Feasibility of Using Commercial Star Trackers for On-Orbit Resident Space Object Detection

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ABSTRACT

The dramatic increase in the number of resident space objects (RSO), including both functioning satellites and on-orbit debris, is a cause for concern throughout the space industry. With several large satellite constellations under planning and development, the RSO population is only expected to rise further, posing significant challenges for existing ground-based and space-based tracking networks and for mission planners and operators. Part of the solution may lie in the RSOs themselves. Many satellites launched today use star trackers for accurate attitude determination and control. What if these wide-field-of-view optical instruments could be dual-purposed to detect RSOs in addition to tracking stars? A network of "backyard observatories" in orbit could then help fill in many of the present and anticipated gaps in space surveillance coverage, further refining orbit predictions and observing objects that cannot easily be viewed from the ground – all the while using existing, previously-flight-qualified hardware. With the support of the Canadian Space Agency, Magellan Aerospace and York University have been investigating this exciting possibility. This paper presents the status of our feasibility study, focusing on the estimated detection rates that can be achieved and the novel technologies that will make this happen.

1. INTRODUCTION

The goal of this project is to assess the feasibility of using a Commercial off the Shelf (COTS) star tracker (ST) to detect RSOs. If COTS STs could be used for RSO detection they would provide a cost-effective means of increasing space situational awareness (SSA). Star trackers are one of the most popular choices for attitude determination sensors. The ability to dual-purpose these sensors for RSO detection would allow a large network of space-based sensors to be formed and contribute to the global SSA catalogue. This network of sensors would complement existing ground and space-based sensors without the need for any new hardware.

To establish the ability of COTS STs to be used for RSO detection, a baseline goal of 1-10 RSO detections per ST per day has been set. Assuming a ST detected one RSO per day over a five-year mission, that would be a total of 1825 detections. If all of those detections were unique then approximately 10% of the catalogued RSO population would be updated by the ST. Even if only 10% of those detections were unique and there were 183 unique detections being made over the 5-year mission, then approximately 1% of the catalogued RSO population can potentially be updated by the ST. That 1% of the population can even be potentially updated multiple times by repeat detections from the ST. With multiple star trackers on multiple platforms, an even larger percentage of the catalogued (and un-catalogued) RSO population can be observed.

2. THE SIMULATOR

To determine the feasibility of using COTS ST for RSO detection, a simulator was created to provide an estimate of the number of objects that will be detectable by a COTS ST in orbit. The simulator is split into two parts: an analytic simulator and an image simulator.

The analytic simulator determines the detection rate of a given ST based on inputs, including different ST characteristics (such as aperture size and focal length) as well as the orbit and orientation of the host satellite for the ST. Based on these inputs the simulator provides four different sets of results: total accesses, unique accesses, total

detections and unique detections. The term "accesses" refers to any RSO that crosses the field of view (FOV) of the ST while "detections" refers to an RSO that crosses the FOV of the ST and is bright enough to be above a certain signal to noise threshold. The term "total" refers to the cumulative number of accesses or detections that occur, including repeat accesses or detections. The term "unique" refers to the number of accesses or detections that occur, not including repeat accesses (i.e. detections of the same RSO multiple times). The "total" number helps give an idea of how much a particular ST can contribute to updating the positions of RSOs for an SSA catalog. The "unique" number gives an idea as to what percent of the RSOs will be updated in the catalogue. There may be a difference in value in detecting the same object one hundred times in a day or detecting twenty different objects five times each in a day.

The image simulator generates images produced by the ST using output data (host satellite position, target satellite position, illumination) produced by the analytic simulator. Images can be produced at any moment of the simulation period. These simulated images will be used to validate and train analytic and machine learning algorithms that are being developed by Magellan Aerospace to detect RSOs within ST images.

3. VERIFICATION USING THE FAST AURORAL IMAGER

The simulator is currently in the process of being verified and validated. To validate the simulator, the results will be compared with the Fast Auroral Imager (FAI) on Canada's Cassiope satellite [1]. The FAI is a payload camera that images auroral emissions near the limb of the Earth, but also in the process sees numerous RSOs cross its FOV. Conventional ST images are used for onboard attitude determination but are not typically downloaded to the ground, and those few that are downloaded are not always readily available for public use. The FAI, however, has similar optical and detector characteristics to a ST and has all of its images freely available online. For these reasons FAI was chosen to validate the simulator.

