A Summary of 5-Eyes Research Collaboration into SSA

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ASTRACT

International research collaboration (IRC) activities are underway within the 5-eyes military community (UK, US, AUS, CAN, NZ) to enhance allied Space Situational Awareness (SSA) capability and identify on-going cooperative and coordinated experiment opportunities.

SSA is a growing international area of interest as increasing domain access have resulted in space becoming ever more contested, congested and competitive. Governments worldwide have greater emphasis on securing access to services provided from and through the space domain. Science and Technology (S&T) plays a key role by exploring novel solutions to enhance SSA beyond existing system capability and account for future domain challenges. The S&T focus is more basic than Research & Development (R&D) and looks to enable or improve R&D through increased fundamental understanding and identification of knowledge gaps limiting current effectiveness.

Since 2014, representatives from the 5-eyes nations have been enhancing SSA S&T collaboration to support shared national objectives with the aim of enhancing allied SSA operations. In particular, a series of distributed experiments have been conducted to explore the fundamental challenges posed by SSA in terms of sensor scheduling, data sharing, access, and processing, and astrodynamics. Novel sensor performance analysis for SSA has been conducted and provided insight into future SSA architecture design options.

This paper will review progress made to date, some challenges (both resolved and open), and set the collaboration vision to support of initiatives, such as Combined Space Operations (CSpO) Emphasis is placed on open areas of S&T and experimentation where we would value additional engagement from the SSA industry base (including academia) and other possible IRC partner nations. Specific examples of ongoing research and analysis related to de-orbit sail technology orbit determination (under the 'Daedalus' experiment), use of non-traditional sensors for Resident Space Object (RSO) cataloguing, and Active Debris Removal (ADR) concept challenges will be covered.

1. BACKGROUND

Comprehensive Space Situational Awareness (SSA) can only be provided by international networks, encompassing sensors, Concept of Operations (CONOPS), data processing, communications, procedures, quality assurance and security elements. The United States, United Kingdom, New Zealand, Canada and Australia (the '5-eyes') have common requirements of continued space domain access and associated services delivered through space that are critical for national prosperity and security. Modern military forces derive battle-winning capabilities from space domain services such as Precision Navigation and Timing (PNT), Satellite Communications (SATCOM) and Intelligence Surveillance and Reconnaissance (ISR) which has led to common interest amongst space-faring allies in managing risks that could affect service delivery. SSA provides information about the manmade population of

Resident Space Objects (RSOs) around the Earth, their interaction with the space environment to enable mitigation of risks and hazards to allied space systems as well as attribution of anomalous events to possible causes.

SSA presents numerous technical and non-technical challenges that must be addressed to develop an effective and adaptable framework capable of meeting present and future national needs. The 5-eyes Science and Technology (S&T) community is working collaboratively to address common these challenges for the purpose of enhancing combined space operations; which forms the topic of this paper.

This paper::

- Presents national perspectives on the drivers related to SSA, from the personal view-points of the paper authors and with specific focus on R&D with the 5-eyes;
- Reviews historic and ongoing SSA collaborative initiatives;
- Details extant research requirements identified by the 5-eyes S&T community;
- Details next steps and opportunities for wider international collaboration.

1.1 UK NATIONAL PERSPECTIVE

The UK has been an active partner and participant in international 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) via the contributing sensor at RAF Fylingdales. UK research activities have historically centred on understanding the optimal utility of data sourced from these networks, whilst also investigating the potential utility of non-traditional 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 has resulted in increased investment into indigenous SSA capabilities to meet both civil and military needs[1]. This was formally recognised by the UK Ministry of Defence (MOD) in the 2015 Strategic Defence and Security Review (SDSR) that committed MOD to develop SSA processing capabilities centred on the UK Space Operations Centre (UK SpOC)[2]. As a consequence of the SDSR in 2015 the MOD Chief Scientific Advisor (CSA) portfolio was enhanced through the establishment of a bespoke space research programme in 2017; which is delivered within the Defence Science and Technology Laboratory (Dstl).

SSA has a specific project in the space programme with two focus areas:

- Enhancement of the UK SpOC,
- Development of capabilities to support characterisation of RSOs.

The project has a broad remit to explore future challenges of the space domain and determine their impact on national needs for SSA systems being developed within UK MOD. Furthermore Dstl undertakes studies and technology maturation activities to help inform on options to enhance UK SSA as our requirements evolve, centred on inputs in the UK SpOC enhancement for cataloguing of RSOs and delivery of operational services; and Joint Forces Command (JFC) with the characterisation of RSOs to support services such as satellite warning.

