# Joint UK-Australian Space Surveillance Target Tracking, Cueing and Sensor Data Fusion Experiment

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**ABSTRACT**

In February 2014 the UK and Australia carried out a joint space surveillance target tracking, cueing, and sensor data fusion experiment. Four organisations were involved, these being the UK Defence Science and Technology Laboratory (DSTL) and Science and Technology Facilities Council (STFC) with the Defence Science and Technology Organisation (DSTO) and Electro Optic Systems (EOS) of Australia. The experiment utilised the UK STFC CAMRa radar located at Chilbolton in southern England and an Australian optical camera and laser system owned and operated by EOS which is located at Mount Stromlo near Canberra, Australia. An additional experimental camera owned and operated by DSTO which is located at Adelaide, Australia also contributed. Three initial objectives of the experiment were all achieved, these being:

1) Use multiple CAMRa orbit passes to cue EOS optical sensor;
2) Use single CAMRa passes constrained by Two Line Elements (TLEs) to cue EOS optical sensor;
3) Use EOS laser returns to provide an updated "reverse" cue for CAMRa radar.

Due to the success of these three objectives, two additional objectives were also set during the trials, these being:

4) Use CAMRa orbits to cue DSTO experimental optical sensor;
5) Use CAMRa orbits to provide CAMRa self-cue.

These objectives were also achieved.

The experiments were performed over two one-week periods with a one week separation between tracking campaigns. This paper describes the experimental programme from a top-level perspective and outlines the planning and execution of the experiment together with some initial analysis results. The main achievements and implications for use of dissimilar and geographically separated sensors for space situational awareness are highlighted. Two companion papers describe the sensor aspects of the experiment (Eastment et al.) and the data fusion aspects (Rutten et al.) respectively.

## 1. INTRODUCTION

The UK's Defence Science and Technology Laboratory (DSTL) and Australia's Defence Science and Technology Organisation (DSTO) are undertaking collaborative efforts in surveillance of space. Access to assets in both the UK and Australia provide an opportunity to study the use of a small number of geographically diverse sensors for orbital catalogue creation and maintenance.

A previous paper by DSTL and DSTO investigated orbital error propagation aspects for space surveillance and sensor data fusion [1]. An update of wider space situation awareness activities in Australia is given in [2]. Previous tracking campaigns have also been performed using the Chilbolton CAMRa radar in support of the ESA 'CO-V1' space surveillance tracking campaign [3].

This paper describes a joint space surveillance experiment carried out by the UK and Australia in February 2014. Four organisations were involved, these being DSTL, Science and Technology Facilities Council (STFC), both UK, with DSTO and Electro Optic Systems (EOS) of Australia. The experiment was planned and coordinated by both DSTL and DSTO. The purpose of the experiment was to investigate the problems of space surveillance target tracking, cueing and sensor data fusion primarily from a sensor systems perspective. The experiment utilised the UK STFC Chilbolton Advanced Meteorological Radar (CAMRa) which is located at Chilbolton in southern England and an Australian optical camera and laser system owned and operated by EOS which is located at Mount Stromlo near Canberra, Australia. An additional experimental camera owned and operated by DSTO which is located at Adelaide, Australia also contributed.

Due to constraints the experiments were performed over two-one week periods with a one week separation between tracking campaigns. This paper describes the experimental programme from a top-level perspective and outlines the planning and execution of the experiment together with some initial analysis results. The main achievements and implications for use of dissimilar and geographically separated sensors for space situational awareness are highlighted. Two companion papers describe the sensor aspects of the experiment [4] and the data fusion aspects [5] respectively.

## 2. AIMS OF EXPERIMENT

The primary purpose of the experiment was to investigate some of the issues surrounding space situation awareness from a sensor systems perspective and to examine how the UK and Australia might contribute to space surveillance. Specifically the problems of interest are target tracking, cueing and sensor data fusion.
Three initial objectives of the experiment were set, these being:

1) Use multiple CAMRa orbit passes to cue EOS optical sensor;
2) Use single CAMRa passes constrained by Two Line Elements (TLEs) to cue EOS optical sensor;
3) Use EOS laser returns to provide an updated "reverse" cue for CAMRa radar.

