Flexible Next-Generation Space-Based SSA Payload

Alan Scott, Craig Haley, Neil Rowlands
COM DEV Ltd., Ottawa, Ontario, Canada

Abstract

COM DEV's compact Sapphire optical payload is currently providing Space Situational Awareness (SSA) in a dedicated low earth orbit mission to better than 16th visual magnitude. This Low Earth Orbit (LEO) instrument is sufficient for imaging the vast majority of large Geosynchronous Earth Orbit (GEO) satellites, but misses a significant population of fainter uncatalogued deep space objects with median apparent brightness near 18th magnitude.

Modern detector technology allows significant increases in sensitivity that will enable future Sapphire variants to catalogue this population within the same compact volume envelope. This enhanced SSA mission could provide a low cost revenue stream to a GEOsat operator with spare resources to act as a host. It could also be accommodated on a smaller dedicated microsatellite bus than the SSTL-150 platform used for Sapphire. Unfortunately, the performance of both options typically requires a precise attitude control system to provide the pointing stability necessary for deep SSA.

We present a compact, high frame-rate optical payload architecture with image stabilization capabilities, and assess its expected performance relative to the Sapphire optical payload.

Introduction

Canada's Department of National Defence (DND) is proceeding on a path to maintain continuity of its Surveillance of Space capabilities being delivered by the Sapphire Space Situational Awareness (SSA) mission since it successfully completed commissioning and data validation on January 30, 2014. Sapphire is an operational mission with a five year lifetime tracking man-made deep-space objects from Low Earth Orbit (LEO) [1]. The Sapphire optical payload is mounted on a customized SSTL-150 platform equipped with three high performance star-trackers to provide the system with state-of-the-art pointing control needed for tracking dim Resident Space Objects (RSOs). The Sapphire space segment is tasked by the Canadian Armed Forces Sensor Systems Operations Centre in North Bay Ontario with input from the Joint Space Operations Centre at Vandenberg Air Force Base to image more than 375 Resident Space Objects (RSOs per day and provide accurate orbital position updates [2]. Canada's Sapphire system offloads the low resolution high cadence catalogue maintenance task from US SSA assets such as SBSS which can be focused on tasks for which they are better suited [3].

Flexible Payload Architecture

Although the key requirement of a Sapphire follow-on is to maintain existing capabilities, in the current era of fiscal constraint the possibility of developing a next generation instrument that could be mounted on a smaller, 'off-the-shelf' microsatellite spacecraft bus has merit. Satellite bus manufacturers and commercial data service providers have expressed interest in a low-cost flexible SSA payload that leverages the high Technology Readiness Level (TRL) of the Sapphire optical instrument, but can also operate from a variety of non-customized platforms.

We present a next generation evolution of the high TRL Sapphire payload architecture that will meet or exceed these RSO detection limits on a smaller SSTL X-50 or SSTL-100 platform, for example, with no need for a high performance attitude control system. CCD-based architectures require long integration times to detect dim RSOs above the readout noise, and without precise attitude control stability the target image will be irretrievably smeared. To meet its RSO detection thresholds, the current instrument requires a customized bus with fine pointing control capability of less than 5 arcseconds over integration times up to 10 seconds duration. The new system will not require fine pointing control, allowing drifts of up to 50 arcseconds/s with minimal performance degradation.

The new architecture also provides the capability for serendipitous detection of previously uncatalogued objects. Previous surveys have shown that there exists a dim population of small uncatalogued objects in Geosynchronous Earth Orbit (GEO) [4]. Fig. 1 shows this uncorrelated population of dangerous debris objects in red, creating a bimodal distribution with the brighter population of tracked GEO satellites in purple. COM DEV's Sapphire optical payload is able to detect RSOs down to apparent magnitude Mv16 in a 4 second integration using either of its low-noise back-illuminated CCDs [5]. In order to detect a significant fraction these unidentified objects, the proposed next generation instrument would identify objects with apparent magnitudes ~Mv17 at high signal to noise levels.