Broadly our technical tasks are grouped as follows:

- Space scenario analysis to support UK requirement definition,
- Characterizing future space domain challenges and possible solutions,

[1] NSSP 2014
[2] SDSR 2015

- Prototyping astrodynamics and data processing capabilities,
- Architectural modelling and assessments to help definition of future UK SSA architecture,
- Advising MOD on options to develop a cataloguing capability,
- Experimentation (national & international) to inform future development,
- Data processing to support pattern of life/ proof of life of RSOs.

This work is delivered by a mixture of activities internally within Dstl as well as by UK suppliers, accessed via the Astrodynamics Community of Interest (ACI) established by Dstl as a route to engage with industry and academia. International Research Collaboration (IRC) forms a central pillar of the project design, with particular emphasis on the opportunities to work within the 5-eyes community exploiting existing collaborative agreements. Dstl has often taken a central role in planning joint SSA experiments with the international community to enable coordinated data collection from geographically dispersed locations that support research into sensor tasking and performance as well as data processing and fusion; to increase our understanding of how novel solutions may be utilised to enhance UK SSA capabilities. These experiments include the 2015 ATV-5 re-entry, 2015 SKYNET relocation manoeuvre, Daedalus de-orbit experiment and RemoveDebris satellite; all of which are detailed further in this paper.

1.2 US NATIONAL PERSPECTIVE

SSA is a broad subject that has many different technical problems that need to be addressed. For simplicity, we break these down into 3 categories:

- Orbit dynamics (including maneuver detection and collision avoidance),
- Data inadequacy,
- Characterization.

For orbit dynamics, the sheer size of the battlespace (roughly 350 earth volumes) makes it hard to detect everything all at once. The growing population of RSOs presents difficult problems just with the sheer number of objects. There is an abundance of data being generated, but many of it remains unprocessed and uncorrelated. The vast battlespace and size of the population presents issues with discriminating between natural and man-made space activities. Even with many observations being generated, this data is insufficient. Areas of GEO are difficult to observe and the observations often don't provide enough information to know what is going on. New launch direct ascent timelines are challenging to track, often with multiple payloads, exacerbating the problem. The evolution of space technology has given rise to more capable systems with lower Size, Weight and Power (SWAP), making them very capable, and hard to observe. Finally characterization needs to assess situations are still being quantified for BMC2. The information needs are not yet well understood and disparate data assessment needs normalization. This drives a need for a holistic view of SSA as well as the need to develop quantified, actionable information needs. IRC with the 5-eyes provides a route to obtain this holistic view of the problem through the engagement with different research communities that have novel ways of tackling these challenges.

1.3 AUS NATIONAL PERSPECTIVE

Australia is increasing its contribution to the global space situational awareness (SSA) problem by committing to acquire and operate SSA sensors. The Australian Defence White Paper was released on the 25th of February 2016 [1] and stated Australia's commitment to strengthen space surveillance and situational awareness, to ensure the security of our space-enable capabilities. In cooperation with the United States, Australian has become home to the space surveillance C-band radar at Harold E. Holt Naval Communications station in Western Australia. The United States Space Surveillance Telescope (SST) will also be relocated to the same location which will significantly increase Australia's capacity to detect and track objects in space.

Along with the Defence White Paper, the accompanying Integrated Investment Program was also released in 2016 [2] which outlines the areas of Defence capability investment. The Australian Defence Force (ADF) will invest in additional space surveillance systems to the order of $1-$2 billion to expand Australia's space situational awareness sensor coverage in the future.

Since 2012, DST Group has been performing research in the field of SSA focussing on the areas of data processing, sensor fusion, uncertainty characterisation and orbit determination, leveraging previous expertise in these fields from other domains. Australia has collaborated successfully with international partners in an attempt to coordinate and eliminate duplication of effort. As an example of this productive collaboration, Australia and the United States have exchanged personnel between DST Group and the Air Force Research Laboratory for extended periods of time.

To complement the SSA research, DST Group has constructed two research grade observatories (one fixed and one portable) to generate SSA surveillance data. The portable observatory is able to be deployed for experimental campaigns to improve observability and demonstrate fusion from different sensor locations. These observatories have been utilised to successfully implement catalogue maintenance, orbit determination and sensor scheduling algorithms [3,4]. The sensors have also been used on a number of experimental campaigns under the CSpO effort and other initiatives with our international partners.

The application of non-traditional sensors to the problem of space command and control has led to a fruitful partnership between DST Group, international partners, academia, and industry. DST Group is performing research into novel sensors that have the ability to perform SSA including event based sensors [5], passive radar [6] and high frequency line of sight radar [7].

The Next Generation Technologies Fund is managed by the Defence Science and Technology (DST) Group and is a forward looking program focussing on research and development in emerging and future technologies. The Next Generation Technologies fund is focussed on nine priority areas one of which is space capabilities to ensure we meet Defence's future needs.