Later in the trials two additional objectives were also set, these being:

4) Use CAMRa orbits to cue DSTO experimental optical sensor;
5) Use CAMRa orbits to provide CAMRa self-cue.

## 3. SENSORS AND CUEING

Only a brief description is given here of the UK CAMRa radar and Australian optical camera and laser systems. The main details of the sensor aspects of the experiment are given in a separate companion paper [4].

*CAMRa Radar*

The CAMRa radar is owned and operated by the UK STFC and is located at Chilbolton in southern England. This is primarily a meteorological radar operating at S-band, but has been modified for use as an experimental space surveillance sensor. It has a fully-steerable 25 metre dish antenna with a 0.28 degree beamwidth and a range resolution of approximately 75 metres. The radar does not have pulse compression, monopulse or a closed-loop tracking capability. Antenna pointing is performed using TLEs and only the range is measured. The radar has previously been used successfully for the purposes of space situation awareness, tracking Low Earth Orbit (LEO) targets during two ESA tracking campaigns [3].

*EOS Electro-Optic Sensor*

The Australian optical camera and laser system is owned and operated by EOS and located at Mount Stromlo near Canberra, Australia. This electro-optic sensor was developed for the purposes of tracking and precision orbit determination of satellites and space debris. It has a visible light acquisition/targeting system as well as a Debris Laser Ranging (DLR) tracking system. The DLR is capable of laser ranging to targets without retro-reflectors and can track objects smaller than 10 cm in diameter with accuracy better than 1.5 metres root-mean-square error in range.

*DSTO Experimental Optical System*

An additional experimental optical system was also employed which is being developed by DSTO and is located at Adelaide, Australia. This provides a test bed to prototype tracking and data fusion algorithms as applied to space surveillance. It comprises a small (10 inch) telescope on an equatorial mount and has a sophisticated image processing chain that gives absolute angular accuracies in the order of 10 arc-seconds.

## 4. EXPERIMENT

One of the primary aims of the experiment was to use CAMRa radar measurements collected from targets of opportunity to cue the Australian sensors. Previous analyses (un-published) had demonstrated that without prior information a single pass of the CAMRa radar using range only measurements would not provide an accurate enough track for forward prediction and successful cueing. An accurate cue would, therefore, require the integration of multiple passes into a single orbit track or the inclusion of additional information. Two methods were thus proposed. The first method (developed by DSTL) used multiple CAMRa radar passes and a batch least squares process to fuse the data and determine a single orbit. This was then forward predicted to the required cue time and location at EOS. The second method (developed by EOS) used single CAMRa passes to produce the orbit tracks which were constrained in the orbit determination using weakly weighted TLEs as prior information. Hence the first method requires the "build-up" of an orbit over time, utilising several satellite passes typically over a period of a few days. The second method may be used to create a cue within the same orbital revolution using a single CAMRa pass, but requires the incorporation of a-priori knowledge (TLEs) in the solution. Once a successful cue was generated it was then intended to fuse the subsequent DLR measurements into the orbital track predictions to provide a "reverse cue" to the CAMRa radar.

Both DSTL and DSTO coordinated the experiment and all parties were involved in the planning. Targets of opportunity were selected using experience from previous tracking campaigns and scenario coverage predictions using TLEs from the US satellite catalogue. These were obtained from Space-Track.org. Communications during pre-planning and over the duration of the experiment were performed via email and occasionally by teleconferencing between the organisations. During the experiment orbit computations were primarily performed on-site at both the CAMRa radar facility and at EOS. The resulting tracks were predicted as necessary and satellite ephemerides prediction files were created and sent via FTP to the EOS optical sensor to provide the cues. The EOS optical sensor then autonomously selected the best viewing time and geometry from these ephemerides files to use the cue. The multiple pass orbits provided by DSTL were given priority in the case of a conflict of cues.