The simulator was run for a simulation period of five hours using the characteristics of the FAI (shown below) and with Cassiope as the host satellite. The FAI was in a nearly ram facing orientation to allow it to look over the limb of the Earth, which is the most promising of its three viewing modes for RSO detection (the other two modes are nadir viewing and pointing at a fixed target on the Earth) [1].There were 2687 LEO RSOs in the simulation, which represents all of the LEO RSOs with updated two line elements sets (TLEs) from the Space Surveillance Network [2] in the last 30 days prior to the simulation.

Table 1: Fast Auroral Imager Parameters *

Field of View	26 degrees
Aperture Diameter	1.7 cm
Pixel Size	26 μm
Focal Length	6.89 cm
Integration Time	0.1 seconds

* CASSIOPE's Fast Auroral Imager has a near infrared (NIR) and a visual spectrum detector. This simulation used the NIR parameters [1].

The results of the FAI simulation are shown below. To validate both the analytic and the image simulator, these results need to be compared with the data from actual FAI images. The detection rates shown below will be compared with FAI images to ensure that the simulated detection rates match those of the FAI images.

There are a couple challenges in comparing the detection rates from the simulator with the actual detection rates of the FAI images. One challenge is that the simulator randomly assigns the sizes of the RSOs according to a distribution that reflects the distribution of objects in the SSA catalogue. This may result in an RSO that is undetected by the FAI being detected by the simulator because it is assigned a larger diameter than the actual RSO imaged by the FAI. Conversely, an RSO that is detected by the FAI may be undetected by the simulator because it is assigned a smaller diameter than the actual RSO imaged by the FAI. After running the simulator, some "fine tuning" of diameters and direct comparison between simulated and FAI images may be required to ensure that RSOs are not incorrectly added or withheld from the simulators calculations of detection rates. The other challenge in comparing the detection rates of the FAI and the simulator is that it is difficult to objectively measure the FAI detection rate. Some work has already been done to determine the FAI detection rate by visually scanning the FAI image archive. 24 strong-candidate RSOs were detected during a 4-month calendar period, representing just over 6 hours of actual imaging time. Extrapolating, this is equivalent to a detection rate of 95 RSOs per day, which is noticeably lower

than the value observed in preliminary simulation. Note that the human-eye method does not guarantee that every RSO in the reviewed image set has been detected, especially with RSOs that are close to the noise floor of the detector. The simulated detection rate will continue to be refined as work progresses. An acceptable level of error between the simulated detection rates and the real FAI detection rates will have to be determined.

Simulated images will also be compared with individual FAI images to determine the accuracy of the simulated images. Positions of stars, RSOs, the Earth and any other objects appearing in the images will be compared to ensure that the simulated images are being generated correctly.

Table 2: Preliminary Results of the FAI Simulation (for a five-hour period)

Total Accesses	2791
Total Detections	247.6
Unique Accesses	984
Unique Detections	143.6

