The Critical Role of Experimentation to Further SSA Understanding

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ASTRACT

Dstl has developed an approach to explore the challenges of understanding the fundamental principles of SSA through the design and execution of a series of national and international SSA experiments conducted since 2008. These have involved a number of nations within different multi-lateral constructs (such as Combined Space Operations [CSPO] and NATO), and have also served as test case scenarios in support of international SSA research collaboration. It has been found that this experimentally-driven approach has been successful in linking government R&D activities to actual operations with UK MOD; enabling enhanced cooperation with academia through the provision of access to sensors and data; as well as an understanding of the operational imperatives and constraints, not usually available or apparent to these institutions. The experiences of the Dstl team over the past 8 years have yielded a number of lessons learnt that we believe the wider international community would benefit from in relation to effective SSA operations, including how to generate closer relationships between communities across government, industry, academia and operators.

This paper describes the overall Dstl approach to a series of SSA experiments designed to inform the UK MOD on the challenges and potential technical solutions related to SSA mission areas. It includes details of the participants, design and execution; and illustrates some major findings of each event to date. Lessons learnt pertinent to the AMOS and wider SSA community are presented that will inform the audience on how this approach may be adopted to meet other SSA scenarios. Finally, it presents the UK roadmap for future experiments identified as possible activities under the CSPO initiative and the EU Space Surveillance and Tracking programme.

1. INTRODUCTION

The UK has been an active partner and participant in international Space Situational Awareness (SSA) activities since the start of the space age, utilising the radio telescope located at Jodrell Bank to track the first Sputnik satellite in 1957. Since that time the UK has continued to support international SSA networks and organisations, primarily focussed on the US Space Surveillance Network (SSN). UK research activities have centred on understanding the optimal utility of data sourced from these networks, with smaller investigations of the potential of non-traditional surveillance of space sensors to augment existing capabilities. However, in the last few years this situation has substantially altered as UK government and industry have become increasingly aware of the need to protect space assets in an ever more challenging situation as the space domain becomes increasingly congested, competitive and contested. This is particularly true of the UK Ministry of Defence (MOD), as recognised in the recent Strategic Defence and Security Review (SDSR) 2015; as a consequence, the recently-formed space research programme within the Defence Science and Technology Laboratory (Dstl, part of the UK MOD) has recognised SSA as a top priority. In addition the UK is now a participant in the EU SST (European Union Space Surveillance and Tracking) project which is aiming to provide SSA services to users initially based on existing traditional and non-traditional assets owned by participating nations.

Technically it is recognised that comprehensive SSA can only be provided by international networks, encompassing sensors, Concept of Operations (CONOPS), data processing, communications, procedures, quality assurance and security elements. These elements must all be understood individually and collectively to provide SSA solutions; in particular the complex interactions within the network present significant coordination challenges that must be addressed to ensure effective SSA operations.

2. SSA AND RESERCH CHALLENGES

The challenge of SSA lies in part from the nature of the objects and environment that we need awareness of, the tools (sensors) and techniques we have to gather information about them, and the ways that we can process that data to get the information required in terms of quantity, quality and timeliness.

In principle, the objects vary from the ISS (~100 m) to pieces of space debris as small as paint flecks. However, in practice, we need to be aware of spacecraft which individually or collectively have some capability that we need to know about or objects which are uncontrolled and could damage one of the precious and vital assets we depend on (~1 cm).

The environment consists of a huge volume above the Earth, from 100km to the graveyard orbits beyond GEO. However, this is not simply empty space; there is residual atmosphere causing drag, and there are electrical and magnetic particles and fields which can cause small but varying forces on our objects and perturb their trajectories. The greatest force acting on these objects is, of course, gravity, which is in itself complex and varies with the nature and shape of the earth and the tides. Gravity effects from the Sun, Moon and other planets also act on these objects to influence their motion. Astrodynamics, the motion of artificial objects in space, is truly chaotic, and a small difference in starting conditions leads to a huge difference in the propagation path in short order.

Our sensors, therefore, have to be sensitive but also have large dynamic ranges for the distances and sizes involved, as we need to search and survey large volumes but get very accurate measurements. We need to be able to process measurements to get accurate (and with known uncertainty) estimates of tracks comprising position and velocity, and we need appropriate models that can fit these tracks to orbits and propagate them to provide our SSA in terms of a catalogue of known objects. To maintain the catalogue we must have the ability to be able to schedule further measurements that can be taken to keep custody of that object to maintain the SSA, and to search for objects that are 'lost' due to unexpected manoeuvre or lack of capability in our process.