## 5. CAMRA RADAR DATA REDUCTION

The CAMRa radar data are primarily in the form of range and intensity measurements as a function of look time. Also provided is the antenna pointing azimuth and elevation, however, since these directions are determined on the basis of TLEs they were not used in the orbital solutions. The measurement process does not utilise pulse compression, the measurement itself being the range for which the corresponding received signal level is at a maximum. Some pre-processing was, therefore, required to remove spurious noise that occasionally rose above the returned target signal level, resulting in spurious range measurements. The procedure developed by DSTL was to iteratively fit a medium order polynomial (typically $8^{th}$ order) to the range data as a function of time and then remove the outliers. Similar methods were used by EOS. An example of pre- and post- processed range measurements for a typical CAMRa pass is given in Fig. 1.

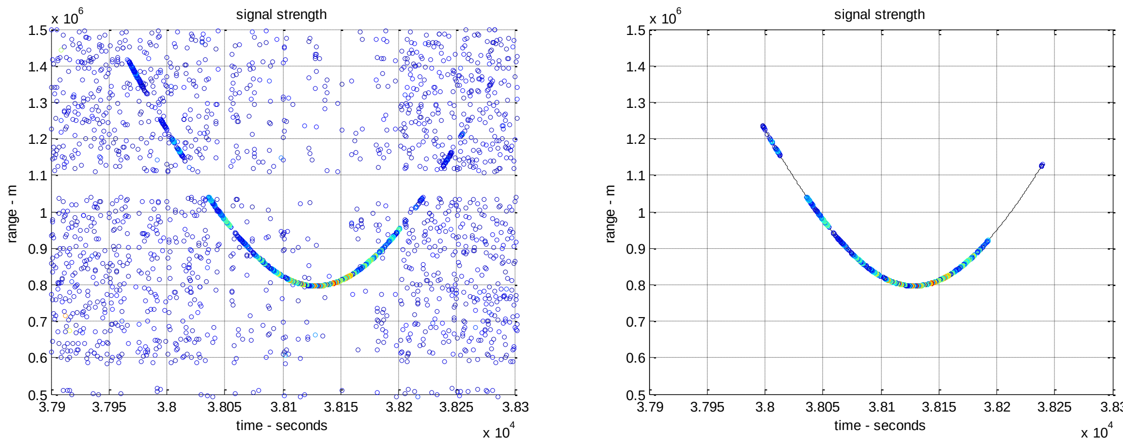


Fig. 1. Raw (left) and processed (right) CAMRa range measurements for COSMOS-1666 (NORAD id, 15889)

## 6. ORBIT DETERMINATION

*DSTL Multiple-Pass Method*

The method used by DSTL for the multiple pass orbit determination and prediction utilised a special perturbations orbit model and a least-squares differential correction procedure. An initial estimate of the satellite start state-vector (position and velocity) was used to predict the orbit and the measurement residuals (observed minus computed range) used in the procedure to find corrections to the start vector. The process was repeated until convergence was achieved. The ballistic coefficient was also determined in this process as a state parameter. The orbital state and partial derivatives were numerically integrated using a Bulirsch-Stoer integration procedure [6]. This is a development code and has a limited force model but was deemed adequate for the purposes of the experiment. The orbital force model utilised the EGM Earth Gravity Field Model up to degree and order 50, and accounted for direct luni-solar gravity and drag. The atmospheric density model used was based upon those of Jacchia [7, 8]. Since range only measurements were used in the orbit determination process it was necessary to include multiple passes of the same satellite object in the solution. Typically this would require that the overall orbit duration spanned several days. Generally at least three passes were required, unless a very good initial state-vector estimate was available, in which case two passes would sometimes suffice.

*EOS Constrained Single Pass Method*

The EOS method used TLEs to provide pseudo-measurement constraints in a batch least squares orbit determination process considering a full set of perturbing forces to enable only a single Chilbolton pass to be used to provide a track cue to the optical sensor. Only loose constraints were used so that the CAMRa radar measurements dominated the orbital solution. A fixed ballistic coefficient was used in the orbit determination, determined from the method described in [9]. If multiple CAMRa passes were available they were used in the orbit determination; however, usually a DSTL cue was available in these circumstances which took priority.