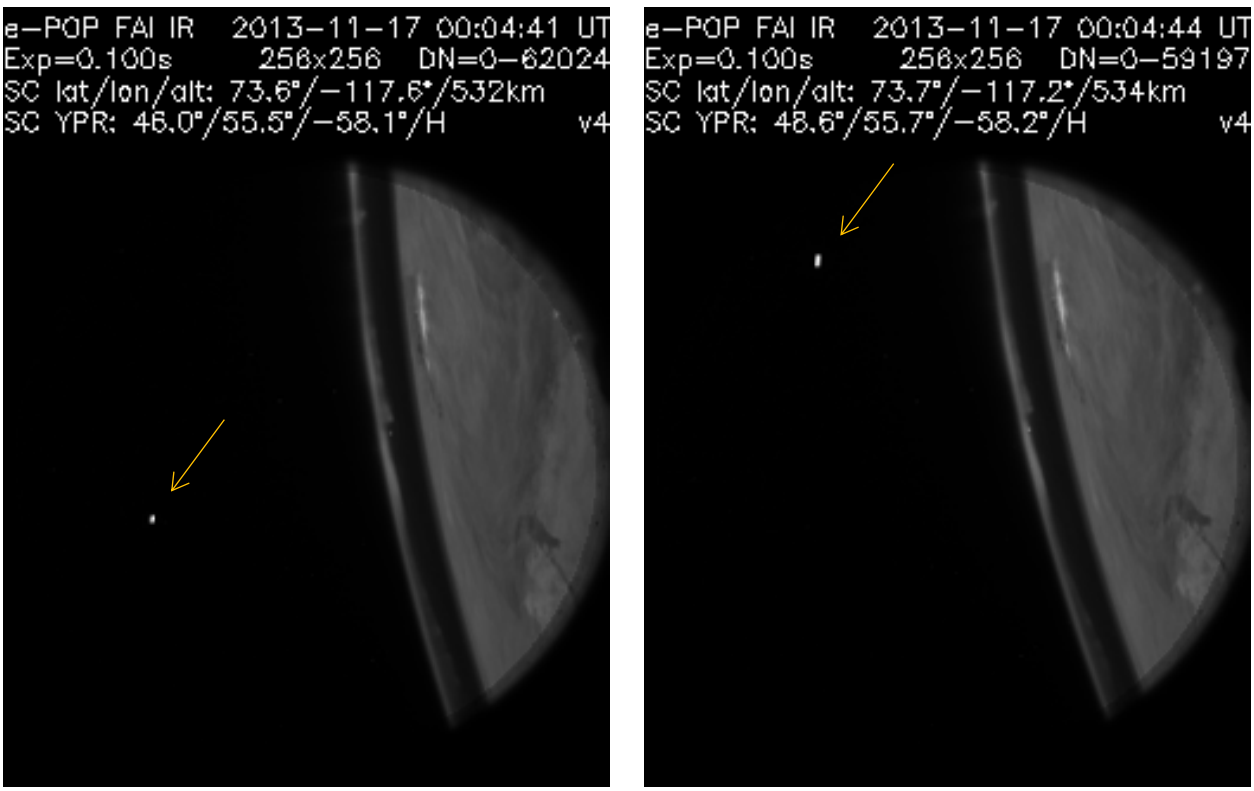

Fig. 1. RSO images taken 3 seconds apart by Cassiope's FAI. Credit: University of Calgary

4. "MODERN" STAR TRACKER SIMULATION

The ultimate purpose of the simulator is to determine the feasibility of a COTS ST for RSO detection. To this end, the simulator was run using the parameters of a COTS ST. The parameters that were used are based on the "modern" ST parameters given by Zakharov (modern referring to STs being produced around 2013) [3]. Due to the range of available parameters even for modern STs, more conservative parameters were chosen to provide more conservative results. The host satellite that was chosen for the ST was MOST because it is a LEO, polar orbiting satellite. A low earth polar orbit is thought to be a good orbit for RSO detection using STs, as many Earth-observing satellites use such high-inclination orbits. The LEO provides a good vantage point to image RSOs because it will be closer to the RSOs than a detector out in GEO, for example. The polar orbit also provides a good view of the North and South poles where many other LEO, polar orbiting RSOs have their orbits converge. The simulator was run for a five-hour period with the same LEO RSOs (for easy comparison with the FAI simulation). A five-hour period was used because it allowed for the simulation of approximately three orbits of MOST (MOST's period is just over 101

minutes). Daily detection rates are desired to characterize the feasibility of the ST to be used for RSO detection but simulation for a day would take an estimated 10 hours to run one scenario. That is why for these preliminary results, simulations of five hours were done to speed up the process but still maintain a complete picture of the scenario by capturing three orbits of the host satellite. After final verification and validation has been completed simulations will be run to get data for a full day to obtain daily detection rates.

Table 3: Star Tracker Parameters

Field of View	10 degrees
Aperture Diameter	1 cm
Pixel Size	10 μm
Focal Length	4 cm
Integration Time	0.1 seconds

The simulator was run four different times using different orientations of the ST in order to see the effect that different pointing directions has on the detection rates. The four orientations that were simulated were a ram facing orientation, an anti-ram facing orientation, a zenith facing orientation and an orientation pointing directly away from the Sun. The ram and anti-ram orientations point along the x-axis (and negative x-axis) of the orbital coordinate system of the host satellite. The orbital coordinate system is centred on the STs host satellite with the z-axis pointing nadir, the y-axis in the negative orbit normal direction and the x-axis completing the right-handed system. For MOST, in a nearly circular orbit, the x-axis is very close to the ram direction. If a more eccentric orbit was used then the x-axis would vary from the ram direction. For this scenario however, due to MOST's nearly circular orbit, the ST can be considered to be pointing in the ram and anti-ram direction. The ram and anti-ram facing orientation was selected because (with the polar orbiting MOST satellite) they provide a good view of the North and South poles where many orbits of other polar orbiting RSOs intersect. The zenith facing orientation was selected because it is a more common orientation for STs being used for attitude determination. Star trackers are often orientated away from the Earth to avoid light reflected from the Earth interfering with their imaging. The orientation pointing directly away from the sun, however, provides the best illumination geometry of RSOs and thus has the potential to provide the best images of RSOs. The results of each simulation are shown below.

