Findings from the UK and Canadian Space Situational Awareness (SSA) Experimentation during the Relocation of SKYNET 5A Satellite

Andrew Ash
UK Defence Science and Technology Laboratory
Lauchie Scott
Defence Research and Development Canada
Will Feline
UK Defence Science and Technology Laboratory

ABSTRACT

This paper describes the planning, execution, analysis and lessons identified from a collaborative Space Situational Awareness (SSA) experiment to observe the SKYNET 5A satellite during a series of orbital manoeuvres that occurred in the summer of 2015. In March 2015 Airbus Defence and Space (Airbus DS) announced its intention to relocate the SKYNET 5A satellite from the Atlantic to the Asia Pacific region to increase its global coverage; this provided an opportunity to observe this high value asset to explore the challenges and technical solutions related to deep space SSA. Within the UK the Defence Science and Technology Laboratory (Dstl, part of the UK Ministry of Defence) were established as the lead agency to plan the observation campaign utilising operational and emerging experimental SSA capabilities. The campaign was then expanded to involve Canada, the United States and Australia under the auspices of the Combined Space Operations (CSpO) Memorandum of Understanding (MOU) to further explore the coordination of observations between operational systems and potential fusion of data collected using experimental SSA assets. The focus for this paper is the collaborative work between Dstl and Defence Research and Development Canada (DRDC) that featured a period of experimentation to explore methods that enable cross cueing between ground-based and space-based SSA sensors, namely the UK Starbrook facility (located on the island of Cyprus), and NEOSSat/ Sapphire space surveillance satellites located in low-Earth orbit. A number of conclusions and lessons are identified in this paper that seek to inform the wider SSA community on the challenges, potential solutions and benefits of operating a distributed SSA architecture such as the one utilised during this experiment.

1. INTRODUCTION

In spring 2015, Airbus Defence and Space (Airbus DS) announced its intention [1] to relocate the SKYNET 5A geostationary communications satellite from its operating longitude at 6° east to a destination longitude of 95° east. This orbital relocation was motivated by commercial reasons to enhance the global coverage of the SKYNET constellation and hence offer excess capacity to SATCOM commercial users [2]. Airbus DS provides SATCOM for UK forces as part of a commercial agreement with UK Ministry of Defence (MOD) via the SKYNET constellation; given the importance of SATCOM to the MOD the health and status of satellites within this constellation is of high importance to the UK and has led to an increased interest in deep-space Space Situational Awareness (SSA). This event provided a rare opportunity to examine SSA issues against an asset of high interest to UK MOD during a period of significant orbital manoeuvres. Within the UK an experiment was initiated by Dstl (part of the UK MOD) to examine the challenges and potential solutions related to deep-space SSA during the SKYNET relocation; consequentially the experiment was referred to as the SKYNET Observation and Relocation Experiment (SORE). A number of operational and experimental ground-based SSA assets available to the UK were identified as candidates for the observation campaign, with focus placed on the Starbrook system operated by Space Insight Ltd.

In addition to the UK component, the experiment included collaboration from the Canadian space-based space surveillance satellites *Sapphire* and *NEOSSat*. The space-based observations were complemented by ground-based data collected by US and Australian sensors from June to August 2015 to characterise SKYNET 5A during the relocation operation. Measurements from the space-based sensors consisted of orbital position (metrics) and object brightness (photometric observations) to characterise SKYNET 5A's trajectory and signature offering a first look at these new space surveillance capabilities. This interchange also enabled the first international cueing of the NEOSSat sensor using ground-based tracking data acquired from the UK Starbrook telescope asset.

The technical interchange between partner nations enabled by the Combined Space Operations (CSpO) agreement revealed lessons-learned applicable to the wider SSA research and operational communities. These findings are described in this paper with an emphasis on the procedure used to establish global SSA observations and the maintenance of orbit custody on a high-value deep-space asset performing significant orbital operations. Recommendations for future SSA practices are identified.

2. EXPERIMENT DESIGN

The experiment was designed as follows:

- Initial planning phase: Dstl in consultation with UK agencies, sensor operators and international partners identified participants for the experiment and specified objectives. This occurred from around February 2015 to April 2015,
- Testing and preparation phase: Initial processes and procedures related to the tasking of sensors and exchange of data were exercised during the period April 2015 to July 2015 prior to the initiation of the SKYNET 5A relocation. This provided an opportunity to de-risk the planned activities during the main experimentation period as well as collecting baseline data to enable comparisons of orbit estimation and signatures of the target,
- Execution phase: Observation of SKYNET 5A and other targets of opportunity to examine the technical challenges identified during the planning phase,
- Analysis phase: Examine orbit estimation, sensor performance and other aspects of deep space SSA in alignment with experiment objectives; this work is currently ongoing with interim results presented in this paper.

3. PLANNING PHASE

A number of specific objectives were identified during the planning phase for SORE, these included the following:

- Explore the utility of operational and experimental sensors to support deep-space SSA missions.
- Identify the technical and procedural barriers to the effective coordination of SSA sensors within the CSpO community and trial solutions to address them.
- Promote enhanced coordination between government, SSA sensor operators, R&D community and commercial operators to improve SSA mission effectiveness.

In order to address the above points it was necessary to identify candidate SSA sensors that may enhance deep-space SSA that are accessible to the R&D community and hence able to participate in this experiment. Given the nature of the relocation, this required ground-based assets to be positioned sufficiently close to the ground track of SKYNET 5A to enable observation, or the use of space-based sensors that can observe the geostationary region. Based on these criteria, and after consultation with relevant agencies, the following sensor assets participated to varying degrees during SORE:

- Starbrook, Cyprus,
- Space Geodesy Facility, Herstmonceux UK,
- NEOSSat, space-based,
- Sapphire, space-based
- GEODSS, Diego Garcia
- DSTG Experimental EO facility, Adelaide AUS,

- Dstl Experimental EO facility (AP113), Salisbury UK.

The relocation of SKYNET 5A offered an excellent campaign tracking object for the Canadian space-based sensors as it exemplified their capability to track objects anywhere in geosynchronous orbit. SKYNET 5A's manoeuvres were not visible from North America making Canada's contribution a space-based one.

The following sub-sections provide some details on the major UK and Canadian contributing SSA sensor assets.

Starbrook

The Starbrook facility is owned and operated by Space Insight Ltd. and located on MOD premises on Cyprus. It consists of three astrographs – optical telescopes which take astronomical photographs. Two sensors operate from UK retained sites on Mt Troodos at around 1775m altitude and on Mt Olympus at approximately 2000m altitude.

Starbrook was designed as a surveying instrument for geostationary satellites, but is also capable of tracking satellites in orbits ranging from near Earth to deep space. The instrument is a computer-controlled refractor telescope housed in a windowed dome. A windowed dome is unusual but does permit the facility to operate in a wider range of weather conditions: wind and condensation are less problematic than for an open dome.