We can use radars and electro-optic sensors stationed at various locations around the earth (or in space) and appropriate models and assumptions (such as the drag of a space object) to start to provide that SSA; as utilised by existing networks such as the US Space Surveillance Network. The inherent challenges of SSA are growing since these networks were originally established: the size of objects of interest is decreasing; the number of objects is increasing; and sensors are very costly to procure & operate and need effective and efficient tasking, scheduling & processing procedures to ensure they are optimally employed. The models must be sufficiently accurate but also computationally scalable to cope with increasing numbers of objects. If there are more objects, there will be more possibilities of close approach which may need operator action to avoid a collision risk. These manoeuvres are inherently costly and limit the life of spacecraft, so the spacecraft operators need more accurate predictions and greater knowledge of the uncertainty of the predictions and risk.

Sensors, models, network operations, communications between sensors and development of efficient tasking are all complex and hence costly. There are a variety of sensor characteristics and performance that could be chosen which have an ability to provide data, and modern research provides novel and alternative processing techniques. In order to determine optimal elements of the architectures to meet these challenges, we need to understand the blend and placement of sensors and processing to provide efficient and effective SSA.

The technical challenges are intricate and inherently convoluted. There is a fundamental national requirement to understand the necessities and trade-offs between the potential solution providers to understand the best national and international contribution that can be made for the restricted funding that is available.

3. APPROACH

To understand these trade-offs we can, of course, conduct theoretical investigation of the elements involved; however, given the complexities and uncertainties and the end need to evolve capability, the approach taken has been to use a series of increasingly complex focused experiments to better understand some of the fundamental science and trade-offs and also to explore the realities. Hence as the experiments have progressed, they have evolved increasingly detailed concepts of operations and the levels of communications needed in ad-hoc and planned networks.

SSA is inherently multi-national, so the experiments have investigated working with other nations and other organisations, and utilised a variety of international constructs for planning and data sharing. The experiments also addressed the use of different sensor types and operating constructs: for example, existing SSA assets were, in some cases, used together with existing assets which have other roles but which are able to provide SSA data. In addition, non-traditional assets, such as deployable commercial off-the-shelf equipment, were investigated.

The gathering of data allowed development and assessment of planning, processing and data fusion algorithms, as well as the fundamental astrodynamics models. Collaboration with other research organisations, both nationally and internationally, allowed comparison and mutual development of methods. An important further aspect of the experiments was to collect much unclassified releasable data which may be provided to the academic and industrial research community. This has been used to enable the growth of the UK Astrodynamics Community of Interest (ACI) in this area to progress UK development of SSA techniques.

4. ASTRODYNAMICS COMMUNITY OF INTEREST

The ACI was originally set up in early 2013 to identify the academic research and centres of excellence within the UK which might be able to contribute to SSA, and to inform them of the challenges and opportunities for new areas of research application. It was initially created in conjunction with the UK Space Agency (UKSA), and a further aim was to co-ordinate any specific (and at that time very modest) SSA related research that both MOD and UKSA might be placing with academia. There was a gratifying response from both universities and other research organisations such as the Satellite Geodesy Facility (SGF, part of the Natural Environment Research Council) and indeed it was also supported by specialist commercial concerns (such as Space Insight Ltd).

This embryonic ACI group was nurtured and grown through the experimental programme as it developed, most significantly from the ATV-5 experiment (described subsequently) and beyond. Workshops were held to identify SSA data needs and possible contributions; such as novel data processing & sensors, how experiment planning could take into account specific data needs, and exploitation routes and benefits. Another important aspect was to allow academia to better understand operational constraints and requirements to this end, the community organically expanded over the series of post-ATV-5 experiments, involving wider industrial organisations including commercial satellite operators and (importantly) engagement from UK military operators. As of April 2016, around thirty UK organisations have been involved in ACI workshops.

The ACI construct has provided huge mutual benefit to academic and government research; so much so that more ambitious SSA academic research programmes are being explored with the science research councils. At the opposite end of the spectrum, visits and placements of academic researchers into specific projects are being developed as a way to speed up exploitation of cutting edge research into operational contexts. Future progress of the ACI will be associated with answering specific technical questions & challenges (raised by operational activities and through lessons-learned) to progress research in key areas of SSA capability

5. EXPERIMENT SERIES TO DATE

5.1 Radar Experimentation with TIRA and RAF Fylingdales (Cooperative Target Tracking)

The initial experiments (2008 - 2009) investigated planning and tasking a traditional operational sensor and utilisation of data from specific radar functions. The Upgraded Early Warning Radar (UEWR) at RAF Fylingdales was used to gather data on Surrey Satellite Technology Ltd. (SSTL) controlled satellites performing known manoeuvres; firstly Tactical Optical Satellite (TOPSAT) and then Disaster Monitoring Constellation (DMC) microsatellites were used. The second experiment was also extended via existing research agreements to share the planned manoeuvre details with the (then) FGAN organisation (Research Institute for High Frequency Physics and Radar Techniques) who could also gather data from the TIRA (Tracking and Imaging Radar) instrument near Bonn, Germany. From this we learned much about optimal planning and tasking of single sensors

A longer series of experiments using opportunity targets were then undertaken with the UEWR radar in association with its operational and support staff. These included separating objects, break-up & debris cloud events and tracking of various sized objects; both controlled and uncontrolled. Contacts with satellite operators, academia and SGF who operate the UK Satellite Laser Ranging (SLR) system at Herstmonceux were able to provide ground truth (in terms of GPS or SLR data).