DST Group has recently published its science and technology strategy for space which details the intention for continued research in the field of situational awareness and automated control. Ground based systems will include an SSA capability that is networked with a global system and a command control system augmented with cognitive processing to enable mission-level user operations and analytics. An early theme target is the demonstration of an automated space domain monitoring capability in year 3 with a further theme target of controlling a constellation in year 7.

1.4 CAN NATIONAL PERSPECTIVE

The Canadian Armed Forces has a significant history in the area of space surveillance. Canadian involvement began with the operation of two film based Baker-Nunn telescopes, from 1958 until the 1990s, that were used to track satellites as a Canadian contribution to the US SSN. Canada's contribution - which continues to this day - includes regular military personnel support including (through NORAD) staffing and operating radar sites which perform Space Surveillance as a part of their continental defence role. In the late 1990s, recognizing the importance of understanding of the situation in space, National Defence initiated the development of the Canadian Armed Forces' first military satellite: Sapphire. Launched in 2013, Sapphire helps Canada meet its Space Surveillance commitments by contributing tracking data on deep space RSOs as a contributing sensor to the SSN. Furthermore in 2014 Canada became a signatory to the CSpO construct, enshrining space operations as a duty of the Canadian Armed Forces as part of an allied partnership of 5-eyes nations. Within Canada, the stand-up of the Canadian Space Operations Cell (CanSpOC) forms the operational backbone of the Canadian Armed Forces' activities in space. Canada's contributions to the SSN, combined with the CSpO partnership, are the key underpinnings of Canada's defensive space activities.

Following the Canadian Forces' lead, research has been initiated in the area of space mission assurance which includes SSA. This SSA work is led by Defence R&D Canada (DRDC) and tailors advice on SSA technology in two primary areas for the Canadian Armed Forces

- Operational Capabilities relying on systems providing security, reliability (e.g. space system heritage) and high performance,

- Technology look-ahead which explores the state of low technology readiness (TRL) technologies where future advantage can be derived, but lacks the heritage requirements for the Canadian Forces operational use in space operations.

Between 2000 to 2018 the technology approach pursued by DRDC in SSA emphasized the use of small optical telescopes within a networked, distributed architecture to provide capabilities of much larger systems (but at reduced capital expenditure) through the integration of commercial off the shelf telescope systems. This research path helped Canada develop the Ground Based Optical (GBO) system, a network of telescopes in Canada which became operational for a short time in 2011. The GBO activities also helped DRDC develop a space-based SSA system: the Near Earth Observation Surveillance Satellite (NEOSSat). NEOSSat, a microsatellite-based space telescope, offered DRDC a chance to explore the role these small satellite systems might have in the military world. Their combination of small size, focused capability, and heavy use of commercial grade parts, offered a low cost entry point for a small organization to begin performing space operations R&D, as well as providing a research capability to explore SSA problems which cannot be performed from the ground.

Canada values the collaborative defensive SSA research partnership offered by the 5-eyes, where the partners' distributed geography, technical skills, and resources provide a collective research advantage working the global problem of space object tracking. Canada is contributing to the 5-eyes SSA research initiative by contributing space-based astrometric and photometric data from NEOSSat, some operational tracking data from Sapphire, and ground based electro-optical tracking data from telescopes operated and maintained by DRDC. Accessing the international reservoir of skilled diverse expertise enables research to be performed in a cost effective manner while helping build the community's collective capabilities.

Since the collaborative SSA research effort was formed, Canada has contributed to the following SSA experimental activities (detailed later in this paper):

- 2015: Observations of the Skynet 5A relocation (Sapphire and NEOSSat)
- 2017: Observations of the CanX-7 Drag Sail deployment (GBO Ottawa)
- 2017: Observation of the OA-8 Re-entry (GBO Ottawa)
- (Current) Observations of the UK RemoveDebris microsatellite experiments (GBO Ottawa)

The R&D program at DRDC directly supports the development of the new operational SSA capabilities for National Defence. Many of the requirements for the upcoming Surveillance of Space 2 project, the follow-on to Sapphire, were derived from the findings of experiments performed during collaborative research with the 5-eyes nations, or technical exchange meetings. Future space surveillance and SSA research performed by DRDC will focus on internal client-related S&T and engagement with academia and industry in future looking space surveillance problems.

1.5 NZ NATIONAL PERSPECTIVE

Since 2014 there has been a steady increase in the SSA capability at the Defence Technology Agency (DTA) and within the New Zealand Defence Force (NZDF). The development started with the preparations for the shallow de-orbiting of ATV-5, originally scheduled to take place in early 2015. Initial plans were made to undertake a joint UK/NZ trial in order to observe this event. Although the original re-entry scenario was subsequently altered by ESA, so that the event was not visible from New Zealand, the joint trial was conducted and a number of surrogate targets were observed using readily available, off-the-shelf equipment, such as CCD cameras fitted with standard photographic lenses. It was demonstrated that relatively inexpensive, portable equipment can be used to determine the position of a satellite in low Earth orbit (LEO) with an average precision of 10-15 metres in space.

