Operations analysis of Australian-based systems for surveillance of space

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ABSTRACT

Due to increasing dependence on space-based capabilities, in recent years Australia has committed to making a greater contribution to generating space situational awareness (SSA). A natural first step has been to acknowledge Australia's privileged geographic location and accept US invitations to host and jointly operate elements of the Space Surveillance Network (SSN), in particular a C-Band tracking radar to help maintain the Low Earth Orbit (LEO) region of the space object catalogue, and the Space Surveillance Telescope to maintain watch over the relatively crowded Geosynchronous sector above the Indian Ocean. The Australian government has also encouraged and supported increased investment by commercial and academic interests in SSA Research and Development capabilities.

Nevertheless, as Australia operates virtually no space systems itself, it has limited understanding of SSA. This can impact the ability to make informed decisions about participation in systems such as the SSN or further investments in Australian capability. Therefore Defence in Australia has sponsored ongoing work by the Defence Science and Technology (DST) Group to build up necessary understanding to support such decisions. This paper describes some of the operational analyses carried out to date in this program.

The program has centred on high-level modelling and simulation of the potential contribution sensors in Australia might make to maintain the unclassified LEO catalogue. This has involved calculating the ability of generic sensors to observe LEO objects, as a function of the sensors' locations and key coverage parameters such as range, elevation limits and operating hours which in turn depend on whether the sensors are active or passive. It has also required identification, computation and refinement of appropriate performance metrics to summarise the output of the simulations. This paper will outline work done, the results obtained and the conclusions drawn to date. In particular it notes findings so far and outstanding issues in carrying out perhaps the most difficult part of this work: assessing the difference new Australian systems might make to the overall performance of an enlarged SSN.

1. INTRODUCTION

The Joint & Operations Analysis Division (JOAD) within the Defence Science and Technology (DST) Group of the Australian Department of Defence undertake rigorous, scientifically-based analysis of Defence operations and capability to provide independent, impartial and timely advice [1]. Within JOAD there is a work program of science and technology research to support the development of the Australian Defence Space Capability. A significant part of this program has involved operational analyses to assess the performance of space surveillance sensors in Australia.

This paper describes work which has been focused on assessing the contribution current and future space surveillance sensors, such as the C-Band tracking radar being established as a dedicated Space Surveillance Network (SSN) sensor at North West Cape in Western Australia, might make to observing objects in the Low Earth Orbit (LEO) catalogue. Analytical Graphics Inc. (AGI) Systems Tool Kit (STK) software was used to develop high-level models of sensors and their locations and run simulations to determine which objects in the current unclassified space object catalogue could be observed, how often they are observed, and the duration between consecutive observation opportunities for each object. The results revealed that there are a number of key performance determinants including range, elevation limits and operating restrictions for the different sensor types. These are explored in the paper. Location, in particular the latitude of a sensor site, can have a significant impact on operational performance and is also analysed.

The paper is structured as follows. Section 2 provides an overview of current and planned future space surveillance systems in Australia operated by military, academia and industry. It also describes limitations of the current United States (US) SSN and highlights the potential benefits of locating systems in Australia. Section 3 outlines the metrics applied to assessing sensor performance in the operational analysis studies. Section 4 describes the modelling and simulation approach and methodology for assessing operational performance of space surveillance sensors. Section 5 presents the results and Section 6 describes the key findings and conclusions from this work. Finally, Section 7 highlights areas for future work including an assessment of the performance improvements from space surveillance sensors in globally dispersed locations.

2. SPACE SURVEILLANCE SYSTEMS IN AUSTRALIA

Space surveillance systems play a crucial role in producing space situational awareness (SSA). However, Australia does not have an established SSA capability and is instead reliant on its allies, in particular the US, to provide this information. Australia has many independent systems, proposed or current, capable of performing space object monitoring and in turn producing SSA, although these are not part of an indigenous network and in most cases do not provide data to existing networks such as the SSN.

Most of Australia's SSA information comes from the US space object catalogue which is generated using sensor observations from the SSN. The current SSN has limited coverage over the southern hemisphere due to most of its sensors being located in the northern hemisphere. This can restrict coverage of up to half an orbit for objects in LEO. Figure 1 shows the coverage of SSN sensors tasked to tracking and cataloguing objects in LEO. Coverage is shown to an altitude of 800 km which represents the most highly populated region of LEO[1]. Most sensors in the network don't have a dedicated or primary mission of space surveillance with many designed as missile warning systems (collateral) and some not owned or operated by the US Air Force (contributing). This further limits the ability of the SSN to produce timely and accurate data for the catalogue.