The understanding of tasking was further developed and utilized during this series of experiments and data analysis methods were refined. The SLR data was also used to investigate the growth in uncertainty in publically available Two Line Element (TLE) entries in the Satellite Catalog. SLR derived orbital position was compared to backward and forward propagated TLEs over different periods of days. A number of different TLEs were used for each object. Figure 1 shows an example of the uncertainty behaviour of TLEs for the Stella object. The lines show (for each specimen TLE) how the uncertainty grows as the TLE is used to predict an orbital position backwards or forwards in time Error bars in showing the estimated inaccuracy of orbit fit are also shown. An example of comparing SLR data with backward- and forward-propagated Two Line Element (TLE) data is shown in Figure 1. The TLE errors for a benign object (being stable and not in high drag region) are relatively small (less than 1 km) and stable for a couple of days but then grow rapidly, and the size and the rate of growth varies with each particular TLE.
Conclusions from data analysis of UEWR cannot be included in this paper but were valuable in terms of understanding radar performance.

Experimentation now turned more to investigation of networks of sensors. The initial experiment in 2011 used a non-traditional S-band dish radar in the UK (the Chilbolton Advanced Meteorological Radar [CAMRa], operated by the Science and Technology Facilities Council) and the Electro Optic Systems (EOS) optical sensor in Australia. This extension allowed the opportunity to extend to a number of additional research organisations (also including the Defence Science and Technology Group Organisation (DSTO), now called the Defence Science Technology Group (DSTG)), and results published at a previous AMOS conference 2014 [2,3,4], where astrodynamics modelling & fitting, cueing, data fusion and planning / CONOPS between diverse locations & time-zones were also investigated.
A number of technical findings on cueing and orbit fitting were reported in in a paper at the AMOS conference other major findings and lesson learned included;

- Challenges due to coordination across many time zones; solution was to rely on pre-planning: access to a coverage tool was critical to enable this to happen.
- Weather dependence for EO systems affects scheduling; particularly pertinent for R&D, non-persistent systems

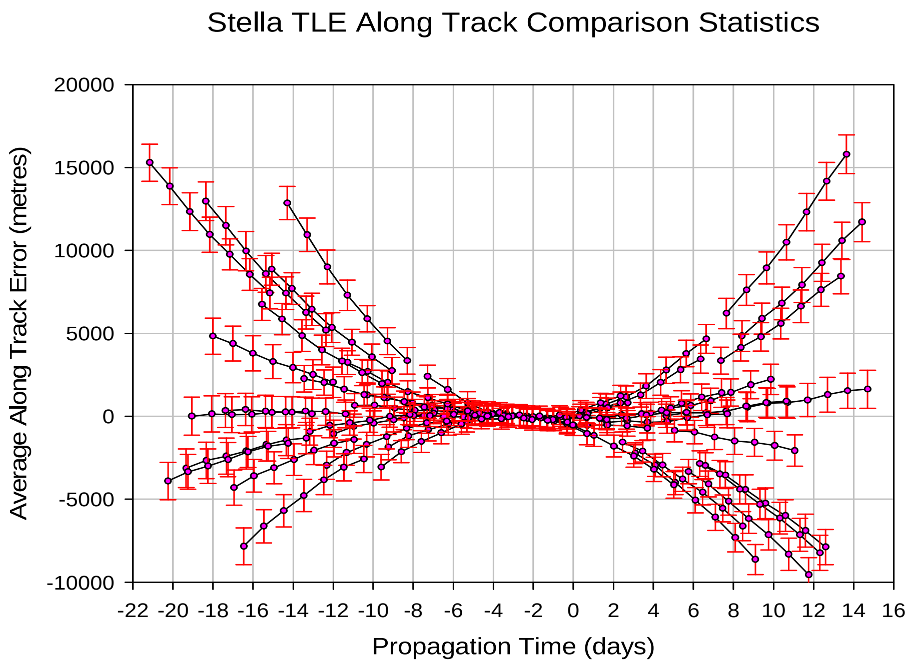

Figure 1: TLE investigation – Stella

5.2 Joint UK-Australian Satellite Tracking Experiments (Distributed Non-Traditional Sensors Network**)**

For the short (two week) period of the experiment, the UK and AUS had its own independent space tracking network (of very modest, but some, capability).
This experience, findings and lessons-learned were invaluable when the opportunity came to expand the experimental remit and challenge with further, targeted events associated with re-entering objects. The network is shown in Figure.2