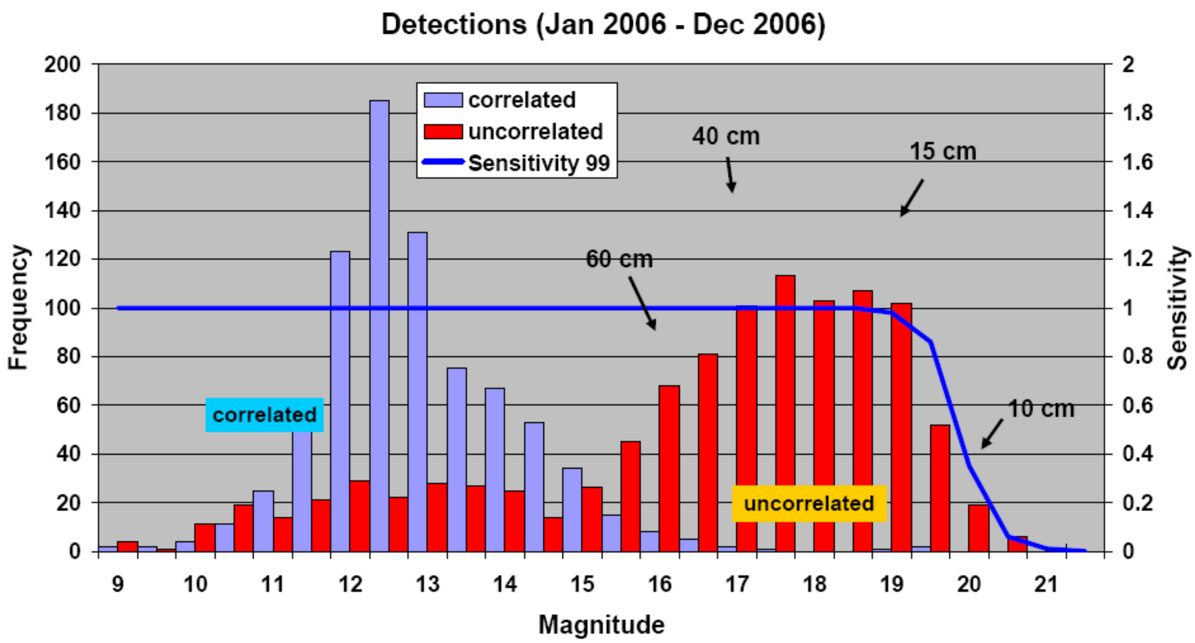

Fig. 1 Ground-based RSO survey showing significant population of small uncataloged objects in GEO [4]

The proposed sensitivity levels are a challenge for several reasons. The zodiacal sunlight scattered from the dust in the plane of the solar system provides background radiance around 23 magnitudes arcsec^{-2} [6]. For Sapphire, the pixel scale of 5 arcsec means that this background will produce a mean background comparable to a stationary Mv18.9 RSO, and this corresponds to multiple photons per pixel even at 10 Hz. This means that pixel size and optical Point Spread Function (PSF) are important factors in determining the limiting magnitude of the system (for stationary targets). Another factor that can affect imaging is stray light and veiling glare from bright objects near the field of view. This is exacerbated by the presence of dust on the optics, and small-scale roughness which create broad scattered-light wings around the image of stars and other RSOs. These factors can both be addressed if care is taken in the details of the design and manufacturing of the imager and baffling.

The most difficult-to-address issue is that of angular motion smearing the target image over multiple pixels. Orbital motion of a GEO spacecraft imparts an apparent motion of ~15 arcsec/s relative to background stars. This level of motion limits the effective integration time to <1 second for a 3-axis stabilized spacecraft and puts a hard cap on the achievable target Signal to Noise Ratio (SNR).