Starbrook can be reconfigured to optimise the observations to the customer's requirements. A typical configuration provides a field of view of 5°×4°, allowing 500 deg^2 to be surveyed per hour. This gives an angular resolution of approximately 6.3"/pixel.

Fig. 1. The Starbrook domes at Troodos, Cyprus.

Starbrook operates from a geographically advantageous location: at a longitude of 32.9°E and latitude of 34.9°N it is relatively close to the equator and can observe the area of the GEO belt of where the SKYNET constellation is largely based. Starbrook's high altitude positions the sensor above much of the atmosphere, resulting in improved visibility conditions. Weather conditions on Cyprus are significantly better than in the UK, although they do deteriorate during the winter months. This provides some mitigation against the principal disadvantage of optical sensors: that their availability is weather-dependent and thus unpredictable.

Starbrook has relatively mature data analysis capabilities. This is a major element of any sensor's capabilities. For the analysis of optical data, the following steps are typically required and can be performed by Starbrook:

- **Co-ordinate transformation**: This is required to translate from the local image pixels to the celestial system of right ascension and declination. This generally uses a process known as astrometry to pattern-match the background stars to a star catalogue.

- **Object detection and identification**: Space objects of interest must be identified, typically by virtue of their motion causing them to streak against a background of stationary stars (or vice versa). Second, the object must be identified; typically by comparison of the object's measured celestial position against orbits within a catalogue, either based on the SATCAT or indigenously generated orbits from previous observations.

- **Orbit determination**: Once correlated, multiple observations can be used to determine updated orbital parameters for the catalogue, either to those obtained from the SATCAT or against a set of locally stored orbital elements on uncorrelated objects.

An example of the output from the Space Insight processor is shown in Figure 2; this corresponds to an observation of SKYNET 5A during a transit in front of an Astra cluster in GEO.

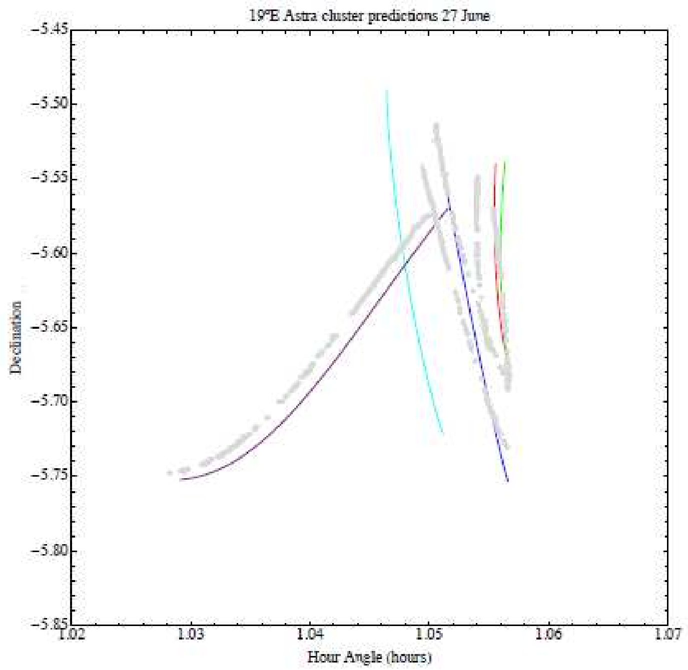

Fig. 2. Example output based on Starbrook observations of Astra cluster, coloured lines indicate tracks based on TLEs; Starbrook observation data is shown as grey markers.

Herstmonceux Space Geodesy Facility

The Space Geodesy Facility (SGF) is located at Herstmonceux in East Sussex. The facility is operated by the Natural Environment Research Council (NERC). Two systems are currently operational which can produce measurements relevant to the SSA community. These are the Geostationary Observation Facility (GEOF) and the Satellite Laser Ranging (SLR) facility, detailed in Table 1.

GEOF is an astrometric system with a 16'×16' field of view and a pixel size of 0.7"×0.9". It provides accurate V-band photometric data and has an experimental astrometry capability initially deployed in 2015. SORE provided an opportunity to test and make improvements to this astrometry system during the observation period.

Table 1: Characteristics of systems located at SGF Herstmonceux.

	SLR Telescope	**GEOF**
Mission	Acquisition and tracking of LEO, MEO targets to allow use of SLR	Observation of targets in GEO

Aperture	50cm	40cm
Field of View	2 x 2 deg^2	0.27 x 0.27 deg^2
Limiting magnitude	~10^{th} (although filter limited to ~8^{th})	~15^{th}

GEOF has been used to collect photometric signatures on targets for a number of years and in that respect can be considered a fairly mature capability. The SLR facility at Herstmonceux (see Figure 3) performs accurate high-speed V-band photometry and accurate positional measurements. The system outputs accurate local horizon (azimuth/elevation) coordinates, but could be extended to produce accurate results for topocentric right ascension and declination. The system does not perform imaging so cannot provide information on multiple targets in its field of view.

Fig. 3. The SLR facility at NERC Herstmonceux [7].

Sapphire

Sapphire is the operational space surveillance capability of the Canadian Armed Forces and is a contributing sensor to the US Space Surveillance Network [4]. The satellite is based on the Surrey SSTL 150 bus with a mass of 148 kg and is approximately 1 m^3 in size. The payload is a 13 cm, three-mirror, visible-band telescope designed to track deep space objects in GEO and Highly Elliptical Orbit (HEO). The instrument field of view is 1.4x1.4 $degrees^2$. Sapphire can detect objects to magnitude 16 in geosynchronous orbit. Sapphire downlinks its imagery to its image processing system via S-band radio downlink using antennas in Abbotsford, British Columbia and Surrey, UK. Sapphire responds to catalogue maintenance tasking messages issued from the Joint Space Operations Centre (JSpOC). The sensor is tasked via the Sensor System Operations Centre (SSOC) located at Royal Canadian Air Force Base 22-Wing North Bay, Ontario. Figure 3 shows the general arrangement of the Sapphire space segment during pre-flight testing in 2012.