After the initial success of the ATV-5 trial, a decision was made to continue building the SSA capability in New Zealand. DTA now operates a small SSA observatory located at Whangaparaoa Peninsula, just north of Auckland. The observatory has a 3-metre dome, equipped with a robotic tracking mount, a couple of 11-inch telescopes and a number of cooled CCD cameras. This gives us the ability to track smaller objects in LEO and GEO (geostationary Earth orbit). Currently, the observatory is undergoing a major modification to become a fully automated facility, for a significant increase in data collection efficiency.

Both astrometric and photometric observations are part of the DTA SSA programme. In addition, a specialised quadruple polarimetric camera (QuadCam) was recently built, using an approach devised in the UK at Dstl. Some modifications to the camera were made at DTA for improved performance. The initial results, based on observations of satellites in LEO, have demonstrated that the polarimetric signature of an object in space provides additional information that cannot be obtained from photometry alone.

At DTA we use our own software tool, StarView, which has been developed specifically for automated astrometric and photometric analysis of images taken with our SSA equipment. The software is capable of fast and efficient astrometric calibration of images covering a range of field sizes, from under one degree to over 30 degrees in diameter. This has been achieved by optimising the image reduction algorithms to best match the sensor specifications.

It has been recognised that New Zealand has a unique geographic location in the South Pacific, which offers an opportunity to monitor satellite passes that cannot be observed from any other location. For example, many satellites scheduled for deorbiting often pass above New Zealand before entering the atmosphere over the Pacific Ocean. Having a robust SSA capability in New Zealand offers a possibility for international collaboration in this area, in particular in support of collaborative efforts between the 5-eyes countries. Given current priorities within DTA our focus is placed on provision of data collection and image analysis for specific satellites that are of interest to NZDF and wider operational community that exploit this geographic advantage.

2. INTERNATIONAL RESEARCH COLLABORATION

"Why we do it"

International Research Collaboration (IRC) is a mechanism by which different nations pool resources to jointly address topics aligned with national priorities. It leverages numerous smaller research budgets to achieve results comparable with a larger programme and strengthens partnerships thereby improving coordination and cooperation among coalition participants. Furthermore, niche expertise within each host nation can be brought to bear to avoid unnecessary duplication whilst achieving results exploitable by the community.

Within the SSA domain, IRC is a key component in developing technical solutions to meet space domain challenges. The nature of SSA requires a global coordinated solution from the outset due to global access and dynamics of RSOs. Furthermore, whilst 'New Space' opportunities (academic, commercial, and government) are looking to enhance national exploitation of space, they pose challenges to SSA systems. Increased access to launch, 'mega constellations', active debris removal, and on-orbit servicing concepts present various challenges that may exceed the original capability of existing SSA systems. IRC presents one method where research communities from multiple nations help investigate these emerging challenges to inform development of future equipment.

"How we do it"

The specific focus of this paper is IRC amongst the '5-eyes' community consisting the UK, US, Australia, New Zealand and Canada; which have a long history of research collaboration in a multitude of technology areas including space. To enable IRC, there are a variety of tools that can be leveraged depending on the activity required for collaboration and the strength of the shared research interests. The foremost tool is a Research, Development, Test and Evaluation (RDT&E) framework agreement that provides the participating nations the ability to explore areas of mutual interest, and once found, to build collaboration through the leveraging and sharing of national resources. A RDT&E framework agreement is often codified as a Memorandum of Understanding (MOU), the most prominent RDT&E framework is The Technical Cooperation Program (TTCP) MOU. With its roots stemming from collaboration activities in the 1950s, the TTCP MOU enables 5-eyes collaboration that spans from basic research and information sharing to collaborative prototyping. It has a unique management structure and has at least nine domain-focused technical groups that manage collaborative activities within their purview.

For IRC related to the SSA domain, the TTCP MOU is leveraged heavily to enable data sharing and to promote a strong cross-flow of communications. More specifically, the SSA interests are incorporated into the Intelligence, Surveillance, Target Acquisition and Reconnaissance technical group to support the development of collaborative interests.

Another RDT&E framework agreement that exists and can be utilized for the SSA domain is the Responsive Space Capabilities (RSC) MOU which not only includes the 5-eyes but also five other space-faring nations. This RSC MOU provides the framework to develop and execute projects, to establish Working Groups, and to exchange personnel for research, development, test, and evaluation among the participants specifically in the area of Responsive Space defense capabilities.