It is possible with emerging detector technology to improve on the performance of the Sapphire optical payload while using the same opto-mechanical input telescope. Electron-multiplying CCDs (EMCCDs), for example, can provide an order of magnitude enhancement on the detection floor of dim objects by applying a high gain to the captured charges. This allows essentially noise-free photon counting, as the electronic read noise is applied after the gain [7]. Drawbacks include increased power requirements, lower dynamic range, and a factor 1.4 increase in the 'shot noise'. The lower dynamic range and increased shot noise are not significant problems as high accuracy brightness measurement is not a requirement of the mission.

The next generation system will use high-frame-rate photon-counting detector arrays with advanced image stabilization firmware. The new firmware is necessary to readout the new detectors and will be programmed to remove residual pointing drift through real time star detection and centroid processing using COM DEV`s patented StarPoint algorithm. This high speed algorithm has been used operationally for over a decade in the CALTRAC™ series of commercial star trackers and will be responsible for stabilizing the James Webb Space Telescope as part of the Canadian Fine Guidance Sensor instrument. With this architecture we can freeze the apparent motion of the target RSO to enhance its SNR relative to background with no need for fine pointing control. Furthermore, the high frame rate allows us to simply discard intermittent transients caused by cosmic rays and energetic proton hits. An agile satellite bus with this next generation sensor could acquire more targets at a higher rate by shortening the time required for attitude stabilization after slewing.

Although photon-counting makes it possible to halve the telescope aperture and still achieve the Sapphire sensitivity levels, for highest TRL the front end optics would remain identical to Sapphire. The dual redundant CCDs would be replaced by Electron Multiplying CCDs in the same flight-qualified packages. The new readout firmware would operate at higher frequency, and would include additional memory for the image stabilization algorithms.

Simulations

To test new SSA architectures and algorithms we have created a parameterized Monte Carlo imaging simulation that accepts Space Telescope Science Institute "Guide Star Catalog II" files as inputs and produces simulated images using a typical '$f \cdot \tan(\theta)$' optical distortion map. The simulation includes zodiacal light plus dark current modeled as a spatially flat distribution with Poissonian statistics. CCD readout performance is parameterized as a pure Guassian noise component. The simulation includes a Gaussian PSF that is meant to account for the telescope image quality as well as satellite jitter. Using a pure Gaussian did not produce a good fit with the observed Sapphire image with too much energy in the central peak. A more realistic PSF was realized with the addition of a logarithmically decaying halo peaking at 10% of the central Guassian, and having a 1/e radius of 5 pixels. This 2-function PSF simulation produces images that bear a close resemblance to actual Sapphire image data under similar conditions (Fig. 2). The wide logarithmic halo is typically due to scattering from dust and imperfections in the optics. Relative star brightnesses will vary somewhat due to colour variations which are not included in the current model. The effects of the type of PSF [5], the inclusion of EMCCD Clock-Induced Charge (CIC) [8], and the incorporation of zodiacal light [6] can be better seen in a logarithmic image of a starfield. The image noise induced by each of these simulation components can be seen in Fig. 3 alongside a simulated Mv17 RSO. The zodiacal background is the single largest noise contribution in the scene, completely obscuring the RSO streak.

The simulation accepts parameterized linear boresight drifts and produces accurate motion blurring of the scene. An RSO can be added to the scene with a specified magnitude and angular rate with respect to the background stars. We have included a model of an EMCCD output with parameterized gain and number of output stages which are individually simulated with a binomial probability model [7]. The output of this simulation for 1-6 electrons input with gain of 1000, and 536 output stages is shown in Fig. 4. This shows how the gain broadens the output distribution and increases photometric noise, while boosting the signal well above the typical CCD readout noise floor of approximately 50 electrons. These gain parameters will be used throughout the simulation as providing an acceptable dynamic range.