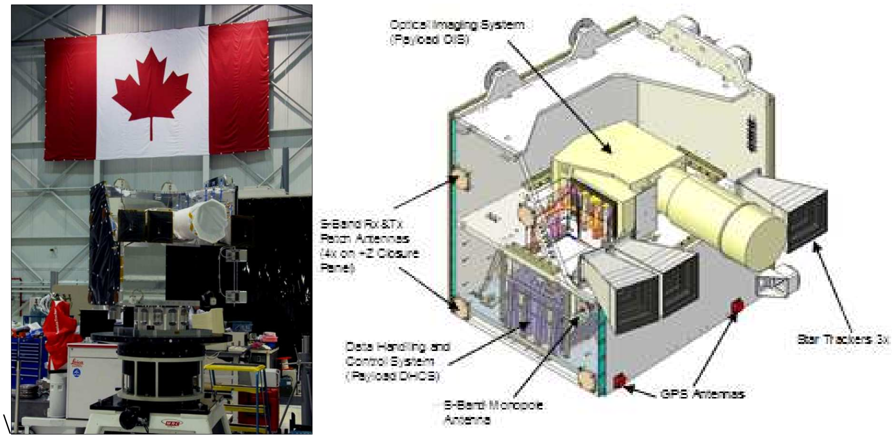

Fig. 4. Sapphire Satellite (Canadian Department of National Defence)

NEOSSat

The NEOSSat microsatellite (Figure 5) was launched into a 785 km dawn-dusk orbit on 25 February 2013 and is a joint project between DRDC and the Canadian Space Agency. NEOSSat is an experimental platform designed to perform space surveillance and Earth-orbit crossing asteroid astronomy observations [5]. The microsatellite was developed by Microsatellite Systems Canada Incorporated (MSCI). NEOSSat weighs 72 kg and has dimensions of 1.4 x 0.8 x 0.4 meters. The spacecraft's instrument is a 15cm on-axis Maksutov visible-band telescope equipped with an external baffle to suppress stray light. The baffle and vane configuration enabled the microsatellite to track space objects within 45 degrees of the Sun.

Fig. 5. NEOSSat Microsatellite (Image credit: University of Calgary, Canadian Space Agency)

4. EXPERIMENT EXECUTION

Execution of the experiment was conducted over the period of June to August 2015, and featured several trial periods during which specific aspects of the deep-space SSA problem were explored. A top-level calendar of events is described below:

- 8th June 2015; observation period initiated by participating sensors,
- 15th June 2015; routine SKYNET 5A station keeping manoeuvre,
- 17th June 2015; orbital burns to reduce SKYNET 5A apogee/ perigee and circularize orbit,
- Fortnightly station keeping manoeuvres by Airbus DS to ensure SKYNET 5A maintains North-South positioning,
- 10th July – 15th July 2015; Dstl-DRDC cueing experimentation period featuring Starbrook and NEOSSat,
- 20th August 2015; orbital burns by SKYNET 5A to begin insertion into 95E slot,

- 25th August 2015; final orbital insertion manoeuvres of SKYNET 5A,
- 29th August 2015; final SORE observations by participating sensors.

Dstl acted as the lead agency coordinating efforts with the UK as well as across CSpO nations; this required close working relationships with research agencies in the other participating nations, namely DRDC (Canada), DSTG (formerly DSTO, Australia) and AFRL (US) who each acted as the interface to their own military space operations centres. This was necessitated by the fact that Dstl had established a dialogue with the satellite operator at Airbus DS that enabled access to information related to the status of the relocation of SKYNET 5A (in particular manoeuvre event times and ephemeris) critical to overall experiment coordination. This information was required in order to enable efficient utilisation of the SSA assets participating in the experiment. The organisational structure for the UK-Canadian aspect of SORE is shown in Figure 6.

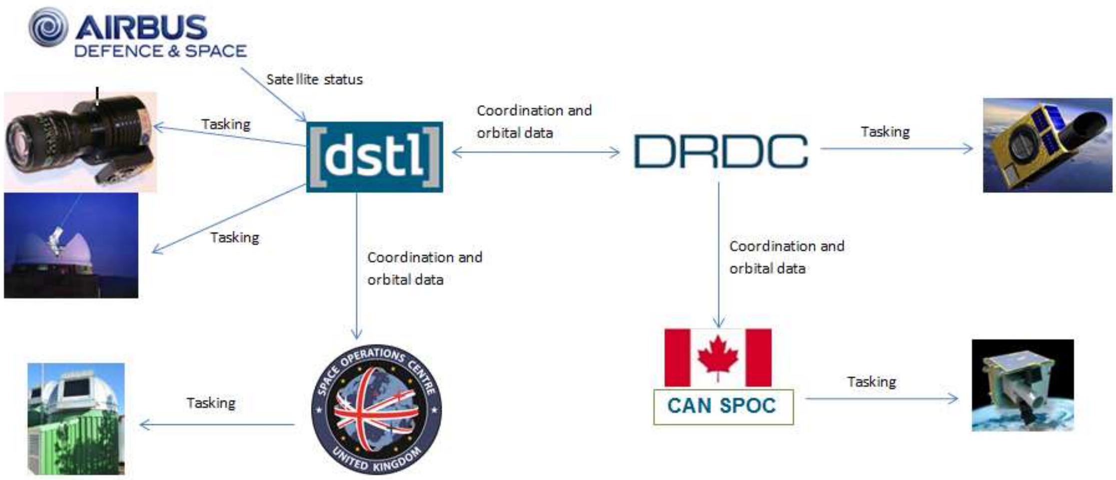

Fig. 6. UK-Canadian organisation during SORE.

Some of the specific challenges, and solutions adopted, during the experiment execution are presented below:

- The experiment featured the participation of several nations distributed globally across a large range of time-zones, this presented significant challenges to the coordination of the experiment, particularly given that the sensors utilised included a number of R&D systems that are manned periodically (unlike more persistent operational assets). To mitigate some of these issues, tasking for sensors was in part devolved to the space operations centers within each nation. This worked well during routine observation circumstances however additional S&T support for the more stressing elements of the experiment, such as cued tasking and post-manoeuvre recovery, were required.

- Short periods of coincident working office hours between participants constrained the execution of the experiment, and meant that real-time coordination was generally unfeasible. To address this, considerable effort was placed on advance planning between organisations and a long-term schedule was established to enable sensor tasking to be generated.

- Lack of a common IT systems/ networks between sensors and participants complicated the exchange of data and limited the ability to task sensors remotely using externally generated data. Data sharing was achieved via unclassified internet communication using by a mixture of a Dstl FTP site, DRDC SharePoint site and email. The SharePoint site formed the primary method of mass data exchange and proved to be well suited to this problem.

- There was uncertainty about the status and dynamics of the SKYNET 5A satellite trajectory during its orbital manoeuvres. This posed a risk that the experimental teams would lose custody of the asset between observation periods. To address this challenge Dstl established a dialogue with Airbus DS (UK) to enable access to information from the SKYNET satellite operations team to support sensor tasking. This was particularly important during the significant orbital manoeuvres performed to initiate and terminate the re-location between Atlantic and Pacific regions. A process was then established by which notification of the manoeuvres was provided to government agencies within the other CSpO nations to enable effective sensor tasking across the experiment participants. This worked well during the execution phase and enabled observations of SKYNET 5A during the challenging manoeuvre period.

Orbital Estimation and Data Sharing

Data from the sensors participating in the experiment were combined to estimate orbits for SKYNET 5A (and other targets observed within their field of view) using three methods:

1. Autonomous short-arc tracking and orbital estimation performed on Starbrook EO data performed by Space Insight Ltd. using an in-house astrodynamics software package.

2. Offline analysis of amalgamated data sets (Starbrook and Herstmonceux) using a sandbox astrodynamics suite of tools known collectively as the UK Mission Planner developed in-house by Dstl; which performs both General Perturbation (GP) and Special Perturbation (SP) orbital estimates and propagation.