Furthermore the 5-eyes community have agreements that enable reciprocal RDT&E data exchanges as well as the exchange of engineers and scientists between the defence laboratories who can work on select projects that match their personal and national interests.

Lastly, there are agreements that help drive policy considerations and capability requirements for the community as it pertains to space operations. One such agreement is the Combined Space Operations (CSpO) Initiative MOU. Although not legally binding like RDT&E framework agreements that allow IRC, CSpO strives to move the 5-eyes community towards more integrated space operations. An outcome to this endeavour is a combined effort to harmonize the national capability development requirements which can help drive the IRC interests and provides indicators to the scientific community.

All told, a variety of tools that enable IRC are at the disposal of the 5-eyes community. The most utilized tool remains the TTCP MOU but other tools are available depending on the specific interests and activities desired amongst the 5-eyes for SSA collaboration.

"Challenges associated with establishing IRC"

The following represent challenges encountered that must be addressed to enable effective research cooperation:

- Understanding the event that precipitated the requirement for coalition forming & extent/lack of sanctioning by international body,
- How coordination of disparate entities can be focused towards common goal; through single leader directing all participants or extensive coordination of each entities direction,
- Clearly defined mission, objectives, and rules of engagement to include timelines for ensuring unity of purpose for common direction,
- Appropriate representation among all entities knowledgeable in entity capabilities/limitations for effective use of entity time and resources,
- Appropriate entity POC cognizant of other entity concerns and positions.

The remainder of the paper explains the process to date against these challenges as related to SSA IRC.

3. UNDERSTANDING OUR SSA IRC NEEDS AND APPROACH

Effective IRC requires an understanding of coalition needs and a mechanism to enable effective coordination of effort; for SSA this is a complex process as the domain features many challenges, both technical and non-technical. Experimentation has been employed by the 5-eyes community to explore and articulate coalition SSA needs. This approach has revolved around a series of focused and increasingly complex experiments to understand collective requirements and capability needs across the group. These experiments have also afforded the opportunity to investigate technical challenges using real world events on targets of interest to military stakeholders, for instance the use of low-cost commercial off-the-shelf sensors to augment traditional expensive legacy SSA assets as well as novel methods for data processing. Furthermore we have explored different mechanisms to coordinate these activities through the use of a variety of international constructs for the purposes of experiment planning and data sharing; which has subsequently help inform the coordination of longer-term IRC.

This section summarises some of the key experiments undertaken by the 5-eyes community to understand national SSA needs.

3.1 ATV-5 RE-ENTRY EXPERIMENT

Background

To better understand re-entry science, National Aeronautics and Space Administration (NASA) and European Space Administration (ESA) planned a slow-controlled and well-instrumented re-entry of ATV-5 in 2015 after its final re-supply of the International Space Station (ISS). A major focus of this work was to better understand break-up science (and refine modelling capability) to support future de-orbit of the ISS. The shallow re-entry and instrumentation presented both unique challenges and SSA research opportunities. NASA and ESA were eager to extend the experiment to include SSA and, as such, an international network of traditional and non-traditional sensors was established to gather data on the event. The 5-eyes community exploited this opportunity to explore SSA challenges as applied to the LEO domain with specific focus on re-entry risk management for a high interest target.

Challenges Explored

The following bullets summarise the technical aspects explored by the 5-eyes community during the ATV-5 experiment:

- Use of deployable non-traditional sensors for LEO SSA, focussed on deployable optical sensors (conducted on a UK & New Zealand bi-lateral basis under a 5-eye MOU),
- Assessment of an existing UK non-SSA radar (originally used for meteorology) to support LEO observations, and enhancement using deployable bi-static radar receiver,
- Data fusion and orbit determination using astrodynamics software developed by UK and AUS,
- Visualisation of non-traditional sensor data used to observe LEO targets using prototype US AFRL tools deployed on an experimental network (bilateral UK-US activity under UNITY PA), shown pictorially in Figure 1,
- Effective co-ordination of sensor task and event monitoring by the 5-eyes space Operational Centres (OCs), conducted under the CSpO umbrella agreement.

Initially a wider investigation of re-entry dynamics and prediction had been envisaged but were not able to be explored due to a change in the schedule for ATV-5 caused by a technical issue with the spacecraft.