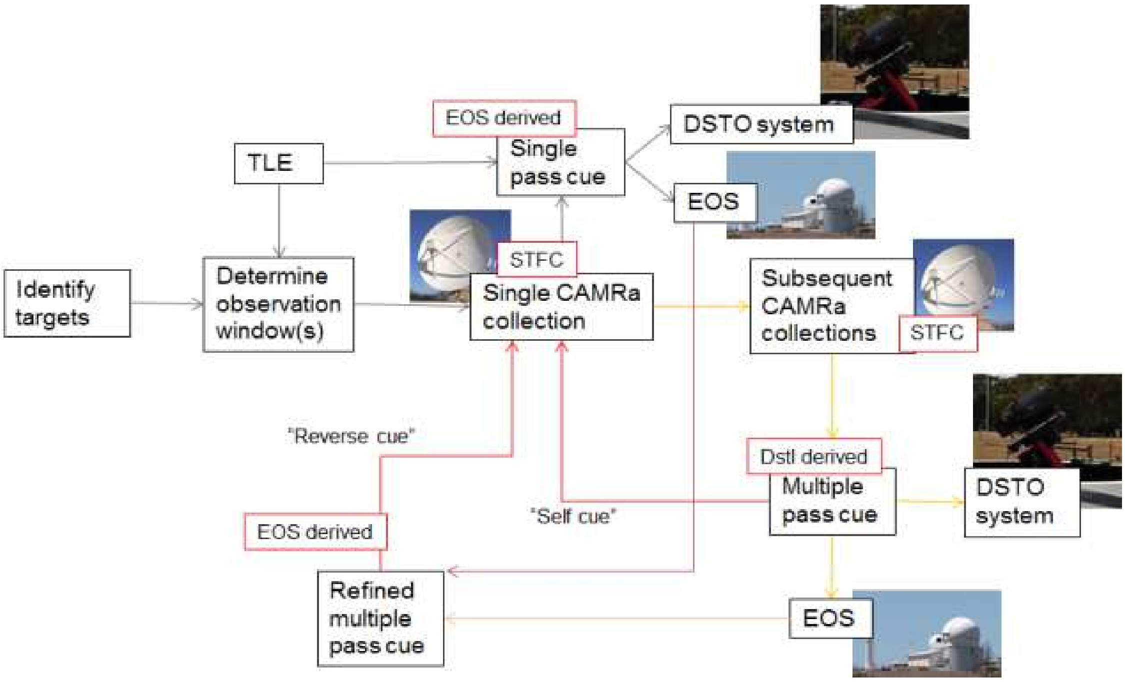

Figure 2 UK – Australian distributed sensors network

A follow-up opportunity, involving de-orbit of the Autonomous Transfer Vehicle-5 (ATV-5) from the International Space Station (ISS) in early 2014 came shortly after publication of the UK National Space Security Policy (NSSP) [1] which highlighted the need for improved SSA and the aim to do this by contributing through international networks and developing civil / military and academic engagement. This provided a timely opportunity to jump-start all of these initiatives.

5.3 ATV-5 Re-Entry Observation (Distributed Traditional and Non-Traditional Network**)**

In order to better understand re-entry science, NASA and ESA were planning a slow-controlled and well-instrumented re-entry of ATV-5 after its final re-supply of the ISS. A major focus of this work was to better understand break-up science (and refine modelling capability) to support the possible future de-orbit of the International Space Station. The shallow re-entry and instrumentation presented some unique challenges but it also occurred to us that this also presented some unique SSA research opportunities. NASA and ESA were eager to extend the experiment to include SSA and, as such, there was scope to set up an international network of traditional and non-traditional sensors to gather data on the event. The Combined Space Operations (CSPO) construct was used to co-ordinate the space Operational Centres (OCs) of 5 nations (UK, US, AUS, CAN, NZ) to monitor the event and task appropriate assets. The research community provided novel and non-traditional assets for inclusion in the experimental framework, including both deployable optical sensors (from the UK to New Zealand) and experimental radar systems (e.g. a bi-static receiver for the CAMRa radar). Visualisation of non-traditional sensors was also investigated within the experimental network by including the Air Force Research Laboratory (AFRL) tool UNITY to allow near real-time visualization of CAMRa outputs. The network is shown in Figure 3.