Table 4: Preliminary Results of the Four Simulations for Modern Star Trackers

	Ram Facing	Anti-Ram Facing	Zenith Facing	Anti-Sun Facing
Total Accesses	767	438	18	678
Total Detections	211.2	113	9.8	78.4
Unique Accesses	386	297	18	481
Unique Detections	115.6	80.8	9.8	54.4

It is clear to see that the ram facing orientation provided the best results in almost every category. It had nearly twice as many total and unique detections as any other orientation. One likely explanation for this is that, as mentioned before, the ram facing ST, as it approaches the poles, is looking directly through the region where many low Earth, polar orbits converge.

The anti-ram orientation had the second most detections. What's surprising is that it is significantly worse than the ram facing orientation. The anti-ram orientation had a 46% decrease in total detections and a 30% decrease in in unique detections. It is presently unclear why there is such a large difference between the two detection rates when one is looking at the pole of the Earth as it approaches and the other is looking at the pole of the Earth as it departs.

The anti-sun facing orientation performed similarly to the anti-ram facing orientation, though slightly worse. What is interesting about this orientation is that it only had 12% less total accesses than the ram facing and 25% more unique accesses than the ram facing. Of those total and unique accesses, it only detected a very small percentage of the RSOs, 12% and 11% respectively. One reason for this could be that the ram and anti-ram orientations are looking in their own orbital plane. The anti-sun orientation is not looking in its own orbit. This may result in the RSOs seen by the anti-sun orientation being farther away from the host satellite than they are when using the ram or anti-ram orientation. The better viewing angles provided by the anti-sun orientation may not be enough to compensate for the potentially larger distances that it is viewing the RSOs from.

The zenith facing orientation had a significantly lower performance than the other three orientations, detecting only ~10 objects in the five-hour period. This is expected because a limb pointing orientation (such as the ram facing orientation) sees a deeper swath of RSOs than the zenith facing orientation does.

All four orientations greatly exceeded the baseline goal of 1-10 RSOs detected per day by a single ST. In only five hours (three orbits of the ST) each orientation had met (in the case of the zenith orientation) or greatly exceeded the baseline daily goal. Projecting these five-hour detection rates to daily detection rates gives very promising results that indicate that detection rates well over the desired baseline goal are possible, even for the zenith facing orientation. It is unclear how representative these five-hour detection rates are with respect to daily detection rates. A more in-depth analysis of the hourly, or orbital detection rates would have to be done but is not possible given the current data. Despite this uncertainty, it is promising that the preliminary results indicate that the baseline, daily detection rates have already been met within a five-hour period.

5. IMAGE SIMULATOR

The image simulator takes the data from the analytic simulator and produces a simulated ST image. An image may contain stars, any number of RSOs, the Moon and the Earth limb. It considers several noise sources: reflected light from the Earth and the Moon, zodiacal light, hot pixels, read noise and dark current. Below are several images generated by the image simulator. Stars in the images can be distinguished from hot pixels by looking at their sizes. Stars take up multiple pixels while hot pixels are just a single pixel. Glow from the Earth can also be seen in a couple of the images.