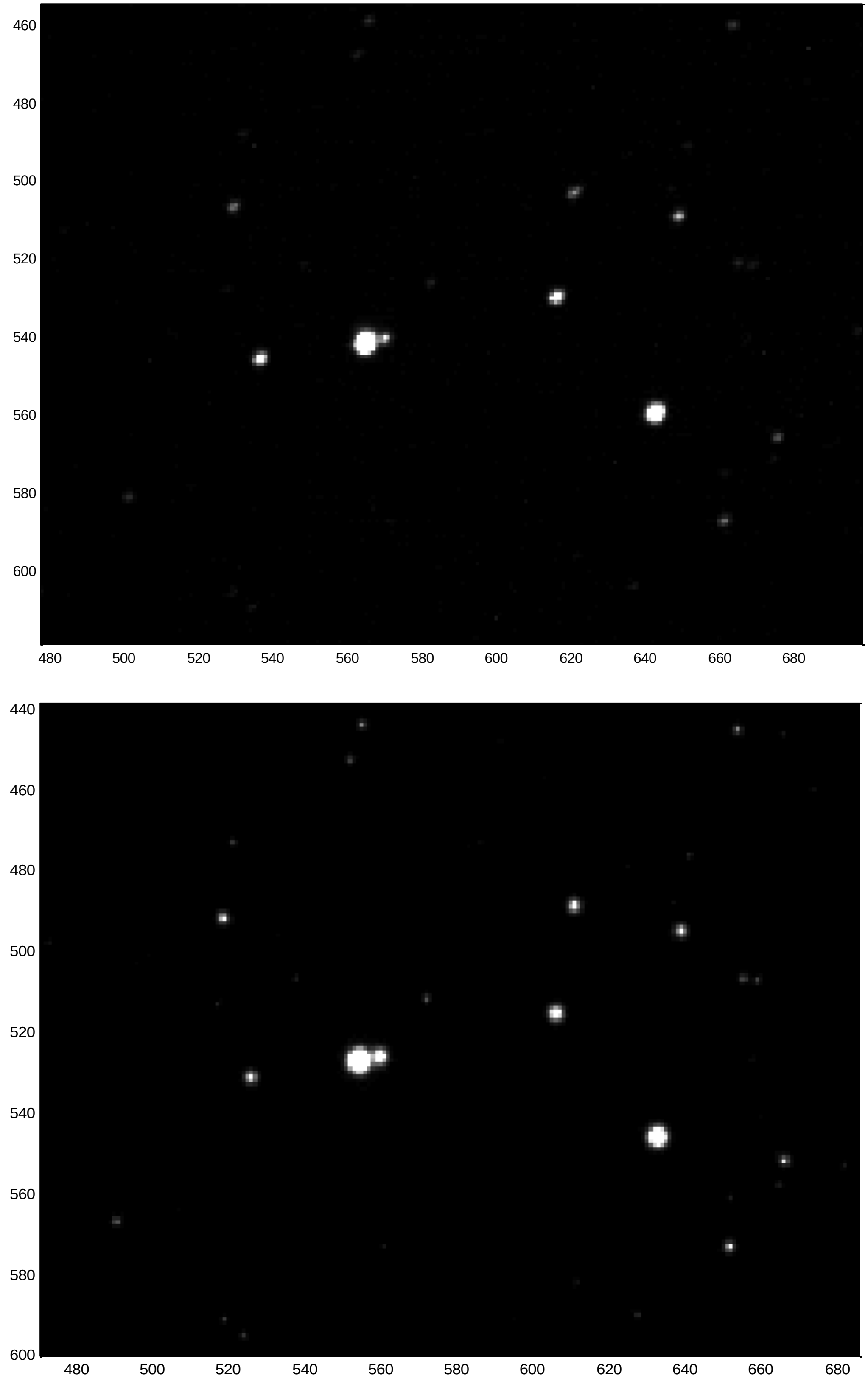

Fig. 2 Part of a Sapphire starfield image [5] (upper) and simulated image (lower), 4 second integration. PSF 3.4 pixels (full width at half maximum) with logarithmic wings.