3. Offline analysis based on observational data from NEOSSat and Sapphire using Orbit Determination Tool Kit (ODTK) developed by Analytical Graphics. This tool was utilised at DRDC to estimate both GP and SP orbits and to perform post-manoeuvre orbit recovery estimates.

For the ground to space cueing experiment orbital estimates were generated by Dstl and provided to DRDC. DRDC then tasked the NEOSSat microsatellite to perform its observations [6].

5. ANALYSIS

This section provides details on the post event analysis that has been performed on data collected during SORE; and highlights major findings on the performance of both sensors and orbital prediction techniques used during the experiment.

Analysis of Ground-based sensor data

Dstl utilised the in-house astrodynamics and data fusion tool suite (known as UKMP) to examine the utility of the Starbrook optical data in terms of orbit fitting. The analysis covers four distinct periods of time:

- Period 1, prior to relocation; 4th June 2015 to 15th June 2015,
- Period 2, during relocation; 13th July 2015 to 27th July 2015,
- Period 3, during final orbital manoeuvres; 25th August 2015,
- Period 4, after relocation; 25th August 2015 to 31st August 2015.

The analysis methodology developed aims to examine the errors associated with each data set available on the target; namely the satellite ephemeris (produced by Airbus DS using ranging data), the Starbrook observation and satellite catalogue information sourced from the US JSpOC. On board telemetry from Global Navigation Satellite Systems (GNSS) is unavailable for the SKYNET 5A satellite, so part of this analysis aims to determine what data may be used to provide 'ground truth' of its position to enable absolute quantitative assessment of the sensor perform and orbit estimation routines.

Data was generated from the experiment at different times using varying sources and quantities/ periods of observation data. Satellite ephemeris from Airbus DS was provided to the experiment on a weekly basis, generated based on radio ranging from the satellite to various terrestrial ground stations. Starbrook data was provided on a notional daily basis based on a previous night's observations, but this was dependent on external factors such as weather, visibility and other tasking priorities. TLEs were sourced from spacetrack.org, with those relating to SKYNET 5A accessed daily. Figures 7a and 7b show comparisons of positions from orbits derived from Starbrook to those from TLEs as referenced to Airbus DS orbits; covering a 4 day and 6 day observation period respectively

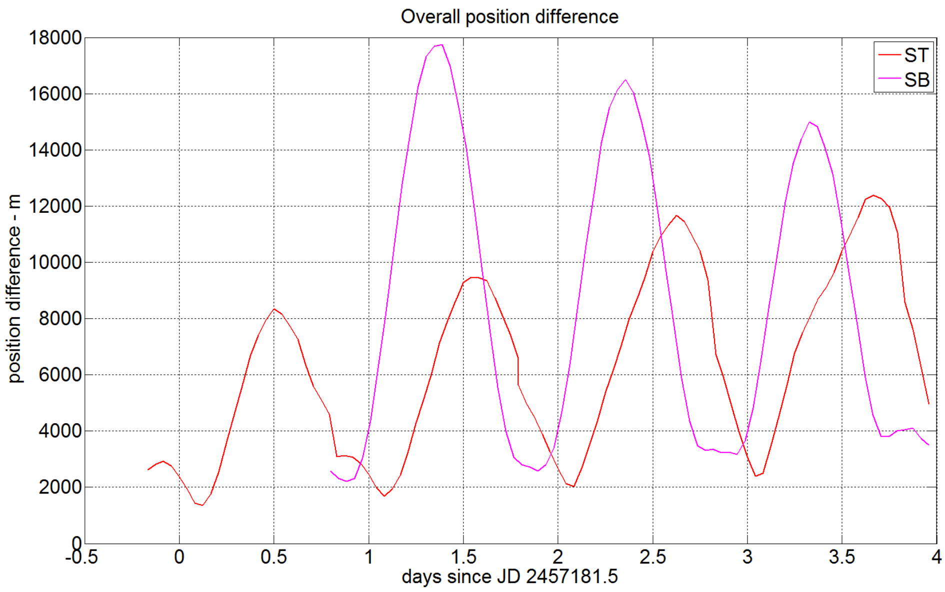

Fig. 7a: SKYNET 5A position comparing Starbrook derived Dstl orbital data (using UKMP), JSpOC TLEs and Airbus DS orbital data derived from RF ranging and telemetry.

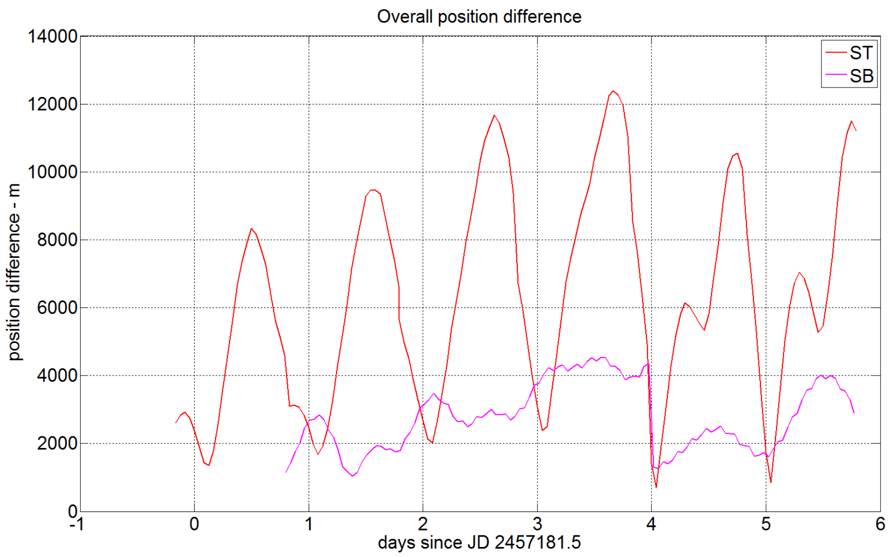

Fig. 7b. SKYNET 5A position comparing Starbrook derived Dstl orbital data (using UKMP), JSpOC TLEs and Airbus DS orbital data derived from RF ranging and telemetry. The discontinuity in the data observed at day 4 corresponds to an update in the SKYNET 5A ephemeris as supplied by Airbus DS.

From Figures 7a and 7b it can be observed that in general the orbits fitted to single-source ground-based EO observational data is in the order of a few kilometres. The orbit fit to 4 days of Starbrook data exhibits high degree of variation from the Airbus derived orbit which oscillates over the period of a day between around 10km and 2km, this corresponds to the observation times from Starbrook. When the orbit estimation is then performed over 6 days-worth of data (Figure 7b) it shows much better agreement with the Airbus DS data with differences of between 2km and 4km with limited diurnal variability. This suggests that the orbit has converged to a better solution with the addition of more observation data, and indicates the amount of single-source data required by this process to generate a reasonably accurate orbit.