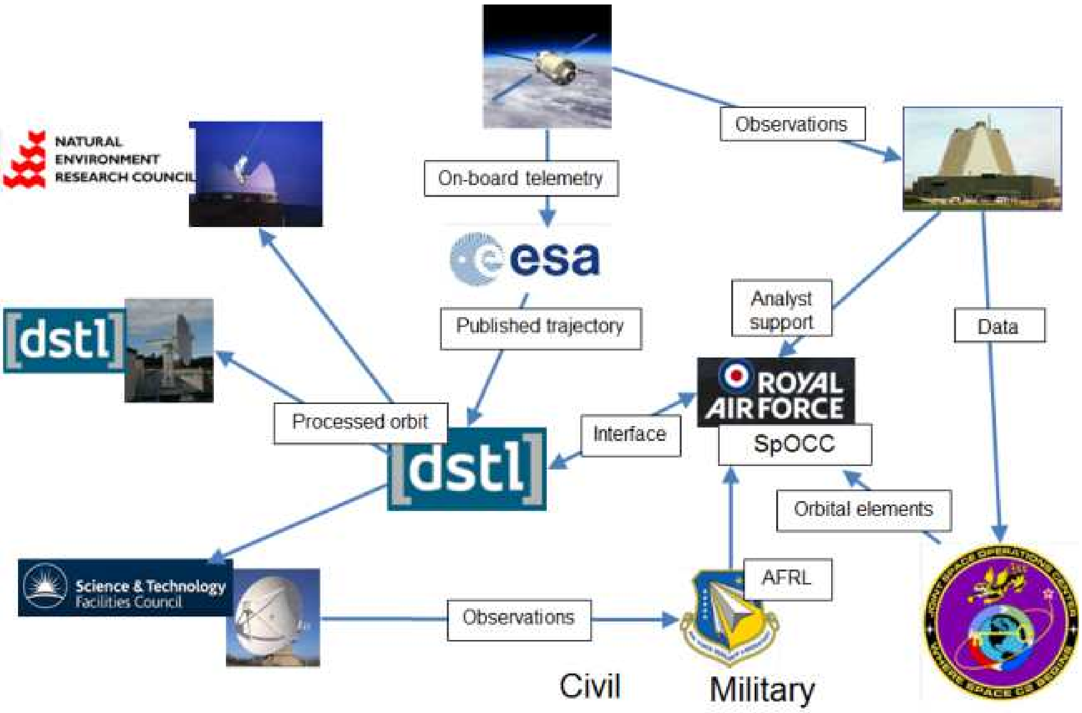

Figure 3 ATV-5 Experiment network

An example of output, from one of the commercial off-the-shelf deployable instruments on a surrogate ATV-5 target, is shown in Figure 4.

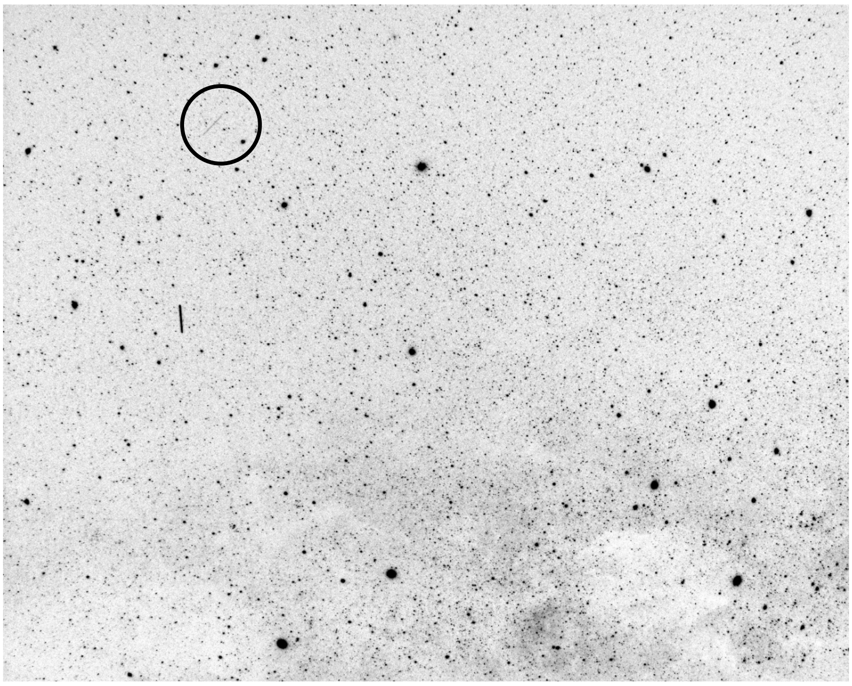

Figure 4: Envisat (the near vertical line) photographed from Lauder, New Zealand on 2015-02-23 10:24 UTC. Note the presence of another, fainter, satellite (circled). The image has been inverted for clarity.

Development and testing of planning & CONOPS procedures for a specific, unusual event was very valuable, and represented the first experimental exercise of coordination of military and civil SSA assets in the UK. Figure 5 shows the development of the processes starting with focused workshops to produce initial procedures which were refined during testing.