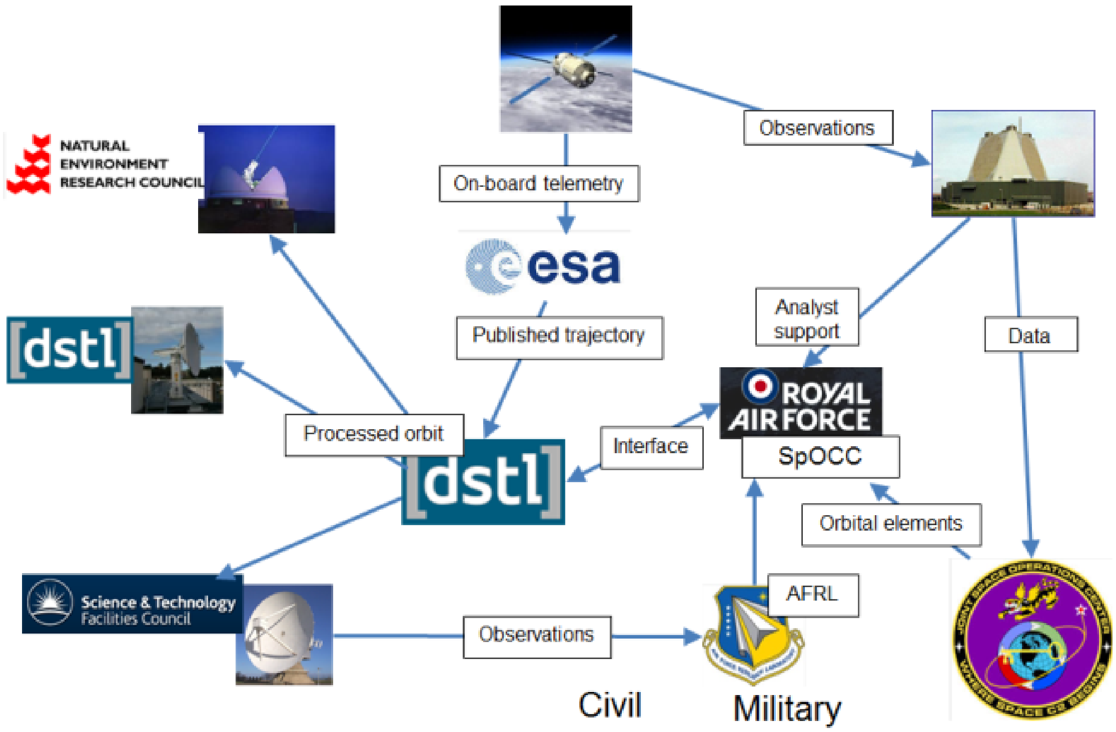

Figure 1: ATV-5 Experimental network

Conclusion
From the experiences of the ATV-5 experiment the following areas were identified as being of high importance to 5-eyes SSA research:

- Sensor tasking and cueing across a geographically and organisationally distributed sensor architecture,
- Use and performance of low-cost EO sensors across all orbital regimes (LEO to GEO) for varying SSA missions,
- Utility of re-purposed tracking radar to support orbit determination and cataloguing,
- Methods to enable data sharing (sensor observations, catalogues etc.) across a network,
- Need for automation of processing to replace the largely non-autonomous & manpower intensive prototype capabilities; understanding the scaleability of these processes for different missions,

3.2 SKYNET MOVE EXPERIMENT

Background
Following on from ATV-5, research switched to investigating SSA of higher orbits; namely the Geosynchronous Earth Orbit (GEO) regime. Via contacts with the operator of the SKYNET constellation (Airbus Defence and Space) Dstl became aware of an impending re-location of SKYNEY 5A along the GEO belt, motivated by the re-distribution of bandwidth across the fleet. This event was utilised by 5-eyes to better understand needs and challenges for SSA missions associated with higher orbits, especially given the importance and value of resident allied assets in GEO. From June 2015 to August 2015, SKYNET 5A was moved from a position over the Atlantic to the Asia-Pacific region, involving a longitude change of approximately 95° or ~1.5degrees per day. A number of sensors located along the transit corridor were utilised to observe the event in concert with 5-eyes SpOCs.

Challenges Explored
The following bullets summarise the technical aspects explored by the 5-eyes community during the move of SKYNET 5A:

- Tasking of terrestrial EO sensors to monitor the manoeuvres of SKYNET, featuring UK and Australian assets,
- Surveillance, initial orbit determination and cataloguing of objects within a given region of GEO, e.g. the destination for SKYNET 5A,
- Data processing and cueing between terrestrial and space-based SSA sensors, using UK Starbrook and Canadian NEOSSat respectively, as represented pictorially in Figure 2,
- Characterisation of deep space objects using photometry data,
- Astrodynamics and data fusion using prototype capabilities.

Conclusion
The following areas were identified as SSA needs from the SKYNET move:

- Need for methods to characterise satellite manoeuvres (known or unknown) and associated methods to incorporate these dynamics within a catalogue,
- Methods to process uncorrelated objects believed to be related to High Area to Mass Ratio (HAMR) objects; techniques to account for their complex behaviour and motion in astrodynamics,
- Initial Orbit Determination (IOD) for angles-only EO data for deep space (GEO and GTO) regimes,
- Catalogue design to account for high drag and/or manoeuvring targets.