Space Based Sensors (NEOSSat, Sapphire) Observations

The frequent manoeuvre profile for SKYNET 5A also presented a technical challenge for the space-based sensors to independently maintain orbit custody. By tracking this allied asset, the experimenters would learn the system capabilities of the space-based sensors to track geostationary objects performing both large (Δv > 1 m/s) and small (Δv ~ 0.1 m/s) manoeuvres.

Sample imagery from Sapphire and NEOSSat are shown in Figure 8 where SKYNET 5A's position is marked. As both space-based sensors tended to view Skynet 5A in the antisolar direction (on Earth's night side), at phase angles of 50 degrees or less, the brightness of SKYNET 5A was generally between magnitudes V_m ~ 10-12. This made SKYNET 5A relatively easy to track by small aperture telescopes and increased the pool of experimental systems which were able to perform metric tracking.

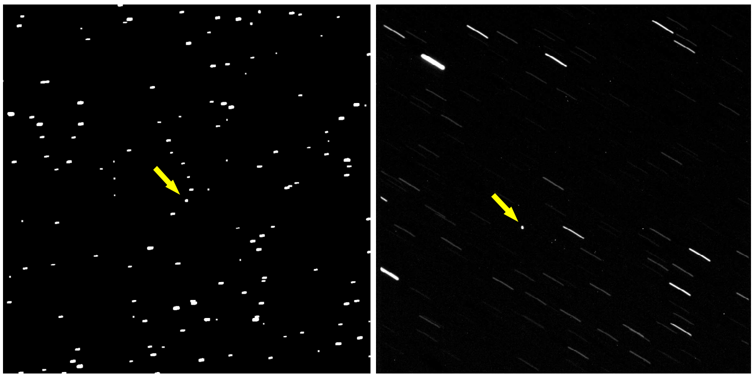

Fig. 8. *(Left)***:** Sapphire image of SKYNET 5A. *(Right):* NEOSSat image of SKYNET 5A from [6]

Figure 9 shows measurements residuals derived from the estimated orbit of SKYNET 5A using space-based tracking data. The vertical blue bars indicate periods where inflated process noise was added to the filter to force it to accept large measurement residuals. These intervals are times where manoeuvres are suspected to have been performed by SKYNET 5A. Manoeuvres were detected by looking for residuals exceeding the 3-sigma filter acceptance limits and adding process noise to that interval. This simple post-manoeuvre recovery strategy is a blunt approach to manoeuvre recovery but it enables the out-of-tolerance residuals to be accepted by the filter and to enable the filter to continue tracking on the object.

Figure 10 shows the position uncertainty derived from the orbit estimate generated on SKYNET 5A; it is worth noting that this does not constitute a measure of absolute error, the challenges of which were discussed previously. The intervals where the process noise was inflated resulted in high in-track position uncertainties during those timeframes. Manoeuvre recovery generally required two days of tracking to reduce the in-track position uncertainty to ~2 km. Manoeuvre free intervals in Figure 10 generally exhibit in-track uncertainty below 2 km. An improved way to handle unanticipated manoeuvres using space-based sensors is an open area of research.

The space based sensors are relatively well placed to sense small in-track manoeuvres (Δv < 0.1 m/s) as the object's resulting drift rates tend to not exceed the fields of view of the space-based sensor on tracks the following day. Larger manoeuvres, such as the drift orbit initiation and drift arrest, are more problematic as ground-based follow-up observations are generally needed to reestablish orbit track. While space-based sensors are well suited to catalog maintenance, they are limited in their ability to search for objects just outside of their fields of view.

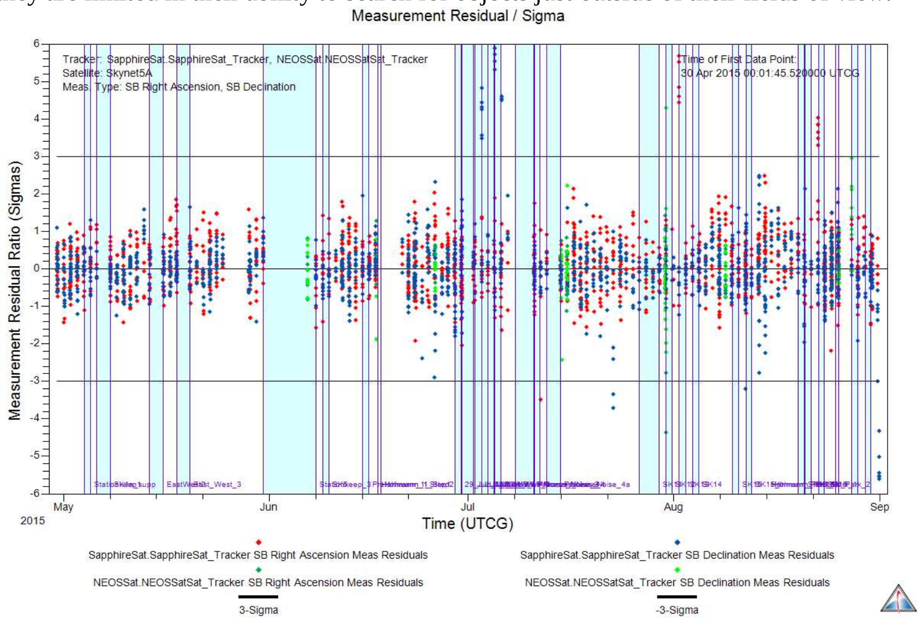

Fig. 9. Combined space-based Sapphire and NEOSSat tracking measurement residual ratios for SKYNET 5A

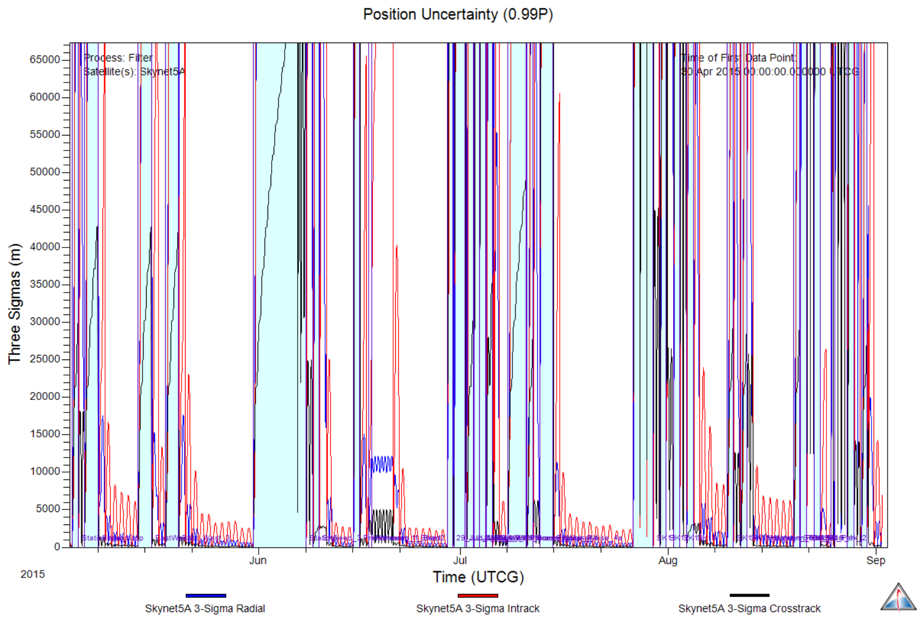

Fig. 10. Combined space-based tracking position uncertainty (3-sigma) on SKYNET 5A