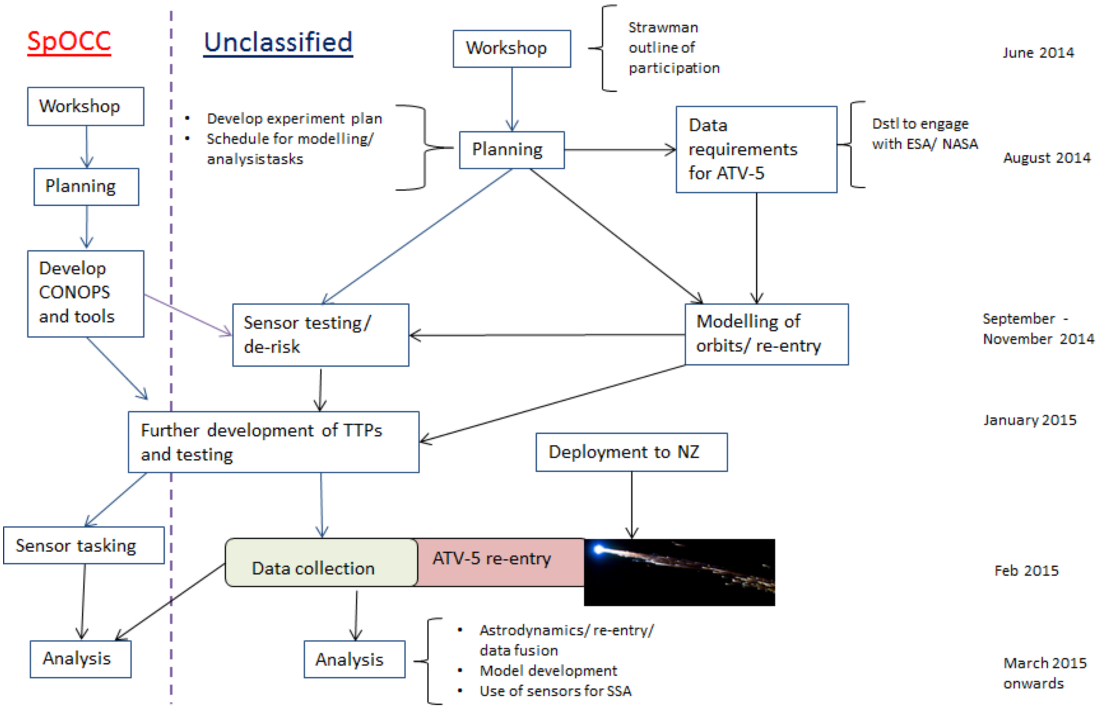

Figure 5 Development of CONOPS for ATV-5

All experimentation can go astray, but detailed and flexible planning and the careful and comprehensive assessment of risk can alleviate this. With approximately two weeks to go, ATV-5 experienced a power failure which led ESA to have to de-orbit it earlier than planned and in a steep dive configuration. The UK military and civil community pulled together to rapidly respond such that we were able to gather data on the re-scheduled manoeuvre prior to re-entry, and also involved use of surrogate targets for the deployed and geographically-dispersed sensors that, analysis showed, would have been able to achieve the original goals of the experiment. Of course, the re-entry aspects were not able to be fully met, but the development and data-gathering exercises were very successful and an invaluable step towards civil-military SSA.

The major achievements and findings of the experiment can be summarized

- Successfully established and executed a large experiment for a one-off event; critical that the approach has inherent flexibility including testing and re-risking of alternative CONOPS. Especially relevant due to re-planning activity at short notice.
- EO sensors deployed at remote geographical locations at relatively short notice.
- Data sharing identified as main barrier to the event; need to establish appropriate mechanisms well in advance.
- Largely utilised non-autonomous & manpower intensive processes: suitable for a one-off event, but highlighted a critical need for further development of standards and network solutions in advance.
- Use of non-traditional sensors meant many SSA functions required development and de-risking[1]: this led to insufficient time to come up with a complete solution prior to the event.
- Unclassified, releasable data collected to support international SSA R&D community, including academia

5.4 GEO SSA and Skynet Relocation Observation (Distributed Architecture [including Space-Based])

Following the success of LEO experimentation, the research now switched to investigating SSA in higher orbits; namely the GEO regime. Although sensor opportunity and events had, so far, tended towards work in LEO, improved SSA in the higher orbits remained a high priority due to the importance and value of resident assets. GEO SSA is primarily supplied by the use of EO assets, either ground or space based. Dstl had previously been working with Space Insight Ltd. to understand potential of EO systems and this coupled with an upcoming manoeuvre of a Skynet GEO spacecraft afforded the opportunity to expand the experimental envelope.

Over the period of a few months, starting in mid-2015, Skynet 5A was moved from a position over the Atlantic to the Asia-Pacific region, involving a longitude change of approx. 95°. This event afforded the opportunity for Dstl to work with the UK Space Operations Centre (SpOC) to further develop, and apply, the planning and assessment concepts from earlier experiments to the higher orbital regime. The SpOC tasked Space Insight to monitor the manoeuvre and also to conduct small scale surveys to de-risk the move. Collaboration with the Defence Science and Technology Group (DSTG), the Australian government research organization, also allowed collection and sharing of data from the end of manoeuvre area.

The Starbrook sensor system, operated by Space Insight on Cyprus, was able to fulfil a number of functions, including detection of the manoeuvre in advance of update of the publically-available TLE catalogue, as shown in Figure 6.