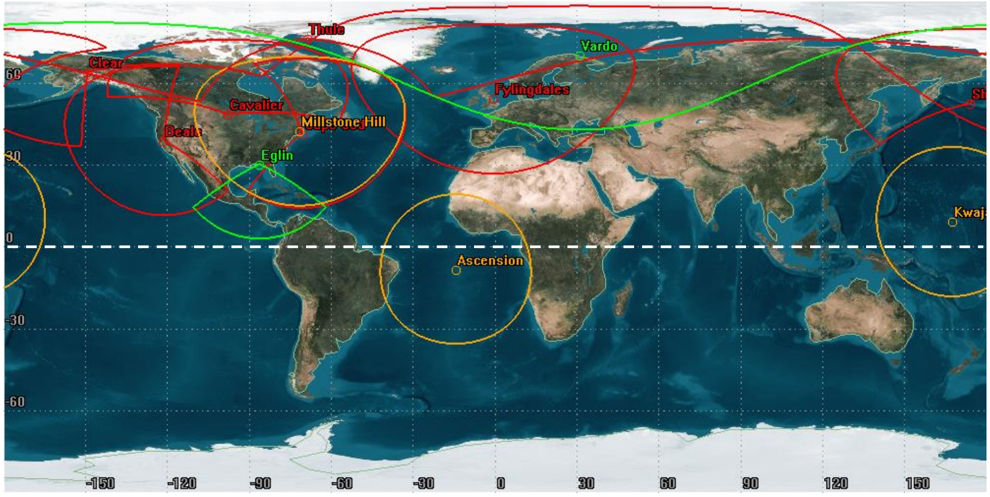

Figure 1. Coverage of sensors in the SSN at an altitude of 800 km. Dedicated space surveillance sensors are shown in green, contributing sensors in yellow and collateral sensors in red. Dashed white line represents the equator.

To improve global coverage of the SSN, particularly in the southern hemisphere, Australia has been invited by the US to host space surveillance systems [2], including a C-Band tracking radar, currently being set up at North West Cape in Western Australia after relocation from Antigua. The system is a mechanically steered dish radar that can provide very accurate tracking of space objects, primarily in LEO. This will be a dedicated space surveillance sensor in the SSN when operational and should provide significant additional coverage of LEO within the network. Also being acquired through a joint Australian/US arrangement is a Space Surveillance Telescope (SST) to survey the

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[1] Analysis of the unclassified space object catalogue (August 2014) shows that around 44% of objects in LEO have a perigee altitude between 700 and 900 km

Geosynchronous region above the Indian Ocean. This system is being relocated from New Mexico, US, to the facility at North West Cape, Western Australia. Despite these planned acquisitions, Australia has limited experience in conducting SSA activities or understanding of what they may contribute to observing space objects. Therefore operational analyses are required to make these assessments and inform Australian investment decisions.

The C-Band tracking radar and SST are not the only SSA systems planned or currently operating in Australia. Within Australian Defence, The National Security and Intelligence, Surveillance and Reconnaissance Division (NSID) of DST Group have also procured several optical telescopes for research in the space surveillance field [3]. These systems are located at the DST Group site in Edinburgh, South Australia. Similar optical systems capable of producing SSA are also operated by academic institutions in Australia. These include an operational node of the US Air Force Academy Falcon Telescope Network (FTN) located at University of New South Wales Australian Defence Force Academy in Canberra [4]. Additional FTN nodes have been proposed for academic institutions in Perth, Western Australia, and Brisbane, Queensland. Industry is also becoming an emerging player in SSA in Australia. Electro Optic Systems Pty. Ltd. (EOS) has developed a ground based laser for high precision space object tracking [3]. A proof of concept system is currently operational at Mt. Stromlo, near Canberra. A second node is planned to be deployed alongside other SSA systems at North West Cape, Western Australia.

These systems provide Australia with the capability to track space objects and produce SSA using a variety of radar, passive optical and laser systems. The metrics to assess the operational performance of these systems for observing objects in the existing unclassified space object catalogue are presented in the next section.

3. PERFORMANCE METRICS

Assessing the potential contribution sensors in Australia might make to maintaining the unclassified LEO catalogue required the identification of suitable performance metrics[2]. The choice of metrics was based on how well they could answer the following questions:

- What can a sensor or network of sensors observe? Where do coverage gaps, if any, currently exist?
- How often can a sensor or network of sensors observe a given object? Is there an acceptable revisit rate to maintain coverage of previously catalogued and newly discovered objects?
- What is the longest time interval that an object may go unobserved? Given the degradation in accuracy over time of Two Line Elements (TLEs) propagated using the Simplified General Perturbations No. 4 (SGP4) algorithm, which objects may suffer from unacceptable position accuracy that could lead to unidentified conjunctions or even objects being declared lost?