Ground-based (Starbrook) Observations

Observations collected by Starbrook were utilised into the same orbit estimation software and the orbit custody performance of this sensor is inspected in this section. A noticeable characteristic of the residual ratios[1] plot (Figure 11) is the cadence of observations which tend to be more separated than the space-based residual ratios shown in Figure 9. This is attributed to weather outages. During August, after several in-track manoeuvres were performed, the observations residuals exceeded the filter's 3-sigma acceptance range (not shown on Figure 11) resulting in very high right ascension residuals that were fully rejected by the filter. However, during manoeuvre-free intervals, such as the timespan near 19 June 2015, Starbrook observations resulted in an orbit estimate with in-track uncertainties less than one kilometer (see Figure 12). Suspected manoeuvres, coupled with weather interruptions, tend to limit a single ground-based sensor's ability to maintain orbit custody. August observations would require a restart of the orbit estimation process by invoking a new initial orbit determination and restarting the filter at a later time. This was not performed in this analysis but is an option for future work.

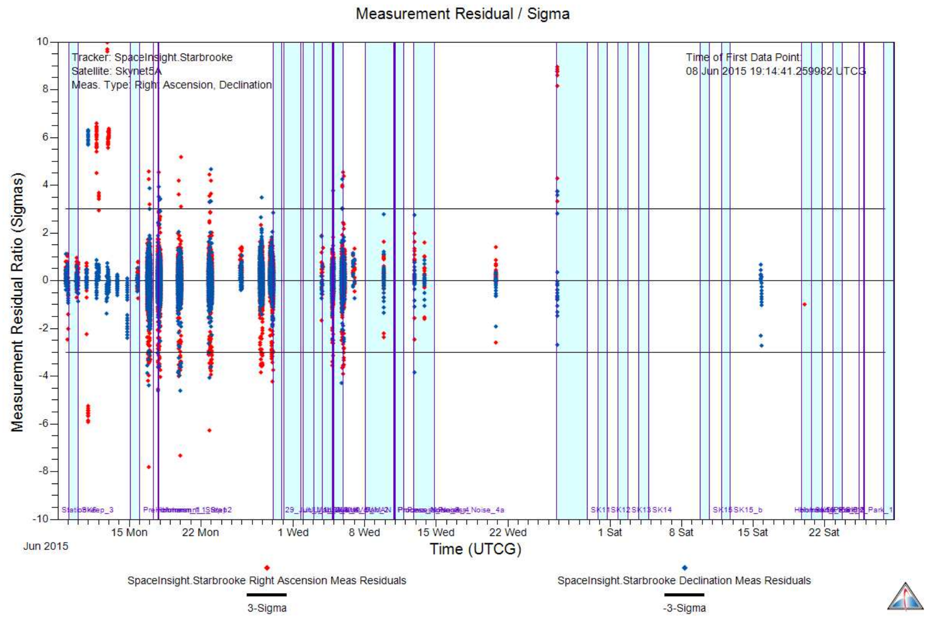

Fig. 11. Starbrook observations residual ratios plot

[1] Residual ratios are the difference between the raw sensor measurements and the measurements resulting from the estimated orbit. The residuals are scaled by the sensor's measurement noise (usually reported in sigmas)

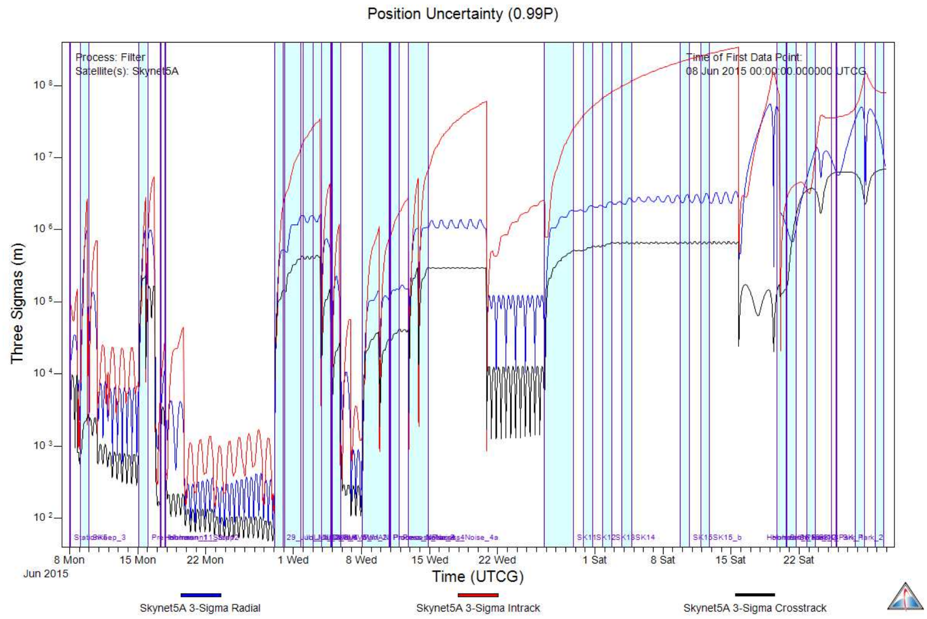

Fig. 12. Starbrook-only position uncertainty of SKYNET 5A (note-log scale on y-axis)

Starbrook and Space-based Observations, Fused Orbit Analysis

Combining space-based (Sapphire and NEOSSat) and ground-based (Starbrook) observations into the orbit estimation process resulted in residual ratios and position uncertainties plots shown in Figures 13 and 14. The space-based sensors can sustain near-daily orbit tracking during the gaps in Starbrook observations, enabling orbit custody to be achieved and accepting the August Starbrook measurements without needing to restart the estimation process. The best position uncertainty (see Figure 14) shows that the combined orbit uncertainty is a little more than 1 km in-track during manoeuvre-free intervals, consistent with the individual test cases in Figures 10 and 12. Some biases in Sapphire and Starbrook data are likely to be the cause of the slight increase in in-track uncertainty and is an open area of investigation.