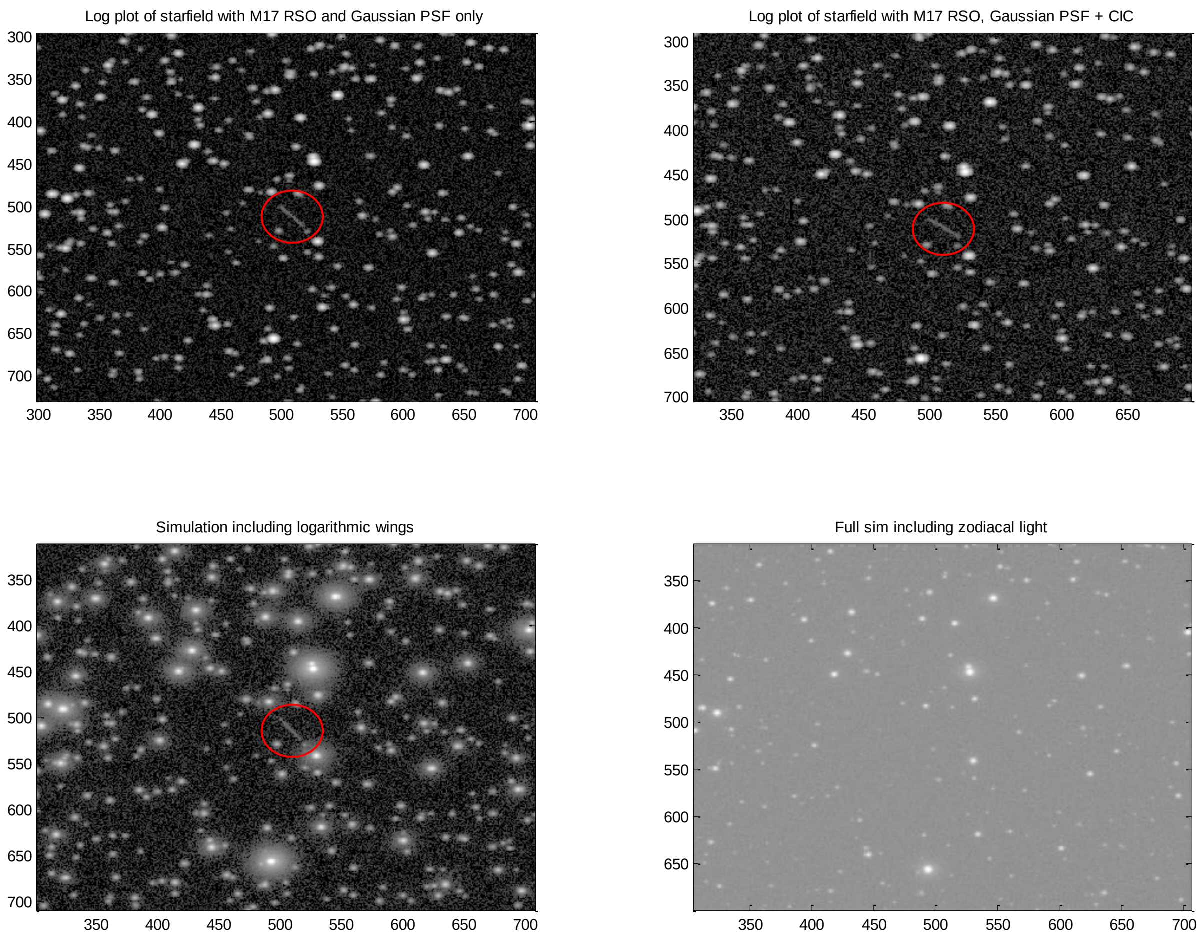

Fig. 3 Log of images with simulated PSFs (Gaussian top left; Gaussian + logarithmic bottom left) and the influence of CIC (top right) and zodiacal light (bottom right)