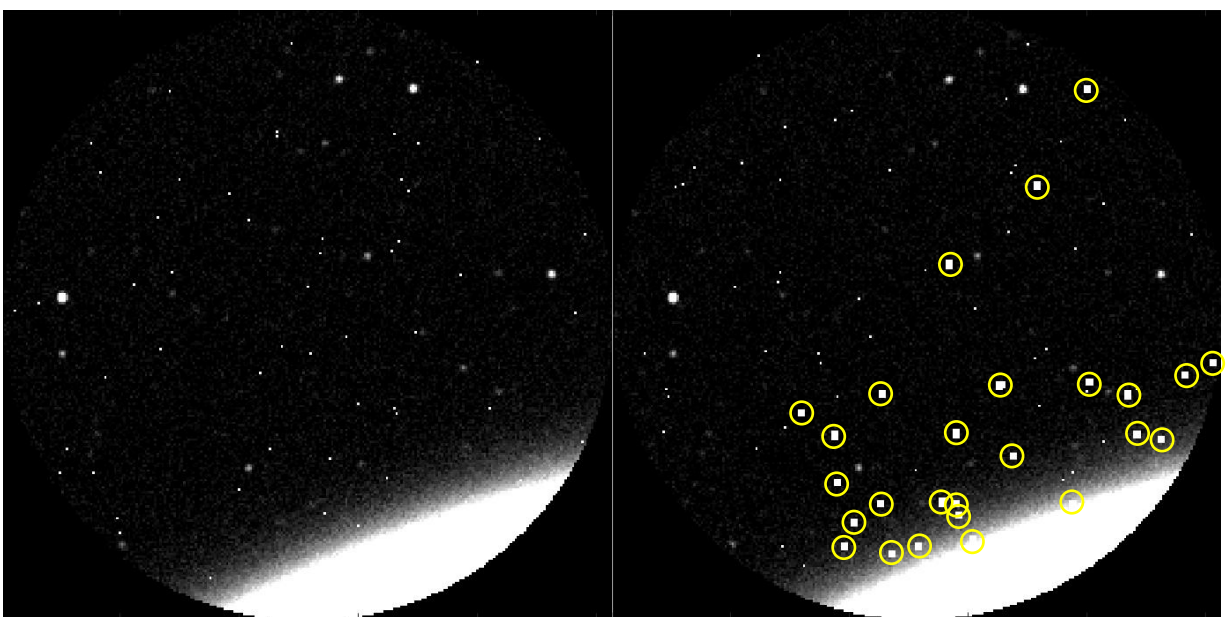

Fig. 2. (Left) Simulated FAI image with 0.5 second exposure. (Right) The same simulated FAI image but with the RSOs exaggerated and circled to be seen more easily.

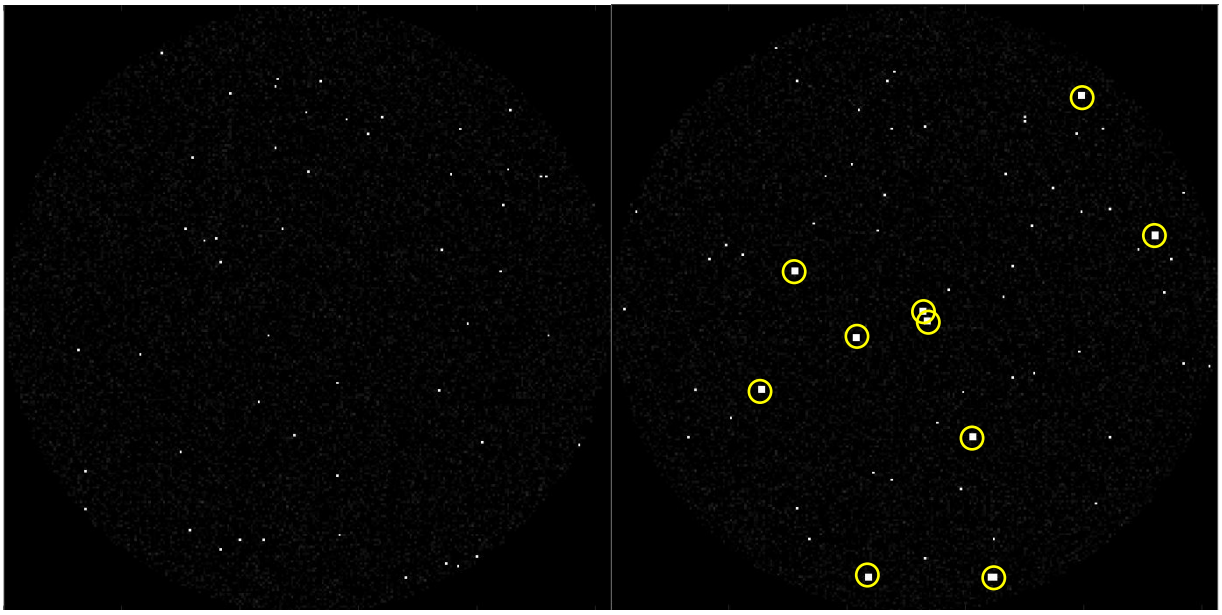

Fig. 3. (Left) Simulated modern ST image with ram pointing orientation with 0.1 second exposure. (Right) The same simulated ST image but with the RSOs exaggerated and circled to be seen more easily.

The short exposure time of FAI and the modern STs makes it difficult to see both RSOs and stars in the above images. Fig. 4 and Fig. 5 show images generated with 10-second exposure times. With the longer exposure times, stars and RSOs are easier to see in the images. The RSOs can be seen as streaks across the image instead of simply points. However, note the difference between the stars in the two figures of 10-second exposures. Both figures have the RSOs streaking across the image. In Fig. 4, the stars can also be seen to streak as the ST slews across the sky during its 10 second exposure. In Fig. 5 however, the ST is pointed inertially away from the Sun and the stars remain stationary as RSOs streak across the image.