## 7. THE SATELLITES

The satellites chosen were primarily Low Earth Orbit (LEO) satellites with altitudes between approximately 500 km and 800 km. These are tabulated in the appendix. These were targets of opportunity, selected on the basis of sensor observability conditions. The target list was largely selected in advance of the trials, although this was adapted during the trials as and when opportunities arose. Where possible both ascending (south to north) and descending (north to south) passes were observed.

## 8. RESULTS

*DSTL-Generated Multiple-Pass Orbit Cues*

Twenty-eight cues were generated using the Multi-Pass orbit determination method on the first week of the experiment and thirty-seven during the second week. Due to poor weather in Australia only four of these cues could actually be attempted, however, all of these were successful. The criteria used for a successful cue was that the target could be acquired by the EOS sensor.

Fig. 2. shows the orbital range residuals as a function of orbit span for the orbital fits for the successful cues. The orbital span here is the total duration of the orbital fit covering the observation and intervening times. Generally the orbital fits are good with range residuals typically of the order of 50 metres for orbital spans of up to about five days and rising to about 100 metres for orbit spans of approximately two weeks. The significant rise in orbital residuals for larger orbital spans is probably due to both the limited force model used in the orbit model and to sensor bias errors. The figure also shows arrows to indicate the time from the cue generation to the actual cued observations at the EOS sensors. For ADEOS and COSMOS-1300 this covered periods of several (three to four) days and hence many (> 50) orbital revolutions. For ALOS and COSMOS-1707 (vertical arrows only) the cued observations were made within the same orbital revolution. The ADEOS cue was also found to be “near the centre of the camera and was quite stable throughout the pass” on two separate cueing observations. For COSMOS-1300 the target “was acquired near the edge of the camera frame and had large biases”. However, this cue resulted from an orbit consisting of only three CAMRa passes and forward predicted over a three day time-period. For the ALOS and COSMOS-1707 cues the orbits were successfully determined across the one week gap between observation periods.

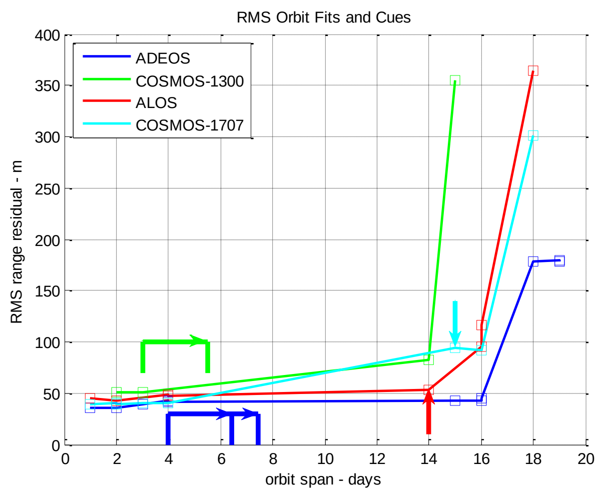


Fig. 2. RMS fit as function orbit span for the successfully cued orbits. The arrows indicate the time between the cue generation and the cued observation time

Due to the sparse nature of the observation set and the nature of residual sensor bias errors, the covariance matrix from the orbit determination process usually underestimates the actual orbital uncertainty significantly. Recognising this, and that as a result it is often difficult to realistically quantify the orbital accuracy with much meaning, we have not attempted to do so here.

For completeness Table 1 gives a summary of some statistics for all of the Chilbolton orbit determinations for the different satellites using the multi-pass orbit determination method. The statistics given are for the largest orbital span before the RMS fit starts to significantly degrade. This is somewhat arbitrary, but typically results in orbital residuals of around 50 metres. Note that the actual cues used may be from slightly different orbit spans and fits.