A suitable approach to exploring this problem is modelling and simulation. Therefore, the metrics chosen to answer these questions needed to be computable in a modelling and simulation environment. AGI's STK software [5] was chosen as the engine for the simulations. STK was originally developed to solve problems involving Earth orbiting satellites. Over the years it has been expanded to cover modelling and simulation of air, land and maritime environments in addition to space. STK was selected since it can accurately model satellite orbits and determine visibility between ground and space objects. Computations were based around access[3] calculations in STK. This is essentially a geometric line of sight calculation with additional constraints imposed including the field of regard of the sensor, atmospheric refraction and lighting.

The metrics used to assess the potential sensor performance and answer the questions above were:

- *Observable objects*: The number of potentially observable objects, *i.e.* the number of objects (represented as percentage of the catalogue) observed over the simulation period.
- *Frequency of observations*: Also referred to as the number of accesses or orbits observed. This represents the number of times a given object is observed (percentage of orbits observed) over the simulation period.
- *Observation gaps*: The time interval (or number of orbits) between consecutive observation opportunities for a given object.

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[2] The metrics and problem solving approach described here have been published in a paper [6] by the author in the Australian Defence Operations Research Review. This is an internal Australian Defence publication.

[3] The term 'access' refers to visibility from one object (*e.g.* a sensor) to another object (*e.g.* a satellite) based on constraints placed upon them in the scenario.

These metrics allow determination of the theoretical maximum performance of a given sensor or network to observe objects in the space object catalogue. These metrics do not assess the capability of the sensor to track the objects since the actual operation of the sensor is not explicitly modelled. For example, a given sensor may not be capable of tracking all objects within the field of regard over a given time period. This may be due to the time required to acquire and process an object track, or limitations in the field of view of the sensor or its ability to rapidly shift its field of view. It is also assumed that an object can be observed by a given sensor if it satisfies the access constraints imposed regardless of its size, radar cross section or visual magnitude since these aspects are not modelled.

4. ASSESSING OPERATIONAL PERFORMANCE

The assessment of the operational performance of sensors against the metrics described in the previous section was accomplished using modelling and simulation. STK software was used to propagate the orbits of objects contained in the space object catalogue, model the sensors for observing space objects, compute visibility between sensors and space objects, and compute the performance metric results.

The simulation developed was controlled by a MATLAB script that sends commands to and receives output from STK. Microsoft Excel spreadsheets were used to manage the input and output files. The simulation flow diagram is shown in Figure 2. The inputs, outputs and processes are aligned with the software tool used to perform each task. The simulation consists of four components aligned to the columns in the diagram:

- Define and generate the STK scenario
- Import and create sensor models
- Import orbital elements sets and propagate satellite orbits
- Compute access and generate output results