One concern is the difficulty in actually seeing the RSOs in the images. All of the images have theoretically visible RSOs in them. However, the only image with an RSO actually visible in it (apart from the exaggerated images) is Fig.4. In Fig. 4 the RSO in the bottom of the image is circled in red. This may be due to an issue with the threshold signal to noise ratio (SNR) used by the analytic simulator in determining which RSOs are detectable. Perhaps a higher threshold is needed. The threshold used by the simulator for identifying when an RSO is detected is an SNR of 6. This threshold is obtained from literature [4]. The RSO in Fig. 4 has an SNR of 223 (per pixel) and yet is barely visible in the image. It seems unlikely that there is such a large discrepancy between the simulation and literature. This suggests that the issue may not be with the threshold being used but perhaps an issue with the image simulator itself, which will be investigated.

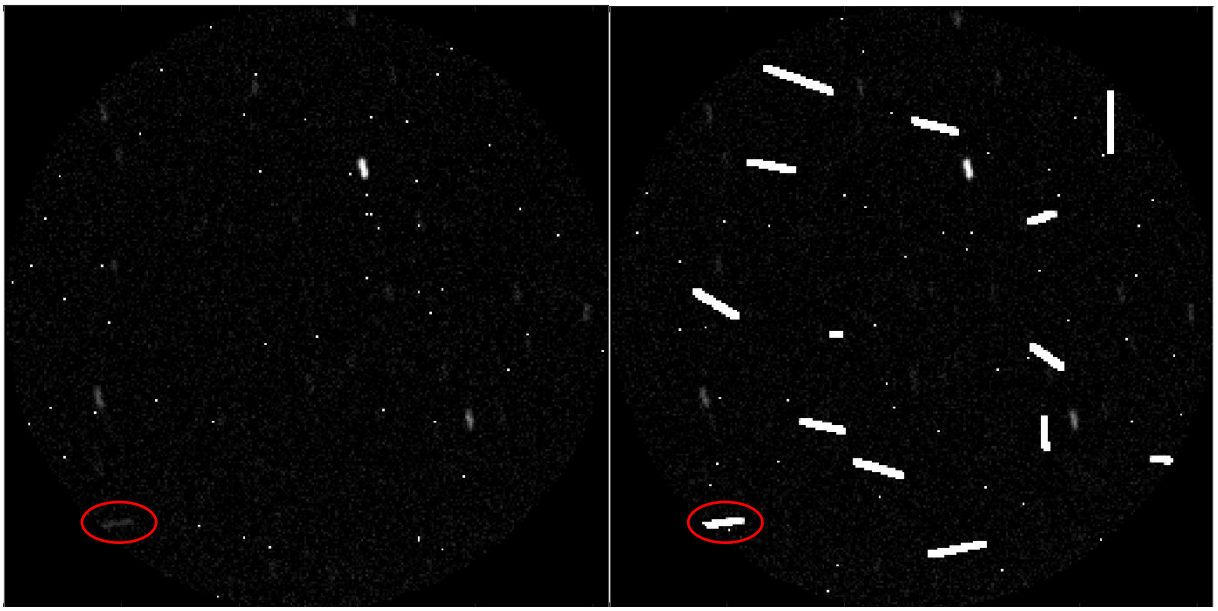

Fig. 4. (Left) Simulated modern ST image with ram pointing orientation and a 10 second exposure time. (Right) The same simulated ST image but with the RSOs exaggerated to be seen more easily. The brightest RSO is circled in red in both images.