Table 1., RMS orbit fit (metres) and span (days) for multi-pass orbit determination cues

| Satellite | NORAD ID | Orbit Span (days) | RMS range fit (metres) |
|---|---|---|---|
| ADEOS | 24277 | 16 | 45.2 |
| COSMOS-1300 | 12785 | 3 | 50.5 |
| ALOS | 28931 | 14 | 52.7 |
| COSMOS-1707 | 16326 | 4 | 40.6 |
| ENVISAT | 27386 | 17 | 54.4 |
| COSMOS-1666 | 15889 | 5 | 39.2 |
| FENGYUN-3A | 32958 | 3 | 31.5 |
| FENGYUN-3B | 37214 | 4 | 48.1 |
| IRIDIUM-921 | 24873 | 5 | 46.2 |
| IRIDIUM-19 | 24965 | 4 | 31.3 |
| AQUA | 27424 | 13 | 52.4 |
| COSMOS-1544 | 14819 | 5 | 43.9 |
| RADARSAT-1 | 23710 | 2 | 39.7 |
| IRIDIUM-18 | 24872 | 4 | 47.6 |
| IRIDIUM-68 | 25291 | 1 | 33.3 |
| GRACE-2 | 27392 | 3 | 49.8 |
| ADEOS-2 | 27597 | 3 | 45.7 |
| RADARSAT-2 | 32382 | 5 | 25.2 |
| COSMOS-1437 | 13770 | 5 | 44.9 |

*EOS-Generated (constrained) Orbit Cues*

A total of twenty-seven cues were generated using the lightly constrained TLE technique. All of these cues used a single CAMRa pass with the exception of IRIDIUM-19, which used 3 passes. Not all of these were attempted, however, largely due to poor weather in Australia during the second half of both observation periods and the priority being given to the multi-pass cues. In spite of this there were six successful cues using this method and two failures, as summarized in Table 2. Note that even though the constraints are light, there is still some dependence using this technique on the quality of the TLE constraints which may account for the failed attempts. In order to assess the utility of this technique more fully it is necessary to build up a larger data set to provide the required statistics.

Table 2. CAMRa-EOS sensor cue attempts from constrained orbit cues; all used a single CAMRa pass, except IRIDIUM-19*, which used 3 passes.

| Date | Satellite | Cue status and comments |
|---|---|---|
| 10/2/2014 | IRIDIUM-19 (24965) | Success |
| 11/2/2014 | IRIDIUM-921 (24873) | Failed (possible software control failure) |
| | IRIDIUM-37 (24968) | Failed |
| | IRIDIUM-19* (24965) | Success (excellent, target right on boresight) |
| 12/2/2014 | IRIDIUM-5 (24795) | Success |
| 24/2/2014 | ENVISAT (27386) | Success |
| | COSMOS-1544 (14819) | Success |
| 25/2/2014 | IRIDIUM-39 (25042) | Success |

*Reverse Cues*

Once a successful cue had been acquired and observed using the laser ranger it was possible to utilise these measurements and further refine the orbits. This was performed by EOS to provide a cue back to the CAMRa radar.

A total of twelve reverse cues were generated. Of these ten were attempted, five of which were successful. Four of these successful cue observations were used to further refine the CAMRa orbits, and hence provide "reverse-

reverse" cues back to the EOS sensors. However, these cues could not be attempted due to the poor weather in Australia at the time. A summary of the attempted reverse cues is given in Table 3.

Table 3. EOS-CAMRa radar reverse cue attempts

| Date | Satellite | Cue status and comments |
|---|---|---|
| 26/2/2014 | COSMOS-1300 (12785) | Success |
| | ENVISAT (27386) | Success |
| | AQUA (27424) | Failed (x 2) |
| | ALOS (28931) | Success |
| 27/2/2014 | FENGYUN-3A (32958) | Success |
| | ENVISAT (27386) | Success |
| | IRIDIUM-39 (25042) | Failed |
| | IRIDIUM-67 (25290) | Failed |
| | IRIDIUM-68 (25291) | Failed |

*CAMRa Self-Cues*

Towards the end of the tracking and cueing experiment enough CAMRa observations had been obtained to produce sufficient quality orbits to attempt to "self-cue" the CAMRa radar. This was attempted for eight different objects on a total of eleven passes. All attempts were successful. Two of these self-cues (ALOS and FENGYUN-3A) resulted from orbits consisting of observations that in turn were obtained from reverse cues and, hence, could be described as "self-reverse" cues. The results are summarised in Table 4.