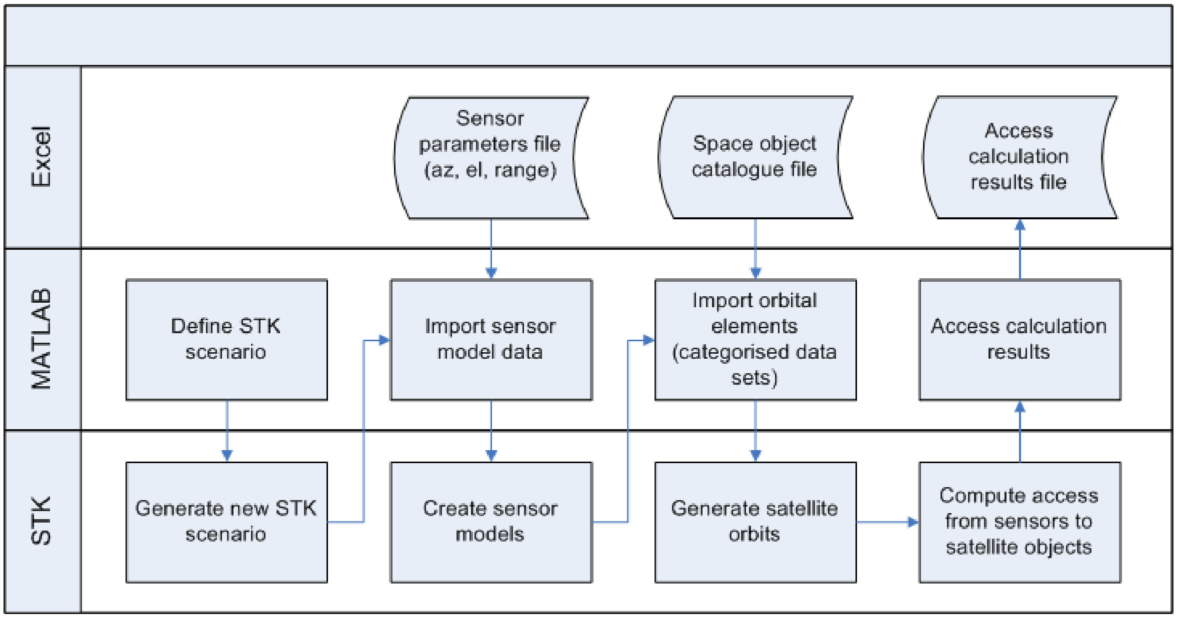

Figure 2. Simulation flow diagram

The operational performance assessment considered the effects of variations in sensor range, elevation and operating hours of radar, passive optical and laser type sensors at varying locations within the Australian region. Radars and laser trackers are active systems, so their performance is primarily limited by the requirement that the object being tracked is within the sensor's maximum operating range. These systems can be constrained by operating hours due to cost, staffing or other tasking even though they can be capable of operating continuously throughout the day and night. Optical telescopes operating in the visible spectrum are instead limited to operating during the terminator periods. This requires objects being tracked to be illuminated by the sun while the sensor site is in darkness[4]. These conditions occur just before dawn and just after dusk.

When observing LEO objects from the ground, the rotation of the Earth makes observability performance essentially independent of site longitude. Therefore, a representative set of Australian sites was chosen for the simulations to span the full range of latitudes from Cape York, Queensland, to Casey Base in Antarctica. The set (Figure 3) includes the locations of the existing and proposed Australian SSA sensors discussed in Section 2 along with some further hypothetical locations, such as Casey Base.

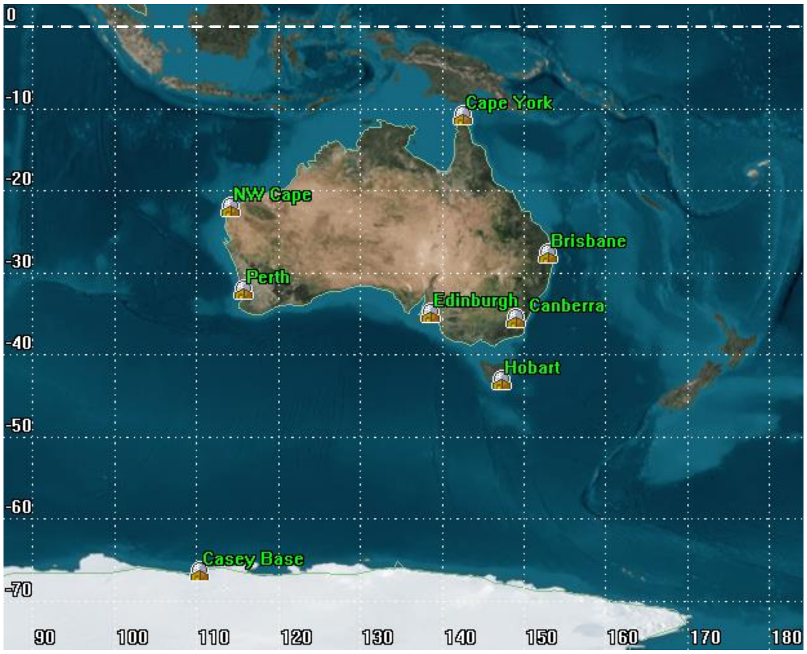

Figure 3. A representative set of Australian SSA sensor locations. The dashed white line represents the equator.

As mentioned previously, three different types of sensor are considered in the analysis for conducting surveillance of space objects: passive optical, laser and radar. The system constraints placed on each of these sensor types in the analysis is presented in Table 1.

Table 1. Sensor types and system constraints

Parameter / Sensor Type	**Passive Optical**	**Laser**	**Radar**
Minimum elevation	20 degrees	20 degrees	10 degrees
Maximum range	Unconstrained for LEO	2000 km	Unconstrained for LEO
Operating hours	Terminator periods where the object is sunlit and the sensor site is in darkness	Terminator periods where the object is sunlit and the sensor site is in darkness	12 hours per day
Minimum observation time[5]	30 seconds	30 seconds	30 seconds

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[4] For this analysis site darkness is considered to be nautical twilight, which occurs when the sun is at least 12 degrees below the horizon [7]. This is modelled in STK by setting the maximum sun elevation angle from the sensor site for access calculations to -12 degrees.

[5] This refers to the minimum time that an object must be visible to the sensor based on access constraints to be considered observable. This is used to account for target acquisition and tracking time required by a sensor observing space objects.