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

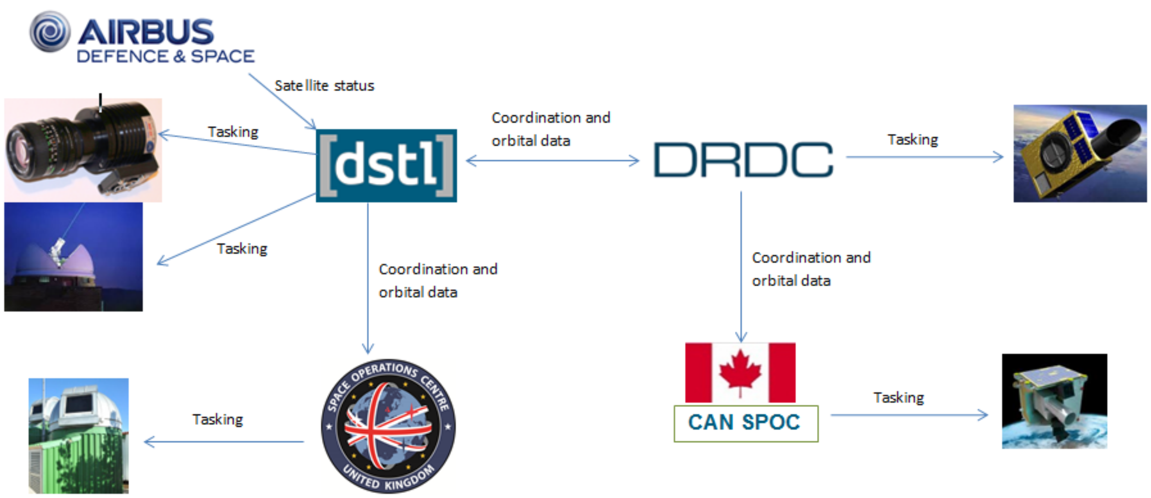

Figure 2: Network used for SKYNET movement cueing experiment

3.3 ORBITAL ATK DE-ORBIT EXPERIMENTS

Background
In 2017 the CSpO S&T community was invited by AFRL to participate in a joint observation campaign on the OA-8 Resupply Mission re-entry and deorbit process. The OA-8 (Cygnus) spacecraft is a commercial unmanned resupply vehicle designed to replenish consumables for the International Space Station. The OA-8 vehicle is a 3.07 m diameter by 6.3m long cylinder with two circular solar arrays each of approximately 3m diameter (see Figure 3) and represent a particular challenge for space surveillance sensors given the nature of controlled de-orbit dynamics. This event provided an opportunity to re-examine the SSA needs captured by the 5-eyes during the ATV-5 experiment, including aspects related to the re-entry portion of the event.

The OA-8 resupply vehicle was identified as SSC# 43006 or Cospar ID: 2017-071A. OA-8 flew in a 51.6 degree inclination orbit to rendezvous with the ISS on 14 Nov 2017.

Figure 3: OA-8 near the ISS (Image courtesy of Orbital ATK)

Challenges Investigated

- Methods to enable the characterisation and tracking of deorbit manoeuvres
- Observations of the OA-8 vehicle for the purpose of target characterisation
- Validation of sensor measurements by comparison of observations to operator reference orbital data to give absolute error estimates,
- Methods to coordinate the sharing of telemetry data between US-based operators to the 5-eyes SSA research community (achieved using a Collaborative Research Arrangement (CRADA) for the duration of the re-entry process),
- General perturbations OD to generate non-SSN TLEs,
- Sensor tasking based on TLEs generated across the research community

Findings

Overall, the 5-Eyes R&D sensor network reported some observations by the UK Chilbolton radar sensor. The Ottawa and Edinburgh optical sensors attempted observations but had issues centering the target (Ottawa) or experienced heavy cloud cover during observing (Edinburgh). The Chilbolton sensor operator's commentary on its observations suggests that OA-8 was detected at low elevation angles but was lost during the remainder of the track with -10 km in-track position error compared to their TLE estimate of OA-8's position. This suggests OA-8 had a large in-track error appearing as detectable near the horizon, but was lost during its higher elevation pass. This is believed to be due to the projection effect of the target's motion as viewed relative to the beam width of the radar transmitter.

Canada did not detect OA-8. It is suspected that the translation between operator ephemeris to TLE (the required format for telescope pointing) was not performed on the correct epoch to track the object. There is also some uncertainty whether or not OA-8's final maneuvers were actually performed by OA-8 during the 12-13 Dec 2017 timeframe. The Australian optical sensor at DSTG was obscured by cloud cover therefore no observations were reported.

