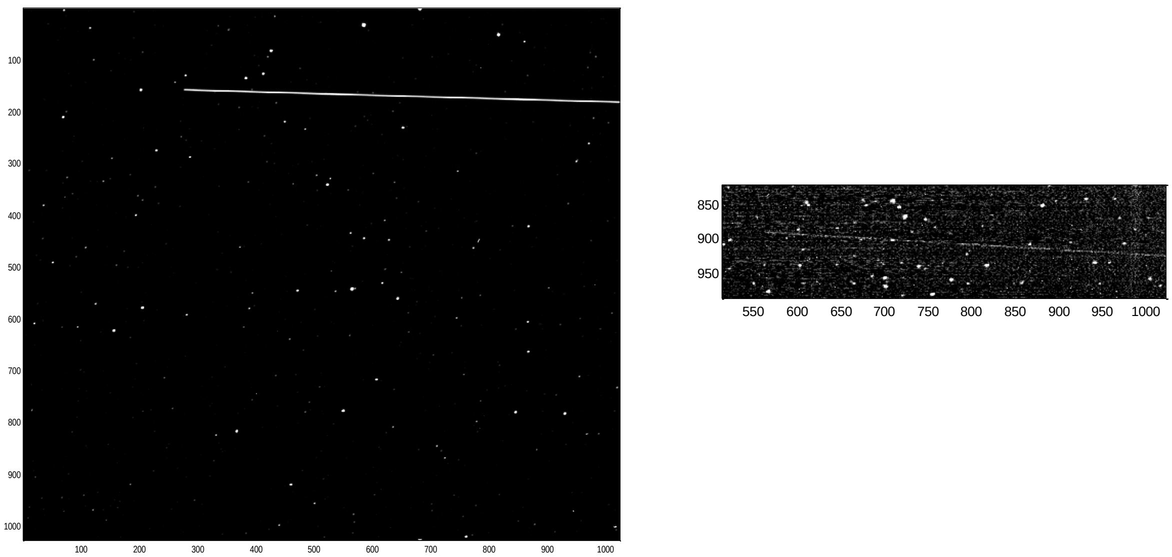


**Fig. 5** Image of a bright RSO streak at 4 seconds integration (left); Zoomed image of a dim RSO streak in the same field a few seconds later (enhanced scale right)

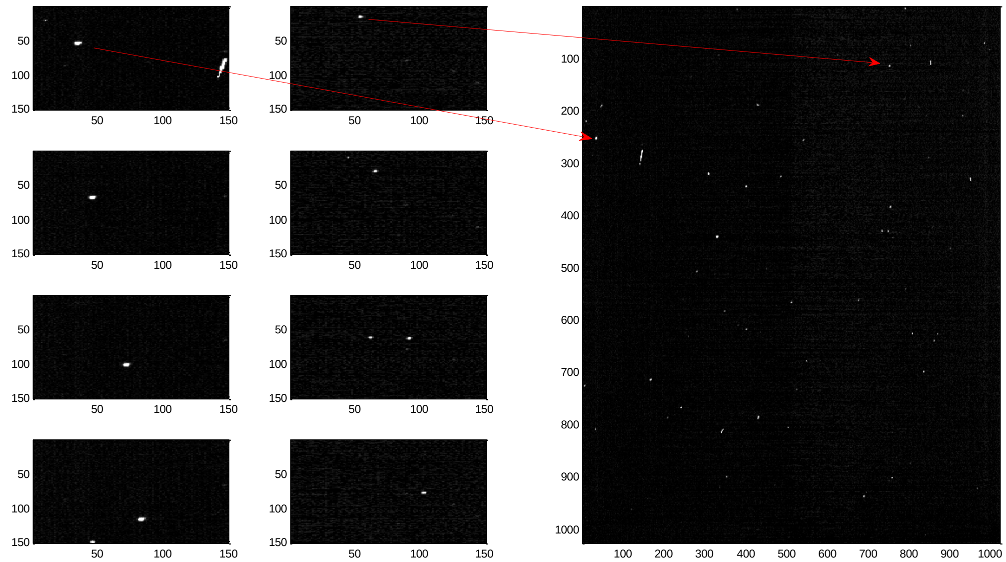


**Fig. 6** Tracking of two bright satellites at 0.1 s integration (AMC9 and BrazilSatB4). Left Top to Bottom shows a zoom of two sub-fields over four consecutive frames (raw data including cosmic ray hits); Right is one full image.