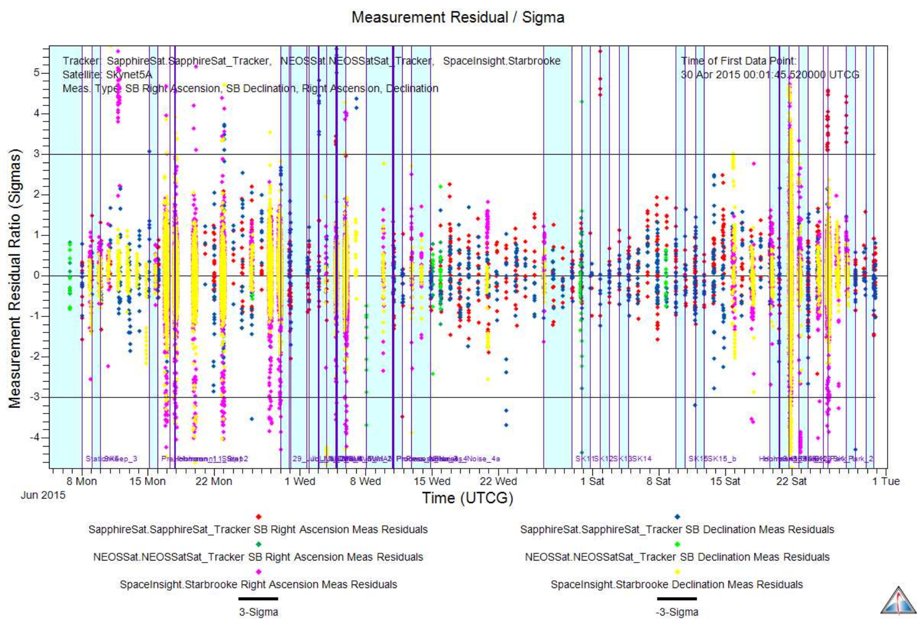

Fig. 13. Combined Space-Based and ground-based residual ratios plot

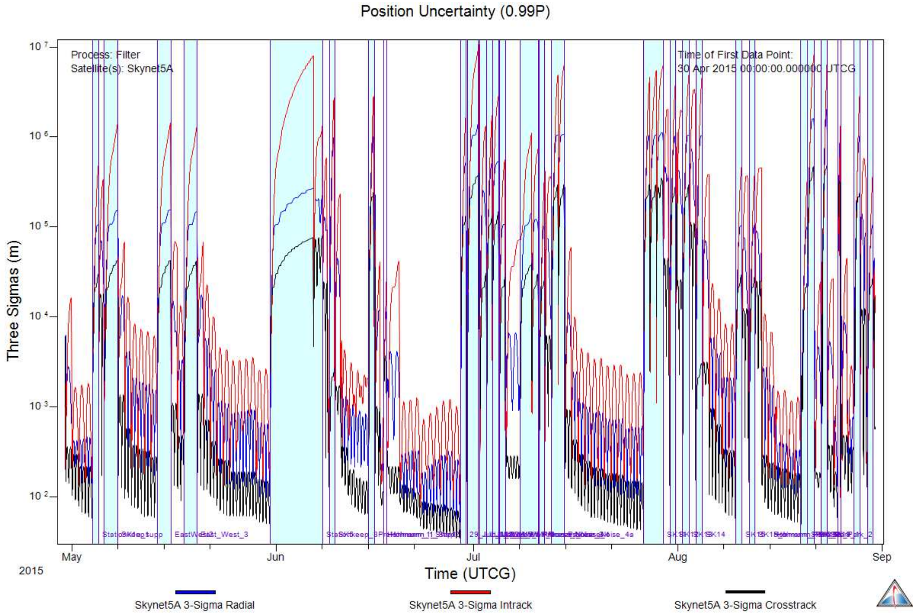

Fig. 14. Space-based and ground-based position uncertainty of SKYNET 5A (note-log scale on y-axis)

6. CUED OBSERVATIONS

Using Starbrook data, Dstl performed the first ground-based cueing of the NEOSSat sensor to track SKYNET 5A. Sample imagery collected by NEOSSat is shown in Figure 15. One of the issues in cueing space-based sensors is that there is a tasking lead time (2 days in NEOSSat's case) where the cue could be corrupted by a geostationary manoeuvre. If a manoeuvre occurred, NEOSSat would have tracked an empty area of space where SKYNET 5A *was* using the previous orbit estimate and SKYNET 5A could likely be drifting just outside the NEOSSat field of view. Fortunately, the NEOSSat cue experiment occurred during a manoeuvre-free interval resulting in a successful acquisition by the space-based sensor. Cueing works as long as the target geostationary satellite does not perform manoeuvres large enough to drift the satellite outside of the space-based observer's field of view [6].

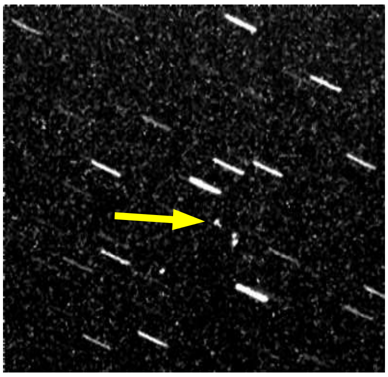

Fig. 15. NEOSSat image of SKYNET 5A (marked) passing the Turksat satellite cluster on 15 July 2015 (from [6]).

7. MAJOR FINDINGS

The measurement precision of Sapphire and Starbrook tended to be better than NEOSSat during this experiment. Sapphire and Starbrook data generally produced orbits of ~1 km of in-track uncertainty during the manoeuvre free intervals of SKYNET 5A tracking. NEOSSat, with its larger astrometric uncertainties, tended to exhibit position uncertainties of ~4-5 km in-track using orbits derived from its observations. This is attributed to the binned mode of acquisition used by the NEOSSat sensor in order to achieve higher observation throughput from the detector. NEOSSat added fewer measurements to the orbit estimate in comparison to Sapphire and Starbrook, hence the orbit quality is largely attributed to measurements by these two sensors.

The frequent manoeuvres performed by SKYNET 5A during the drift orbit phase were easily detected by the space-based sensors. The ground-based systems, which experience periodic weather outages, would have required a new initial orbit determinations to maintain orbit custody during later stages of the tracking interval (see Figure 11). This was expected as periodic tracking interruptions reduce a ground-based sensor's ability to maintain orbit custody. In contrast, the space-based sensors exhibit weakness during larger manoeuvres (drift initiation and drift arrest). In this case, ground-based sensors assisted the space-based systems reacquire SKYNET 5A to resume normal tracking custody.

The ground-based cueing of NEOSSat where Dstl cued NEOSSat using Starbrook derived orbit estimates was successful and metric data was acquired. The SSA community should be mindful that the tasking process for space-based sensors is not real-time and tasking lead times are required. A space-based sensor tasking lead time, typically 1-2 days, can be incurred between the time that a space-based sensor is tasked and the time of receipt of observations. If a large geostationary satellite manoeuvre occurs within this tasking lead time, the space-based sensor may not detect the geostationary satellite as the satellite may be drifting just outside of the observer's field of view.

Orbit measurements from both Space and ground based systems were merged into ODTK relatively easily with exception of some observation format conversion needed for the Starbrook observations. ODTK did not handle ingestion of observations which were not in time-ordered sequence and observation sorting was needed to time-order the observations.