5. RESULTS

Simulations used space object catalogue data from Celestrak [8] and corresponding TLEs from Space-Track [9]. While both websites essentially contain the same information that forms the space object catalogue, the data from Celestrak was used in addition to the Space-track TLEs since it could be easily imported and manipulated in an Excel spreadsheet for input into MATLAB. Simulations were run for 30 days duration. Due to computational limitations at the time it was not possible to run the simulations for longer. However, seasonal variations can have a significant effect on the performance of optical systems. To compensate for this effect it is necessary to either run a longer simulation (say over a period of at least one year) or run multiple simulations over different months. Results are presented here for optical systems using simulations run during both winter and summer months to show these seasonal variations in performance.

Simulations commenced on the first day of the months of December 2013 (southern hemisphere summer) and August 2014 (southern hemisphere winter) at 00:00 UTC. These input data sets were used in previous analyses. Objects were propagated forward over 30 days using the SGP4 algorithm implemented in STK. A single TLE was used for each object and not updated during the simulation. TLE data sets were downloaded from Space-Track corresponding to the first day of each month considered in the simulations.

The performance of individual sensors for observing objects in the catalogue (first metric) was extremely good across all locations for the radar type sensor, but varied considerably for the passive optical systems depending on the month. Figure 4 shows the percentage of observable objects in LEO for different sensor types at each of the locations shown in Figure 3. The December 2013 optical result for Casey Base is not shown since for this month no objects in the LEO catalogue were observable.

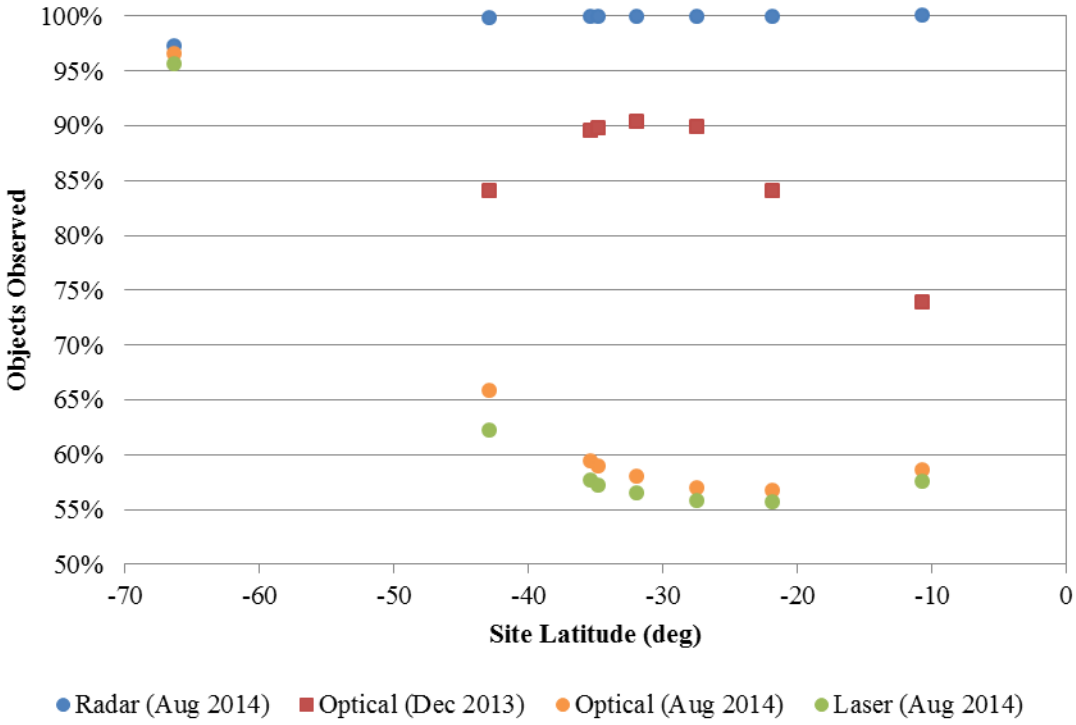

Figure 4. Observable objects for different sensors types and locations

Excluding some optical results for Casey base, the frequency of observations decreases as the site approaches the equator (Figure 5). This is most likely due to sites further away from the equator being able to observe more orbits of objects in the highly populated sun synchronous orbital region (around 98 degrees inclination). The results for Casey base show both the overall advantages of high latitudes for all sensors, along with the degree to which these advantages are heavily modified by seasonal factors for optical sensors.