[1] These included functions such as cueing of a non-autonomous tracking dish radar from a TLE, a number of possible antenna steering strategies were considered but could not all be tested to determine the best

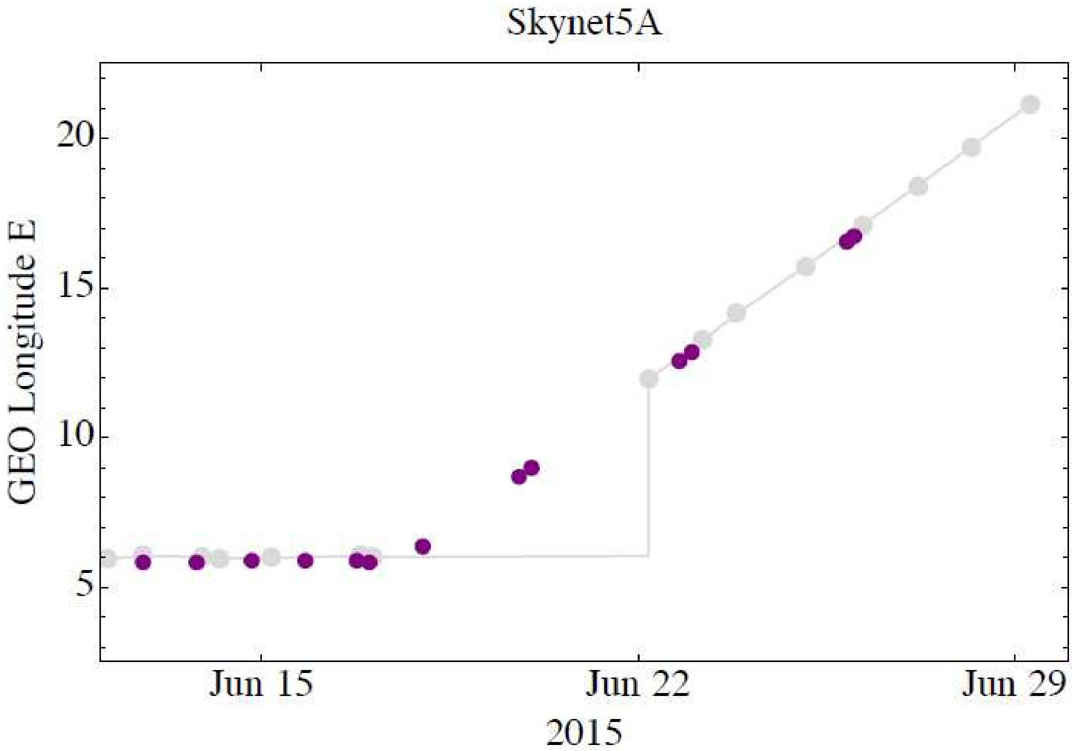

Figure 6: Starbrook observation (purple) showing change of position in advance of public TLE update (grey).

The operator of the spacecraft (Airbus Defence and Space) was actively involved in the planning and analysis which, again, included a series of workshops with wider academia and industry for other contributions of sensors and data exploitation. The University of Warwick exo-planet hunting telescope, SuperWASP, was used to investigate the potential of novel non-traditional sensors. Airbus also supplied ranging information for comparison with sensors.

The CSPO MoU afforded a vehicle to include a space-based SSA element, the Canadian NEOSSat spacecraft, so that the combination and comparison of data from both space-based and ground-based EO sensors could be undertaken. Another AMOS paper describes this in detail.

The experiment not only extended the understanding and investigation of SSA to the higher orbit regime, it included more interaction with the Satellite operator and gave greater insight into their imperatives. Major findings and lesson learned were:

- Processes relied on pre-scripted, non-real-time coordination which was well matched to the operational tempo.
- A delay was observed in accounting for satellite manoeuvre from the publically-available SATCAT TLEs; this was mitigated using EO tasking.
- A number of uncorrelated objects were observed, perhaps corresponding to High Area to Mass Ratio (HAMR) objects that do not behave predictably and therefore deviate from the analyst sets, or are intermittent to observe.
- Data sharing was also identified as barrier to the event; but less critical with lower operational tempo at GEO.
- Collaboration with the active satellite operator was extremely valuable and helped to shape the experiment with actual SSA demands. In this instance, interest was in characterising the object's pattern-of-life at target destination following the manoeuvre.

Figure 7 shows the major sensors and connections utilized in the experiment.