## GEO Hosted Payload Discussion

COM DEV is assessing various ways of enhancing the capability of the Sapphire system for future SSA applications. One scenario that is being considered is a hosted payload on a GEO platform [4]. Because of the unique geometry, combining GEO-based measurements with ground- or LEO-based measurements significantly improves the accuracy of RSO orbit determination in the GEO arc [5]. One of the more significant design changes that is required to adapt the Sapphire instrument to a GEO application concerns increasing the radiation lifetime from 5 to 15 years. A detailed radiation analysis has shown that this change can be reasonably accommodated by adding ~3 mm of aluminum shielding around the preamplifier in the optics head. The analysis also shows a possibility of single event upset from solar flares and galactic cosmic rays that can be addressed through high reliability upgrade of the memory and processor.

While the CCD is radiation sensitive, the energetic proton environment at GEO is no worse than the current LEO mission. Protons cause displacement damage in the silicon pixels resulting in decreases of charge transfer efficiency. Without additional shielding, the increased GEO ionizing radiation environment would result in larger flat band voltage shift and an increase in surface-generated dark current. The high energy electrons responsible for the majority of this damage can be mitigated with 5-8 mm of aluminum shielding.

In operation, the Sapphire optical payload is hard-mounted to the bus and the Sapphire spacecraft is slewed to point the instrument at the target fields. For a GEO-hosted payload the addition of a 2-axis gimballed pointing mirror will allow the sensor to be targeted at RSOs of particular interest, and to direct the field of view away from the sun when necessary.

Other issues to consider include the stability of the platform, and the accuracy of the host satellite positional knowledge as it relates to orbit determination for the target object [5]. Vibrational jitter should be constrained to a few seconds of arc over the period of integration. Spacecraft-level cleanliness and outgassing requirements should be considered with reference to optical performance. A significant keep-out zone would be necessary to ensure that performance is not degraded by stray solar reflections.

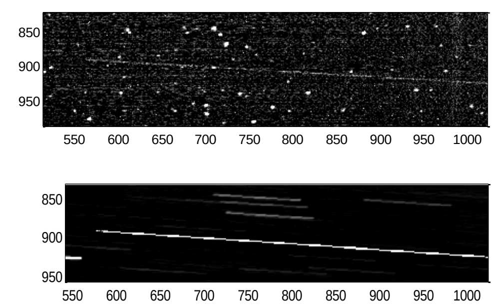
On a GEO platform, most other GEO objects will have very low angular rates allowing for longer frame integration times if the platform pointing stability allows. This would allow detection of smaller, dimmer objects with the same system, or else a more compact fixed multi-head optical system could be designed to monitor multiple assets with a single instrument. As mentioned in [4], at least two hosted payloads on well separated platforms would be needed to have full coverage of the GEO arc. If a host opportunity comes available, a single payload on a retrograde GEO bus could be ideal.

A single Sapphire-like payload on a GEO platform could offer clients the opportunity to continuously monitor a high value asset at high revisit with relatively short interruptions due to eclipse and sun-in-field. This is a potentially valuable new service that a LEO platform cannot provide.

## Upgrades and Improvements

New functionalities can also be considered to enhance the system performance for a next generation payload. Simulations show that advanced on-orbit image processing algorithms could be added to the system to improve removal of cosmic rays and stray light allowing imaging closer to the earth limb or the sun. New advances in large format, back-illuminated scientific CMOS arrays can be leveraged to provide a radiation tolerant lower power imaging solution with high speed readout at a comparable signal to noise ratio. Fig. 7 shows how a fast-moving object on a known trajectory could be enhanced by either physical tracking, or by co-adding of multiple short low-noise image frames with an appropriate offset in the direction of motion.

**Fig. 7** Simulation of enhanced RSO detection through co-adding of multiple short, low-noise images

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## REFERENCES

[1] Maskell, P. and Oram, L., *Sapphire: Canada's answer to space-based surveillance of orbital objects*, Proc. AMOS, 2008.

[2] Hackett, J., Brisby, R., and Smith, K., *Overview of the Sapphire payload for space surveillance*, Proc. SPIE 8385**,** 2012.

[3] Wang, D., Gardiner, L., Wong, W., Hadfield, P., *Space based visible all reflective straylight telescope*, Proc. SPIE 1479, 1991.

[4] Hackett, J., and Li, L., *Sapphire-like payload for space situational awareness*, Proc. AMOS, 2012.

[5] Lowe, J., Vallado, D., and Hall, B., *Technical Analysis of Commercially Hosted Optical Payloads for Enhanced SSA*, Proc. AMOS, 2010.