This analysis has highlighted the difficultly in determining absolute errors (and hence performance) when there is a lack of defined ground truth data.

Tuning the ODTK filter by inspecting the measurement noise from Starbrook and Sapphire occurred relatively quickly and did not require significant effort. The combination of the space-based and ground-based observations resulted in elevated in-track position uncertainties during manoeuvre-free intervals of SKYNET 5A's track. It is suspected that sensor bias may be cause of this elevated uncertainty and is an open area of investigation.

Manoeuvre detection was performed by monitoring measurement residuals rejection by the filter. Once a manoeuvre was detected the timespan where the geostationary satellite was flying on the dayside of the Earth was generally filled with increased process noise (~0.1 N) for approximately 12 hours. This forced the acceptance of the new measurements *post-manuever* but is not a fully robust way to handle propulsions events. The next step is to attempt manoeuvre reconstruction to see if the components of the thrust vector can be estimated. This may be viable for the SKYNET 5A tracks as the satellite uses impulsive manoeuvres for station keeping.

8. CONCLUSIONS

Experiment planning and execution

There is an inherent value in performing a distributed SSA experiment such as SORE to provide practical experience and data that can advise on the challenges and potential solutions that are required to enhance coalition SSA capabilities. A number of specific challenges were experienced during the planning and execution of the experiment that affected the ability to perform coordinated SSA operations and several of these were successfully addressed during the test and observation phases of the experiment, as detailed in section 3. This event provided an opportunity to engage with agencies across the 5-eyes CSPO community and bring together prototype capabilities (both sensors and processing) that has increased the understanding on how distributed SSA may be conducted to enable mission sharing across national boundaries.

Critical to the successful execution of the experiment were the links established (including data sharing) between the satellite operator (Airbus DS), government agencies (Dstl and DRDC) and sensors. Dialogue with the satellite operator enabled sensors to be effectively tasked to observe the orbital manoeuvres that would not have been possible using publically available SSA data. Furthermore this enabled insight into the issues of concern to the operator where additional data sources can support their mission, for instance observation of debris objects around the vicinity of the spacecraft (especially those that are not currently correlated with the catalogue) and understanding the pattern of life of active spacecraft that may come into proximity during its movement.

The experiences of SORE have highlighted the utility in operating a sensor network that comprises multiple sensor types of modalities; specifically the complimentary nature of ground and space-based SSA assets. Starbrook has been designed to operate as a surveillance system, providing multiple observation opportunities against deep-space targets within a single evening; this enables orbits to be generated and associated with an existing catalogue in relatively short order (a few nights using its native processes or around seven nights with a more general purpose tool). This wide area coverage has significant benefits in terms of its ability to maintain awareness of the population at large and alert a user to a change of status, including new objects and possible manoeuvres. However ground-based assets will always suffer persistence issues due to local conditions including the weather. The use of Starbrook was of key importance for this experiment to enable re-acquisition of SKYNET 5A once its relocation had initiated.

Space-based systems offer several advantages in terms of availability and improved observation conditions by virtue of their location above the tropospheric environment. NEOSSat and Sapphire can both provide observations of deep space targets for extended periods of time that allows for localised 'neighbourhood watch' reconnaissance functions that can inform on the behaviour of satellites within a specific region of space. However effective cueing is required in order to make effective use of these assets that have relatively small fields of view and modest search capacity. This modus operandi was exercised through a practical experiment in July that successfully demonstrated the acquisition of SYKNET 5A during its relocation by NEOSSat using an orbit estimated by Dstl comprising data sourced from Starbrook only. It is therefore postulated that this mode of operation should be explored for existing and future SSA systems to maximize the use and utility of sensors available on the ground and in-orbit.

There remain significant barriers that prevent or limit further collaborative efforts on SSA; it is reasonable to believe that these may also be pertinent to the wider SSA community:

- Lack of a common network and associated message standards required to enable efficient and effective SSA data sharing amongst user groups,
- Lack of automation of sensors, including data processing and reduction, that limits the ability to share observational data efficiently amongst a distributed SSA architecture,
- Inability of current satellite dynamic models to effectively characterise and predict behaviour of satellites during manoeuvre periods which in turn complicates sensor tasking and data association problems,

These represent challenges that are candidate for further collaborative experimentation as part of CSPO and/or wider SSA community.

9. FUTURE WORK

The analysis phase is ongoing on the data collected from SORE to assess the performance of SSA sensors and how orbital estimation can vary dependent on the data utilised (particularly fusing multiple sensor data types) and modelling approach adopted. It is anticipated that results from this follow-on analysis will be presented at future SSA conferences or technical papers.

SSA is a topic of high priority within the UK and Canadian research communities, cutting across both the civilian and military domains; and similar activities are underway within the US, Australia and New Zealand under the auspices of the CSPO initiative. There are many technical challenges associated with SSA where further research is required, which should include contributions from government, academia, industry and international partners. This community is exploring opportunities to engage with the wider international SSA community to meet future SSA needs; and it has been shown that joint experimentation can be exploited to bring different groups from the community together (discussed further in the accompanying Dstl paper at this AMOS 2016 conference).

10. ABBREVIATION AND ACRONYMS

CSPO	Combined Space Operations
DRDC	(CAN) Defense Research and Development Centre
Dstl	(UK) Defence Science and Technology Laboratory
LEO	Low Earth Orbit
GEO	Geosynchronous Equatorial Orbit
NEOSSat	Near Earth Object Surveillance SATellite
ODTK	Orbit Determination Tool Kit
SSA	Space Situational Awareness
SGF	Space Geodesy Facility

11. REFERENCES

1. Selding, P., “Britain’s SKYNET 5A Reassigned to Asia-Pacific”, Spacenews.com, 16 March 2015.
2. Brown, N., “Spacecraft Realignment Rationalizes SKYNET Coverage”, Janes International Defence Review, Corsham, UK, IHS.com, 24 July 2015.
3. SpaceTrack.org, https://www.space-track.org, retrieved 29 March 2016.
4. Maskell, P.,Oram, L., ”Sapphire: Canada’s Answer to Space-Based Surveillance of Orbital Objects”, AMOS Technical Conference, Maui, HI, 2008.
5. Scott, R.L., Wallace, B.J., Sale, M., Levesque, M., Thorsteinson, S., “Toward Microsatellite Based Space Situational Awareness”, AMOS Technical Conference 2013, Maui Economic Development Board, Kihei, Hi, 2013.
6. Scott, R.L., Bernard, K., Thorsteinson, S., Ash, A., Feline, W., “Canadian Lessons Learned from the Space-Based Tracking of the SKYNET 5A Geostationary Satellite Relocation”, NATO SCI 283 Symposium on space capabilities Paper 18, May 2016.
7. Ash, A., Utility of Existing UK Sensors for Space Situational Awareness of Deep Space; DSTL/CR92462.