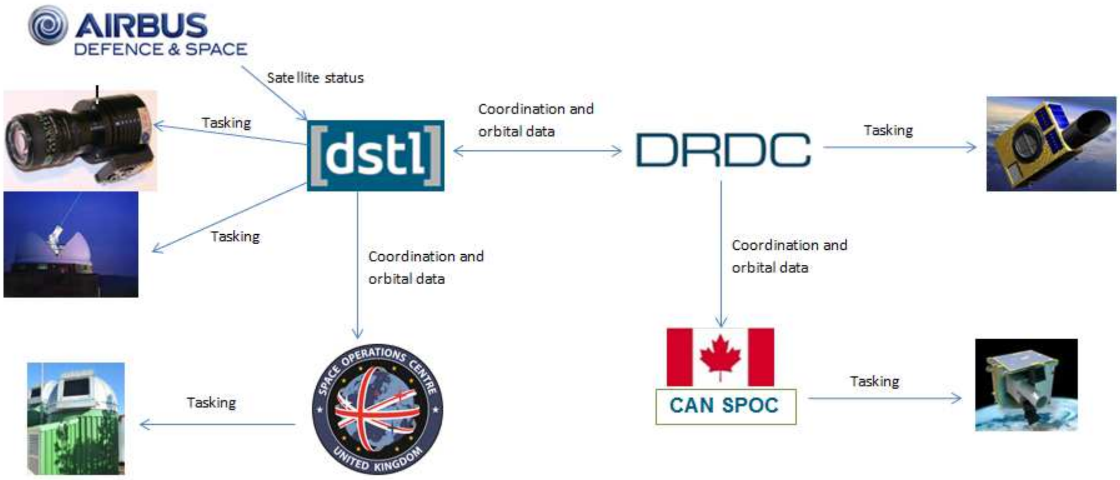

Figure 7 Network used for Skynet movement experiment

5.5 EU Space Surveillance and Tracking Experiments

The follow-on phase of this GEO experiment, building on Skynet observation, focused on further refining the procedures, methods and tools to support UK SSA capability in deep space and in support of the UK SpOC preparations for delivering GEO conjunction services as part of the EU SST framework with FR, DE, ES and IT.

This took the form of a ”pipe-cleaning” exercise. These activities were conducted with Starbrook (Space Insight Ltd.) and the GEOF optical sensor operated by the SGF, and concentrated on developing planning, CONOPS and tasking for UK sensors to prepare for delivery of SST products via the EU SatCen on behalf of the UK which began on 1 July 2016

As well as further developing CONOPS for the network to supply services, development and prototyping of tools to plan operations and manage data were also included. The main achievements and findings from this phase included;

- Processes relied on pre-scripted, non-real-time coordination which was well matched to the operational tempo.
- A delay was observed in accounting for satellite manoeuvre from the publically-available SATCAT TLEs; this was mitigated using EO tasking.
- A number of uncorrelated objects were observed, perhaps corresponding to HAMR objects that do not behave predictably and therefore deviate from the analyst sets, or are intermittent to observe.
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6. ROAD MAP

The methodology of iterative collaborative experimentation has proven an invaluable and efficient way of improving UK understanding and capability in SSA, and has allowed the UK to be better-positioned to respond to the directives of the NSSP and SDSR. The size complexity and demands of the experiments have grown as we have learned more, but also in step with the increasing interest and profile of SSA in both the military and government view.

The SSA future roadmap includes a further set on notional experiments that will be turned into reality as opportunity, requirements and details emerge. Currently, focus is on SSA of a de-orbit sail spacecraft, and planning is already underway.

7. SUMMARY OF FINDINGS AND LESSONS IDENTIFIED

The use of a series of experiments has been critical in progressing UK SSA research. These experiments have progressively increased in complexity and allowed strong relationships to be built across national and international communities. These have occurred over a time frame when the UK policy and involvement in SSA and the technical challenge have grown rapidly.

The findings from the continuing experimental activities have been both technical and logistical. Many of the technical findings have already been reported in separate papers or classified reports, but some key findings are included here for clarity.

Some key findings from this are:

- Demonstration of the rationale for and benefit of using an experiment-centric research methodology
- The use of experiments is highly productive in understanding basic science and constraints
- SSA experimentation provides an avenue to gain involvement and mutual understanding between military, industry and academia
- Capability can be developed as part of the experiment and grown in subsequent ones
- Experimental CONOPS, methods and tools can be transitioned to operational use with increased confidence and speed
- Academia can be engaged to evaluate novel methods and sensors for SSA
- Through involvement in the experiment design, academia can better understand constraints and needs of the operator / end user
- When focused, international research collaboration can produces products in defined time scales
- It has provided valuable insight and contact with international partner nations plans and activities to improve collaboration
- Similarly provision of awareness of UK SSA research to partner nations is highly beneficial for improved collaboration

Some practical lessons identified:

- Appropriate planning tools are essential for SSA operations
- The planning tools do not have to be complex but need to be robust
- Data sharing is a key activity and needs appropriate agreements / mechanisms in place
- Modest non-traditional sensors can make significant contributions to SSA
- Workshops between government, military, academia and industry are highly beneficial
- Placement of academics in specific SSA projects is mutually beneficial
- Leave sufficient time for testing and define and examine alternate operating strategies to determine the best (and have fall-backs)

8. REFERENCES

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