Table 4., CAMRa self-cues. ALOS (28931) and FENGYUN-3A (32958) are also reverse cues

| Date | Satellite | Cue status and comments |
|---|---|---|
| 27/2/2014 | ADEOS-2 (27597) | Success x 2 |
| 28/2/2014 | FENGYUN-3A (32958) | Success |
| | ALOS (28931) | Success |
| | ADEOS (24277) | Success x 2 |
| | FENGYUN-3B (37214) | Success x 2 |
| | RADARSAT-2 (32382) | Success |
| | RADARSAT-1 (23710) | Success |
| | ADEOS-2 (27597) | Success |

*DSTO Experimental Camera Cues*

Eleven cue attempts were made using the DSTO experimental camera. Seven of these were multi-pass cues (DSTL method), two were single pass cues (EOS method) and two used both methods. All these cue attempts were successful and are given in Table 5. The criteria used here for a successful cue is that a sufficient number of images were obtained. DSTO also developed an experimental constrained circular orbit determination technique to produce self-cues. These are not included in the table, but achieved four successes out of seven cue attempts.

Table 5., DSTO experimental camera cue attempts (multi-pass cues from DSTL, single pass cues from EOS)

| Date | Satellite | Cue status and comments |
|---|---|---|
| 25/2/2014 | ALOS (28931) | Success – multi-pass cue |
| 26/2/2014 | COSMOS-1666 (15889) | Success – multi-pass cue |
| | IRIDIUM-19 (24965) | Success – multi-pass cue |
| 27/2/2014 | COSMOS-1666 (15889) | Success – multi-pass cue |
| | CZ-4 DEB (26121) | Success – single pass cue |
| | FENGYUN-3A (32958) | Success - multi-pass and single pass cues, both near centre of field-of-view |
| | ALOS (28931) | Success - multi-pass and single pass cues |
| 28/2/2014 | ADEOS-2 (27597) | Success – multi-pass cue |
| | COSMOS-1666 (15889) | Success – multi-pass cue |
| | CZ-4-DEB (26121) | Success – single pass cue |
| | FENGYUN-3A (32958) | Success – single pass cue |

## 9. THE EXPERIMENT IN A WIDER SPACE SITUATIONAL AWARENESS CONTEXT

*Space Situation Awareness (SSA)*

There are many increasing challenges in SSA such as the increasing object numbers, smaller objects of interest and dependency on legacy systems and processes. This is being recognised and responded to at both national and international policy level and there is correspondingly an increased focus on SSA research initiatives. The UK National Space Security Policy [10] notes the importance of space and SSA to the UK and the need for improved use of existing sensors, joint civil-military initiatives and collaboration with international partners and networks.

DSTL has previously been conducting research into the potential use of existing non-SSA specific sensors and novel techniques for improved SSA capability [1]. The experiment described in this and the accompanying papers demonstrates the next step, using a UK government owned non-military asset (the CAMRa radar) with latent SSA capability and international collaboration. The collaborative assets used here are the EOS and DSTO assets, and the international collaborations are between the UK and Australian government military research organisations (DSTL and DSTO respectively), the UK STFC and industry (EOS). The aim of the experiment was to investigate the utility of data fusion methods to fulfil a number of SSA functions outside the normal capability of the individual assets. In addition the Concepts of Operations (CONOPS), cueing and connectivity issues between the organisations in different countries was explored and resolved. The experiment concept was grown "bottom-up" between the collaborating organisations and the experiment design was evolved through a series of remote teleconferences.

As reported in this and the accompanying papers a number of objectives were set. The experiment was successful in achieving these objectives and two additional objectives that were introduced and realised during the trials. An underlying objective, the development, comparison and proving of astrodynamic and data fusion methods was both demonstrated and advanced. This aligns with supporting the needs of international SSA networks highlighted in [11]. Conducting collaborative experiments such as this enables us to better understand the options, issues, capabilities and trade-offs.