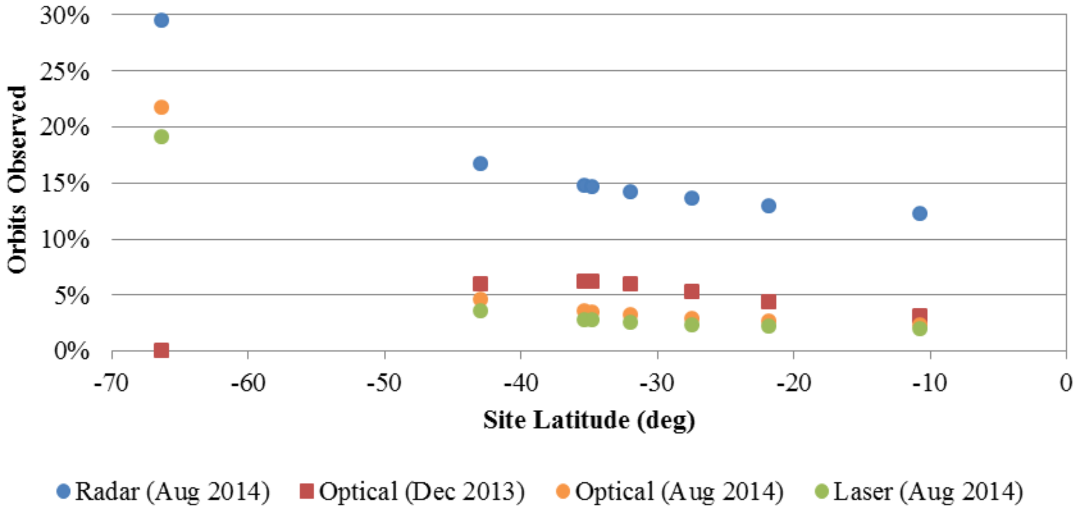

Figure 5. Frequency of observations. Shown as observable orbits for different sensor types and locations.

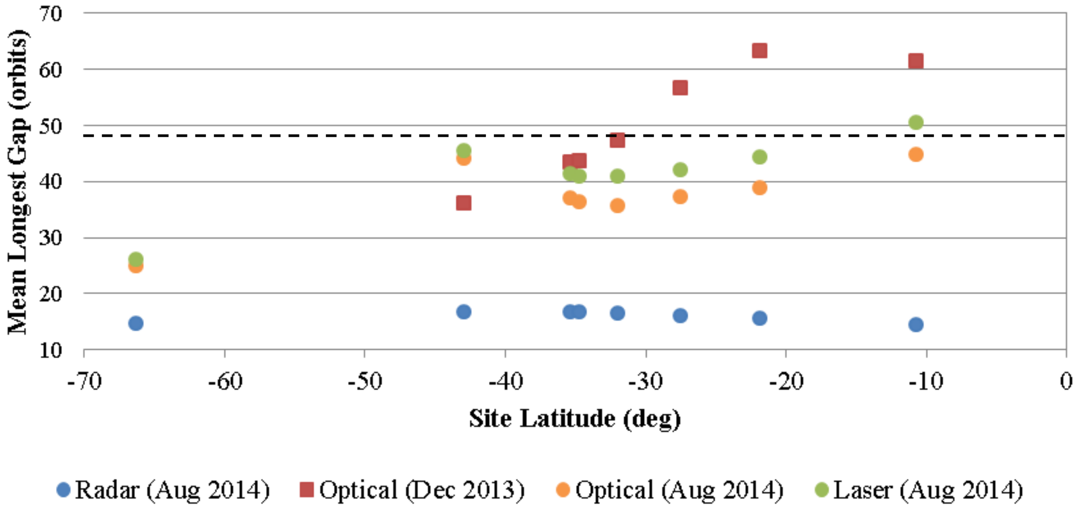

Figure 6. Mean across all objects of the longest observation gap for different sensor types and locations. For a typical LEO orbital period of 90 minutes, 48 orbits (dashed line) is the equivalent of 3 days.

Performance differences between optical and radar sensor types are primarily due to their hours of operation. While passive optical systems are restricted to operation during the terminator periods, radar sensors can potentially operate continuously throughout the day and night. The effect of radar operating hours at North West Cape on observed objects and orbits, and access gaps are shown in Figures 7 and 8 respectively. There appears to be minimal benefit in operating a radar for more than 12 hours per day in terms of the percentage of the catalogue that is observable (Figure 7). Longer operating hours will, however, provide more opportunities to observe objects. Similarly, access gaps increase significantly as operating hours are reduced below 8 hours per day (Figure 8).