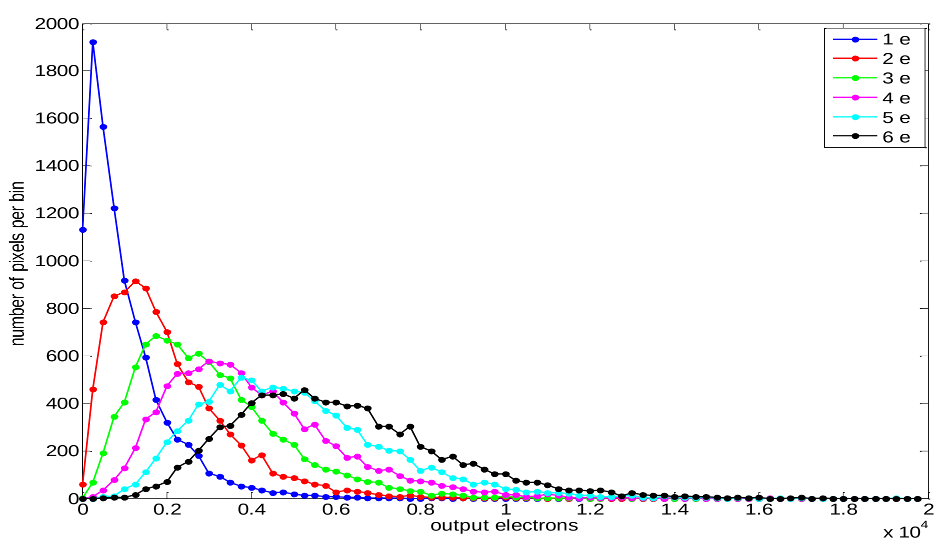

Fig. 4 Simulated EMCCD output histograms for 1-6 input electrons, gain = 1000, 536 output stages.

Results and Discussion

The model was used to calculate positional determination accuracy and precision as a function of magnitude assuming a 0.1 second integration time for both CCD and EMCCD outputs. The results of 100 centroid determinations at each magnitude from Mv10 to Mv15 are shown in Fig. 5. In general, the EMCCD has lower centroid standard deviation for all magnitudes, however for brighter objects the brightest pixels in the EMCCD reach saturation and this creates a small systematic error in the centroid, as can be seen in the upper left figure where the EMCCD centroid determinations are offset from the centre of the CCD results at Mv10. In this case the magnitude of the offset is negligible at <10% of a pixel, or about 0.35 arcsec.

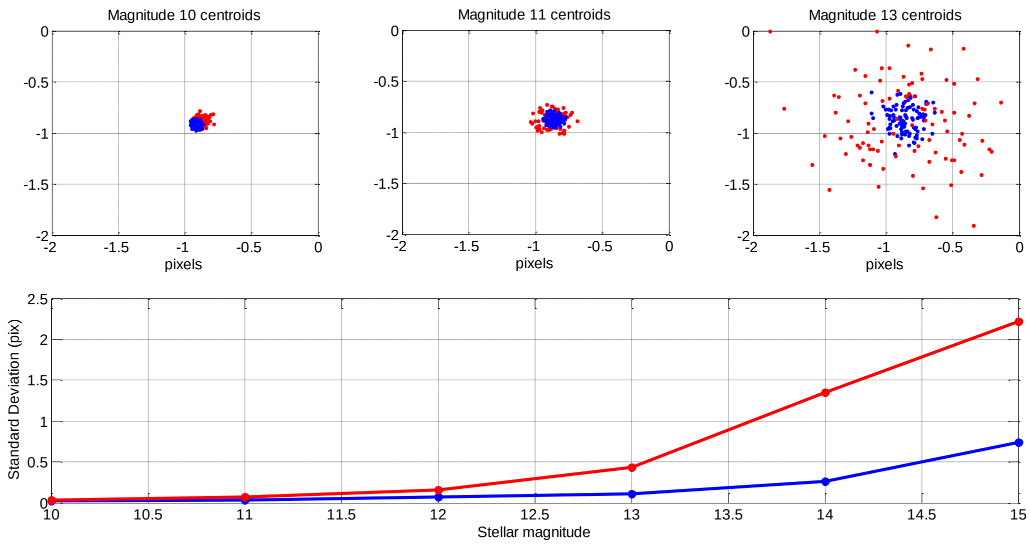

Fig. 5 Centroid accuracy vs magnitude for CCD (red) and EMCCD (blue), 0.1 s integration