*System Implications*

In terms of systems implications a number of considerations have been highlighted by this experiment:

- A non-SSA sensor such as the CAMRa radar can provide useful observation data when processed using appropriate astrodynamics and data fusion methods;
- Modelling can be used to determine the optimal use of assets, the capability of networks and to understand the benefit of potential improvements to individual sensors;
- For a small number of objects improved quality track data can be obtained, but this will depend on the location and availability of the assets;

- The current variability and lack of information on TLE accuracy is a limiting factor on how well potential augmenting SSA sensors can be used;
- Cueing with better quality data than TLEs can allow improved utility of existing assets.

## 10. FUTURE WORK

The forthcoming Automated Transfer Vehicle (ATV-5) de-orbit event will provide a well observed and characterised, but challenging, SSA target. It is believed that this will provide some unique opportunities to explore not only re-entry and break-up science, but also much wider SSA and astrodynamics research. A series of orbital manoeuvres in low orbital regimes will be challenging in terms of sensor tracking, orbit determination and prediction, fusion and cueing. The organisations and collaborators involved in this experiment, together with ESA and NASA are involved in determining contributions to a wider science campaign. The results and experience obtained in this work will feed into this campaign. DSTL are currently investigating and de-risking the radar and optical systems that may be used to contribute to the science programmes. This includes making plans for data sharing internationally and with wider government and academic researchers, so as to enable mutual contributions to a better understanding and provision of SSA.

## 11. CONCLUSIONS

These results demonstrate that limited sensor assets geographically spread across different countries can provide a limited space surveillance capability. Additionally, the self-cueing of the CAMRa radar demonstrates that, in principle at least, this sensor has a limited autonomous operational capability once an orbit for a particular target has been determined. This experiment was the first time our organisations have collaborated in a joint exercise of this nature and future efforts would streamline the processes. This space surveillance collaboration between the UK and Australia is continuing. In the very near future the forthcoming ATV-5 de-orbit will provide another challenging and unique opportunity to explore the science of space surveillance. The organisations and collaborators in this experiment as well as ESA and NASA are currently involved in determining contributions to a wider science campaign.

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**APPENDIX – TABLE OF CHOSEN SATELLITES**

Table A.1 – The satellites chosen for observation together with some pertinent parameters (EO = Earth Observation, Comms = Communications, Met = Meteorological, Intel = Intelligence)