A dashed line is shown in Figures 6 and 8 to represent the number of orbits that a LEO object with orbital period of 90 minutes would be unobservable for 3 days. Figure 8 shows that a mean longest observation gap of less than 48 orbits (the dashed line) is achieved when operating for at least 8 hours per day. Long gaps between observations of space objects could lead to unacceptable position accuracies. However, TLEs propagated forward for 3 days still have reasonable accuracy. A study by Gangestad *et al.* [10] comparing positional differences of propagated TLEs and high precision Global Positioning System (GPS) fixes for a CubeSat formation orbiting at 480 by 780 km altitude showed that the error growth for TLEs can be in the order of 25 km along track and 1 km both cross-track and radially after propagating forward 3 days. Although error growth for the along track component was shown to grow exponentially and be much more significant than for the cross-track and radial components. A study investigating the accuracy of TLEs for the GPS constellation by Kelso [11] showed a similar trend in error growth although there was significant variation between the different satellites analysed.

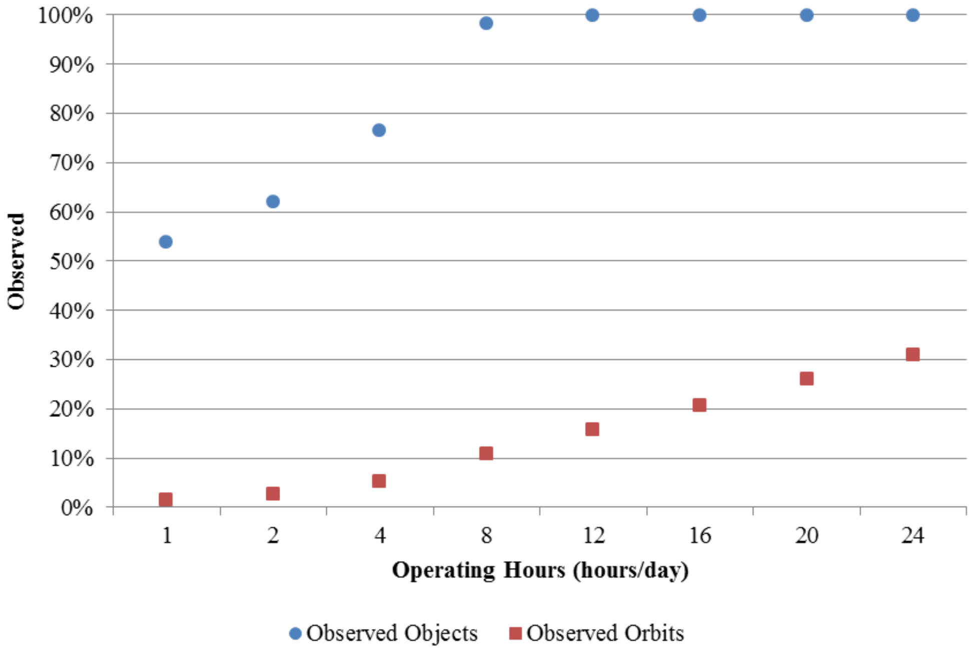

Figure 7. The effect of radar operating time on observed objects and orbits at North West Cape, Western Australia

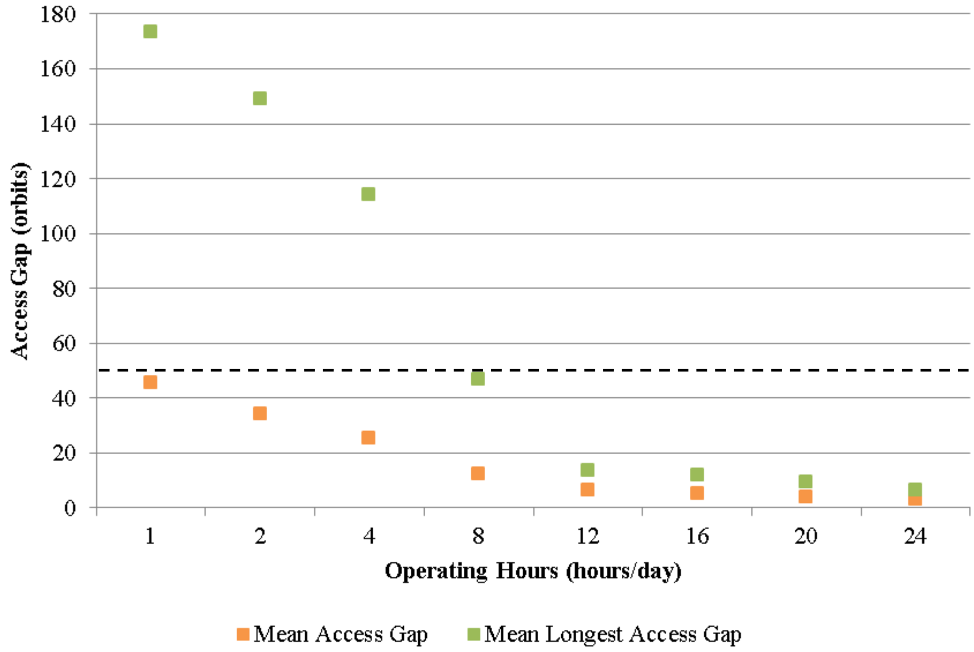

Figure 8. The effect of radar operating time on access gaps for North West Cape, Western Australia. For a typical LEO orbital period of 90 minutes, 48 orbits (dashed line) is the equivalent of 3 days.