These centroiding results are important in demonstrating feasibility for the proposed architecture, and show that one could in principle correct for satellite pointing drifts on the order of the PSF in software at 10 Hz frame rate using an EMCCD if a few widely-spaced stars of ~14th magnitude or brighter were available. Operating the satellite bus attitude orientation control system at lower accuracy could be a significant cost savings for future SSA missions and could allow an EMCCD optical payload to be hosted as a secondary payload on a non-optical primary mission. At this frame rate, satellite drifts of up to 50 arcsec/s can be accommodated with no loss of sensitivity. The Sapphire spacecraft supplied by Surrey Satellite Technology Ltd. must point and stabilize the imager to less than 5 arcsec for extended periods [5], allowing simple co-adding of subsequent frames without significantly blurring the PSF in each individual frame. The main limiting factor on target rate in this scenario is the time it takes to slew to a new target and stabilize the satellite for imaging. A loosened pointing drift requirement would allow an agile bus to acquire more targets in the same amount of time as a CCD-based imager.

The simulation shows that Sapphire, with its current CCD, can detect GEO objects moving at 15 arcsec/s against background stars down to about Mv16, in agreement with the current performance [5]. The same instrument, equipped with a photon-counting EMCCD, would have similar detection performance near Mv16 (Fig. 6 upper frames) where a moving RSO becomes background limited by zodiacal light. The EMCCD is the only architecture that allows one to co-add short frames with an appropriate offset to counteract RSO smearing (Fig. 6 lower right). For CCDs this is not really practical because the read noise quickly overwhelms the signal when using short frame times (Fig. 6 lower left). EMCCD simulations show the brightest pixel with SNR~17 for a Mv16 RSO, and with an SNR~10 for a Mv17 RSO, when using a total integration time of 10 seconds.