| NORAD ID | Designator | Satellite | Type | Inclination (degrees) | Period (mins) | Perigee Height (km) | Apogee Height (km) |
|---|---|---|---|---|---|---|---|
| 12154 | 1981-008A | COSMOS-1242 | Intel | 81.2 | 91.4 | 351.1 | 352.3 |
| 12785 | 1981-082A | COSMOS-1300 | Intel | 82.5 | 95.5 | 544.9 | 552.3 |
| 13120 | 1982-027A | COSMOS-1346 | Intel | 81.1 | 94.2 | 482.7 | 489.7 |
| 13402 | 1982-079A | COSMOS-1400 | Intel | 81.1 | 92.9 | 421.3 | 429.8 |
| 13770 | 1983-003A | COSMOS-1437 | Intel | 81.2 | 94.4 | 488.5 | 507.5 |
| 13818 | 1983-010A | COSMOS-1441 | Intel | 81.1 | 91.4 | 350.3 | 353.1 |
| 14819 | 1984-027A | COSMOS-1544 | Intel | 82.5 | 95.1 | 520.2 | 545.2 |
| 15889 | 1985-058A | COSMOS-1666 | Intel | 82.5 | 95.4 | 532.5 | 561.3 |
| 16326 | 1985-113A | COSMOS-1707 | Intel | 82.5 | 95.6 | 545.5 | 565.6 |
| 16986 | 1986-074A | COSMOS-1782 | Intel | 82.5 | 95.9 | 561.8 | 580.3 |
| 19045 | 1988-032A | COSMOS-1939 | EO | 97.2 | 91.4 | 350.8 | 354.4 |
| 23710 | 1995-059A | RADARSAT-1 | EO | 98.6 | 100.7 | 797.9 | 799.7 |
| 24277 | 1996-046A | ADEOS | Intel | 98.6 | 100.8 | 801.4 | 803.7 |
| 24793 | 1997-020B | IRIDIUM-7 | Comms | 86.4 | 100.4 | 783.1 | 786.5 |
| 24795 | 1997-020D | IRIDIUM-5 | Comms | 86.4 | 100.4 | 783.4 | 786.2 |
| 24836 | 1997-030A | IRIDIUM-914 | Comms | 86.4 | 100.1 | 770.8 | 771.9 |
| 24842 | 1997-030G | IRIDIUM-911 | Comms | 86.4 | 99.7 | 740.9 | 764.5 |
| 24869 | 1997-034A | IRIDIUM-15 | Comms | 86.4 | 100.4 | 783.1 | 786.5 |
| 24871 | 1997-034C | IRIDIUM-920 | Comms | 86.4 | 100.1 | 762.0 | 778.2 |
| 24872 | 1997-034D | IRIDIUM-18 | Comms | 86.4 | 100.4 | 783.2 | 786.4 |
| 24873 | 1997-034A | IRIDIUM-921 | Comms | 86.4 | 95.9 | 562.9 | 574.8 |
| 24903 | 1997-043A | IRIDIUM-26 | Comms | 86.4 | 100.4 | 781.2 | 784.5 |
| 24965 | 1997-056A | IRIDIUM-19 | Comms | 86.4 | 100.4 | 783.1 | 786.5 |
| 24968 | 1997-056D | IRIDIUM-37 | Comms | 86.4 | 100.4 | 783.1 | 786.6 |
| 25041 | 1997-069C | IRIDIUM-40 | Comms | 86.4 | 100.4 | 783.2 | 786.3 |
| 25042 | 1997-069D | IRIDIUM-39 | Comms | 86.4 | 100.4 | 783.2 | 786.3 |
| 25105 | 1997-082B | IRIDIUM-24 | Comms | 86.4 | 100.0 | 759.1 | 776.8 |
| 25170 | 1998-010B | IRIDIUM-56 | Comms | 86.4 | 100.4 | 783.0 | 786.6 |
| 25290 | 1998-021F | IRIDIUM-67 | Comms | 86.4 | 100.4 | 783.2 | 786.5 |
| 25291 | 1998-021G | IRIDIUM-68 | Comms | 86.4 | 100.4 | 783.2 | 786.5 |
| 25319 | 1998-026A | IRIDIUM-69 | Comms | 86.4 | 100.1 | 769.1 | 774.7 |
| 25320 | 1998-026B | IRIDIUM-71 | Comms | 86.4 | 100.1 | 767.8 | 772.8 |
| 25468 | 1998-051B | IRIDIUM-81 | Comms | 86.4 | 100.4 | 783.1 | 786.6 |
| 25527 | 1998-066A | IRIDIUM-2 | Comms | 85.5 | 95.5 | 543.5 | 555.2 |
| 25778 | 1999-032B | IRIDIUM-21 | Comms | 86.4 | 100.4 | 782.3 | 787.3 |
| 26121 | 1999-057H | CZ-4-DEB | Debris | 98.7 | 96.7 | 564.8 | 654.3 |
| 27386 | 2002-009A | ENVISAT | EO | 98.4 | 100.2 | 772.7 | 774.3 |
| 27392 | 2002-012B | GRACE-2 | Geodetic | 89.0 | 89.0 | 416.8 | 428.4 |
| 27424 | 2002-022A | AQUA | EO | 98.2 | 98.8 | 708.3 | 710.9 |
| 27597 | 2002-056A | ADEOS-2 | EO | 98.3 | 100.9 | 809.4 | 811.2 |
| 28931 | 2006-002A | ALOS | EO | 98.0 | 98.6 | 697.2 | 700.4 |
| 32382 | 2007-061A | RADARSAT-2 | EO | 98.6 | 100.7 | 798.0 | 799.8 |
| 32958 | 2008-026A | FENGYUN-3A | Met | 98.6 | 101.5 | 827.1 | 842.3 |
| 36508 | 2010-013A | CRYOSAT-2 | EO | 92.0 | 99.2 | 717.9 | 733.5 |
| 37214 | 2010-059A | FENGYUN-3B | Met | 98.8 | 101.5 | 833.6 | 835.8 |