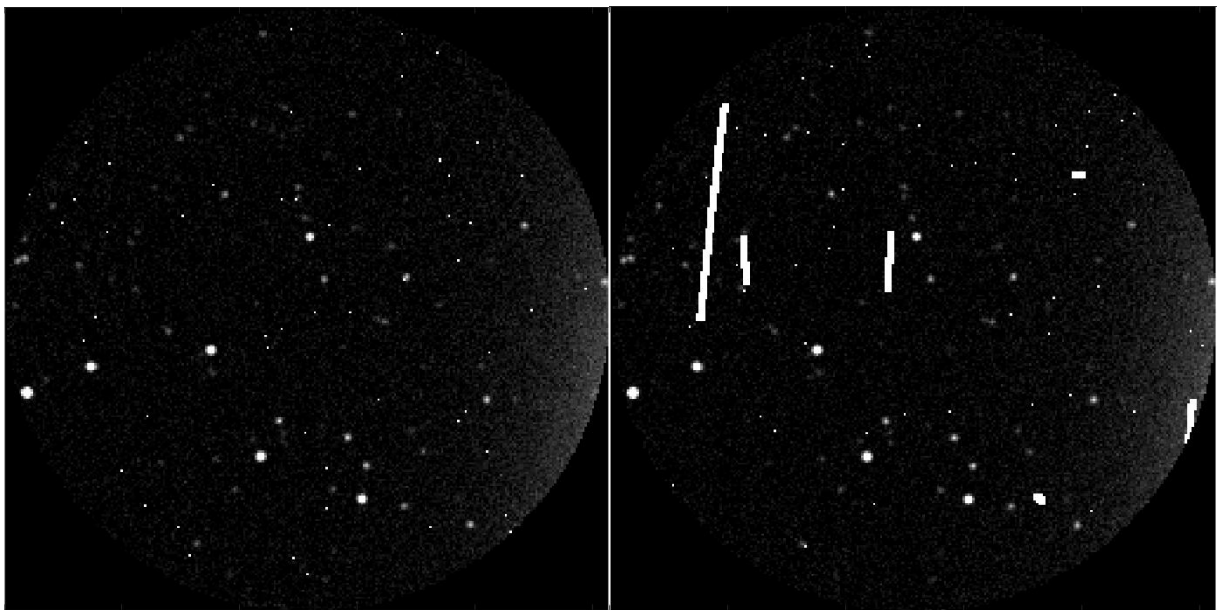

Fig. 5. (Left) Simulated modern ST image orientated away from the sun and with a 10 second exposure time. (Right) The same simulated ST image but with the RSOs exaggerated to be seen more easily.

6. RSO DETECTION TECHNOLOGY

In parallel with the RSO simulator development and detection rate assessment being performed by York University, Magellan Aerospace has been researching novel methods for identifying RSOs in ST images. Two technology streams are being developed, one based on analytic methods and another based on machine learning.

The RSO detection analytic approach, also known as STARED (Star Tracker Analytic RSO Enabled Detector), uses conventional image processing techniques to distinguish RSOs from background noise by comparing two processed sequential ST images. Each image is scaled and converted to a binary image using a tuned threshold that is dependent on the ST characteristics. Foreground objects are then labeled using a two-pass raster scan and properties

of each object are extracted. The objects are then filtered, leaving a set of potential RSO candidates. The processed image is finally overlaid onto the subsequent processed image. Objects from the previous and current processed images that are close in proximity (stars with similar row and column coordinates) are filtered out, leaving behind true RSO candidates.

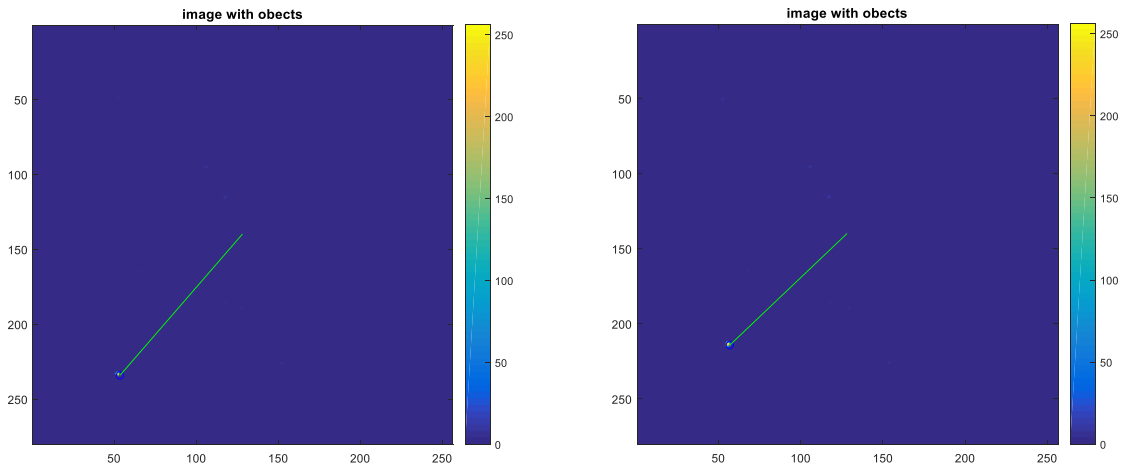

Fig. 6. (Left) processed FAI image and (Right) subsequent processed image FAI image (See Fig. 1) using STARED. The Earth limb has been removed and the green vector represents the image boresight to the RSO.