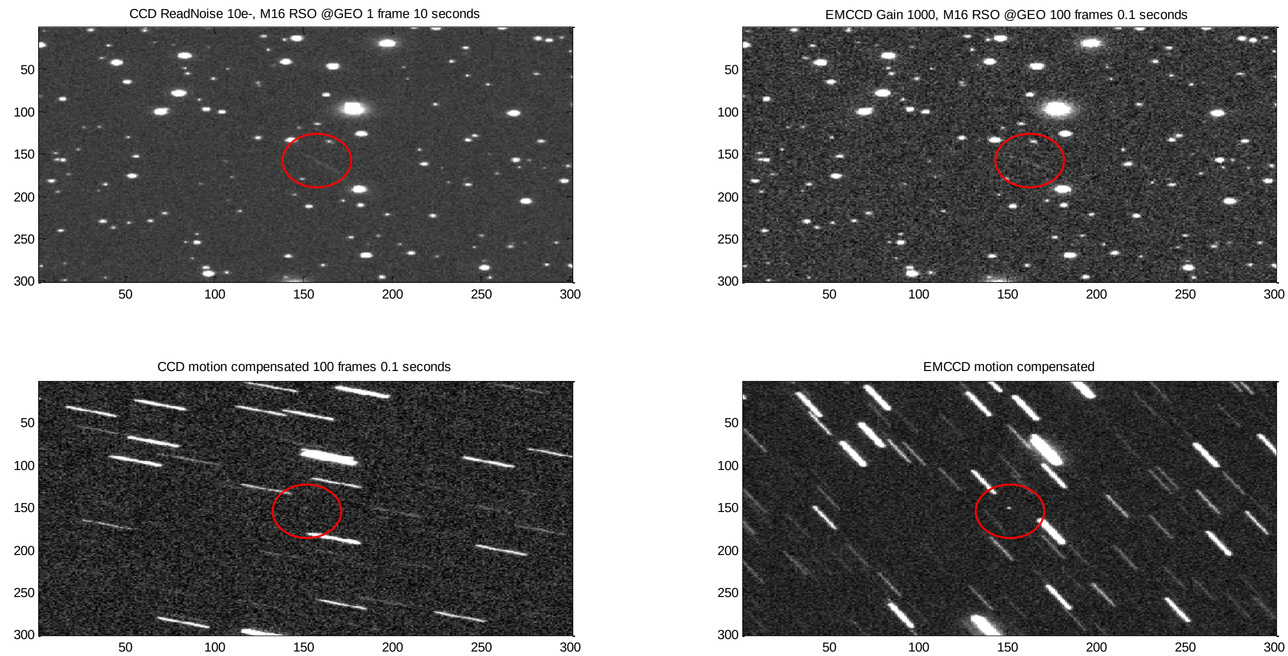

Fig. 6 Simulations of Mv16 RSOs: CCD (left) and EMCCD (right); fixed (upper) and RSO motion compensated (lower) using ephemeris knowledge.

One challenge in this approach is to select the appropriate offset for serendipitous object detection. This requires a good idea of the orbital motion of the debris in question or a sophisticated on-board image processor. Fig. 7 shows that the assumption of a perfect geosynchronous orbit will add an angular rate compensation error of <3 arcsec/s for low-inclination objects of interest for collision avoidance near GEO. This means that an LEO based, Sapphire like EMCCD system should detect Mv17 objects crossing declination 0° with SNR>5 up to about 7 degrees of inclination with the only image processing assumption that the RSO is in the GEO belt. Serendipitous detection of fast-moving objects in LEO or MEO, however, would be limited to brighter objects, as there is a much larger range of altitudes and orbital inclinations to choose from, and high angular rates would make digital RSO motion compensation difficult.

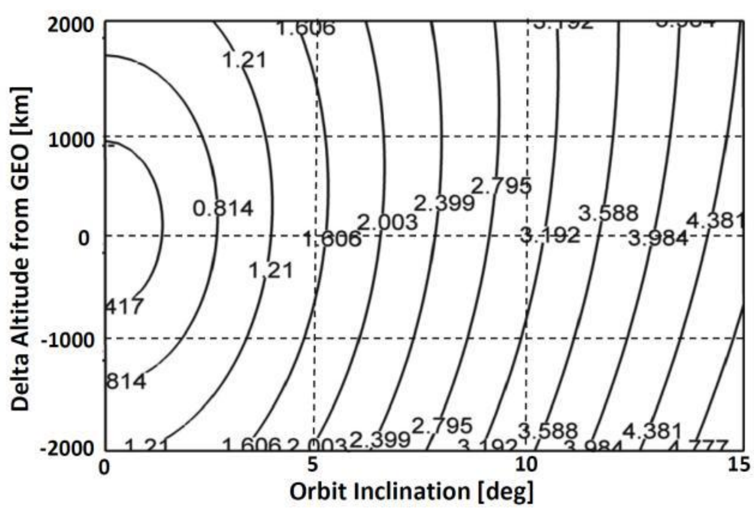

Fig. 7 Angular rate of RSOs crossing 0° declination from geosynchronous orbit in arcsec/s [9].

Conclusions

The current Sapphire optical payload has a mass of 28.5 kg and requires an average power of 14 W [5]. An EMCCD-based version could perform the same catalogue maintenance mission with an order of magnitude looser pointing drift requirement. Additional power is needed to drive and cool the EMCCD, plus additional real-time data processing firmware for motion compensation based on ephemeris data. For the same sensitivity limit of the current Sapphire payload, a reduced aperture instrument would have a mass of about 15 kg and require about 30 W average power. This does not include additional TEC power for cooling of the detector and would depend on having an efficient thermal sink available through a radiator.

An EMCCD-based SSA optical payload of the same size as the current Sapphire payload with the same high TRL opto-mechanical front end, but with 30 W average power, would be able to detect dangerous uncatalogued debris objects in low inclination GEO orbits down to about 40 cm in diameter.

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