Range limitations can also impact performance of radars and laser sensors. Simulation results varying the maximum range parameter in Table 1 between 200 and 2000 km showed that a range of at least 1500 km is required for adequate observability performance of LEO objects[6]. The results presented above for the laser sensor were range limited to 2000 km. When compared to the optical sensor for the same month, there was a slight degradation in observability performance although this was not significant. The proposed C-Band radar at North West Cape is not range limited for objects in LEO.

The third system constraint explored was elevation. Radars are capable of operating very close to the horizon (down to a minimum elevation of 5 degrees or less) but can be restricted by terrain obscuration or radiation safety requirements. Telescopes can also be affected by terrain obscuration but are primarily limited from operating close to the horizon due to atmospheric distortion. Typically telescopes conducting SSA will operate at elevations of at least 15 to 20 degrees. The elevation constraint had the least impact on observability performance compared with range and operating time constraints. When the minimum elevation was increased from 5 to 45 degrees, there was a small decrease in the percentage of objects observed but the frequency of observations decreased significantly.

6. CONCLUSIONS

This paper presented an overview of some of the SSA operational analyses conducted within JOAD, DST Group of the Australian Department of Defence. The work to date has explored the operational performance of Australian-based sensors for observing objects in the unclassified space object catalogue. A modelling and simulation approach was employed using STK software to develop high-level models of sensors and their locations and run simulations to determine which objects in the current catalogue could be observed, how often they are observed, and the duration between consecutive observation opportunities for each object.

The simulation results revealed that for the Australian mainland latitudes there was minimal variation in the percentage of observable objects for the radar type sensor, which could observe almost all objects in the LEO catalogue. For the optical and laser sensor types, there was significant variation due to seasonal effects.

Performance determinants of sensor systems, such as range, elevation limits and operating hours, were also explored given the impact they can have on observability performance. The key result discovered was that operating a radar type sensor for more than 12 hours per day gave little or no increase in the percentage of observable objects but did provide more observation opportunities of the objects that are observable.

7. FUTURE WORK

The focus of this work, undertaken within the DST Group JOAD program, has been on operational analysis studies assessing the observability of objects in the catalogue by independent sensors. However, the more important question of how Australian based sensors might add value to an existing network such as the SSN is yet to be answered. This will be explored in future studies but will require better information to model existing SSN sensors and development of new metrics for assessment. The first step in this process might be to develop sensor diversity metrics to determine which parts of an orbit are observed by globally dispersed sensors. Orbital estimation accuracy is significantly improved when an object is observed at different points around its orbit [12]. This could be achieved by either observing both ascending and descending passes from a single site, or by observing the object from widely separated locations, although a suitable metric to analyse this is yet to be developed.

Another consideration for this work is optimising locations for a network of Australian SSA sensors. Initial work has applied the modelling and simulation techniques described here to determine the best locations for a second SSA sensor in the Australian region if the location of the first sensor is fixed at North West Cape, Western Australia. This work will be expanded to consider multiple sensors in an indigenous network and how they might produce an independent space object catalogue.

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[6] A sensor with a maximum range of 1500 km and operating for 12 hours per day still observed around 95% of objects in the LEO catalogue for the August 2014 simulation.

Analysis to date has also been restricted to observability of objects in the LEO catalogue; however, other orbital regimes are also of interest. In particular there are plans to extent this analysis to consider objects in highly elliptical orbits with a perigee over the southern hemisphere. These objects are of particular interest given that they are difficult to accurately track at high altitudes when they pass over sensors situated in the northern hemisphere.

For optical systems, the analysis has considered some aspects of the seasonal variations that affect their performance. Comparisons have been made by running simulations for different months of the year, but in order to properly account for these effects simulations need to be run for a longer duration (at least one year) or for every month of a year. Additionally environmental effects, such as cloud cover, significantly impact the operation of optical systems and need to be incorporated into the simulation and analysis for selecting suitable sensor locations.

Finally, to assist decision makers in selecting the best locations for SSA sensors, additional trade-offs need to be included in the assessment. In addition to object observability which has been the primary focus of this work to date, future work will need to consider other factors and constraints including but not limited to cost, facilities, infrastructure, maintenance and staffing. Multi-criteria decision making could be a useful tool for this type of assessment.

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