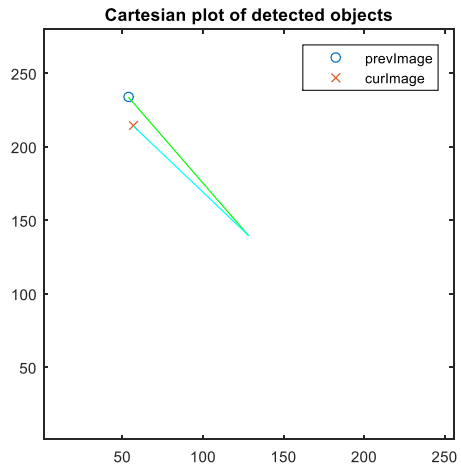

Fig. 7. Overlaid two sequential processed FAI images clearly showing the centroids of the RSO in pixel row and column with the origin at the lower left corner.

The machine learning approach makes use of convolutional neural networks (ConvNets) to identify an RSO in a given image or image sequence. By learning features that are specific to RSOs, and which distinguish them from stars, hot pixels, particle hits, and other light sources in the image, the RSO-specific data can be identified and downlinked to the ground for identification and analysis. The input images are first scanned ("convolved") to extract low-level features, using trained convolutional filter weights. Subsequent layers in the ConvNet apply pooling to the image pixels and then convolve the resulting image with additional filters that identify higher-level features to narrow down the RSO identification. Fig. 8 shows a sample network developed by Magellan as exercised on an RSO detected by the FAI (see Fig. 1). By the third layer all non-RSO objects (including the Earth limb) have been suppressed, and the strong activation from the RSO itself is clearly visible.

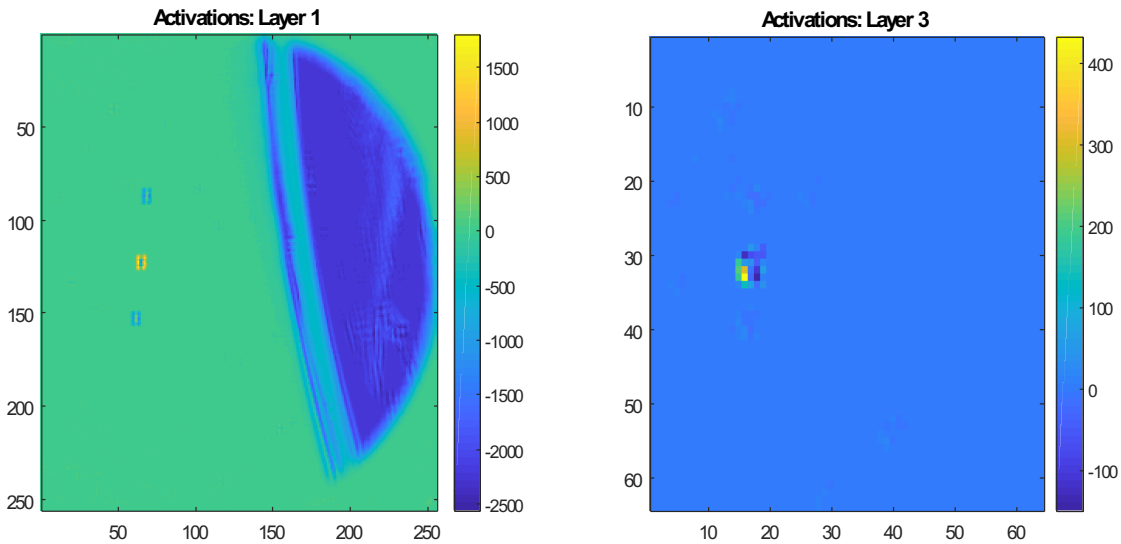

Fig. 8. (Left) Activations from the first layer of a sample ConvNet, based on images of the RSO seen in Fig. 1. (Right) Activations from the third layer, showing suppression of the Earth limb and surrounding stars, but with strong activation from the RSO.

7. CONCLUSION

There is still work to be done on the simulator before any of the results can used to determine the feasibility of COTS ST as a means of RSO detection and later to be used as a means of verifying and training Magellan Aerospace's analytic and machine learning algorithms. The simulator's verification and validation must be completed. First, individual components of the simulator must be verified. This process is well under way. Once that is completed the simulator as a whole can be verified using the results and images of FAI. There are also a few issues to work out as well (such as the SNR thresholding discussed above). Once verification and validation have been completed, the simulator can be used to officially determine the feasibility of COTS ST as a means of RSO detection. If feasible, the project will move on to the next stage, verifying and training Magellan's analytic and machine learning algorithms.

That being said, the preliminary results that have been obtained by the simulator are promising and indicate that detection rates above the baseline goal of 1-10 detections per day are likely.

8. REFERENCES

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