In terms of SSA needs the following points were captured:

- Further development of tracking and astrodynamics to account for de-orbit manoeuvre profiles to help manage risks during these events,
- Effective data sharing agreements need to be established between spacecraft operators and SSA operators,

3.4 DAEDALUS EXPERIMENT

Current SSA sensors and processes are designed for objects exhibiting near-ballistic dynamics. This assumption was somewhat reasonable given the original system requirements for SSA that were primarily concerned with the observation of large, low area to mass satellites used for Earth Observation purposes in orbits that were relatively stable. Astrodynamics processes based on general perturbations methods are well suited to this purpose but sacrifice fidelity of physical dynamical models in order to be computationally efficient given computing available in the 1960s.

However the dynamics exhibited by satellites becomes very much more complex as satellites have reduced in size, increased their manoeuvre capability and now occupy orbits more susceptible to the effects of non-conservative forces excluded from GP models. In recent years the growth of the space debris population has necessitated a re-examine of how the environment is managed. The Inter-Agency Debris Committee (IADC) has recommended to the UN in a 25-year de-orbit requirement be adopted for new satellites launched into LEO; this guideline has been adopted across a broad segment of space-faring nations, including 5-eyes.

De-orbit is traditionally achieved using rocket motor burns but this is expensive, so alternatives are being explored that will meet the 25-year requirement with low-cost technology. SSTL satellites TechDemoSat-1 (TDS-1) and Carbonite-1 (CBNT-1) are fitted with Cranfield University Icarus de-orbit sails designed to effect re-entry within 25 years. University of Toronto CanX-7 nanosatellite has a similar sail. These de-orbit sails increase the effect of non-conservative forces (primarily in the form of atmospheric drag) on the host satellite.

The Daedalus experiment aims to explore the effect of this technology on current and emerging SSA systems. A collaborative team across the 5-eyes community has been involved in the experiment planning and execution since 2016 with the following stated aims:

- Quantify impact of de-orbit sails on current SSA astrodynamical processes & hence infer their potential impact on SSA services
- Comparison of TLEs to ground-truth telemetry data
- Capture implications for current and future UK systems and requirements (processing & sensors)
- Assess process that can provide change detection / signature characterisation during sail deployment
- Quantify the efficacy of the de-orbit sail via drag determination

Status

At the time of publication the 5-eyes have collected photometric observations on the CanX-7 nanosatellite during its sail deployment. Figure 4 shows photometric data during the first two sail segment deployments using DRDC sensor assets during a pass over Eastern Canada on 4 May 2017. The step in the light curve near the 82.5 minute mark is an indication of the first sail's unfurling increasing the cross sectional area of the microsatellite.

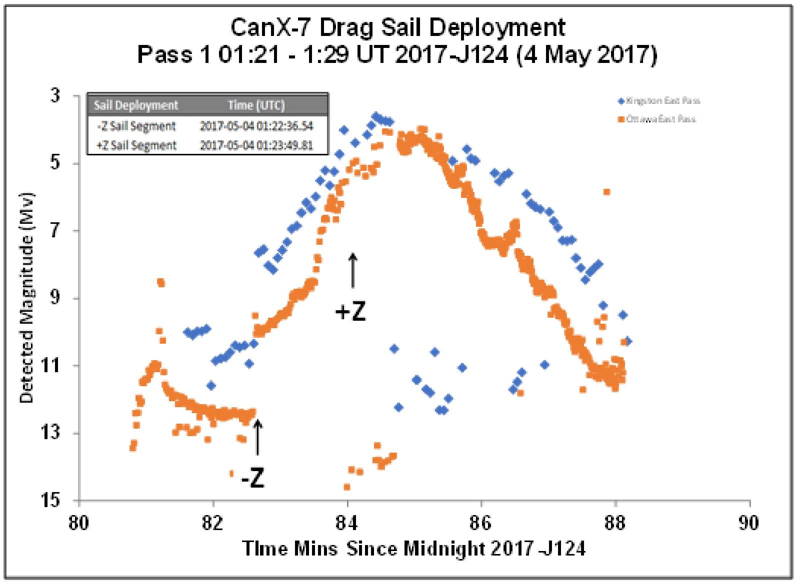

Figure 4: Photometry of the CanX-7 Drag sail deployment[3]

The UK has utilised the iTelescope network (via a contract with BAE) to observe the CanX-7 satellite. Figure 5 represents the locations of the sensors within the iTelescope network and Figure 6 provides an example image during one of the observation periods.

Figure 5: UK Sensor Network including iTelescope harnessed during CanX-7 deployment

[3] Scott, R.L., Thorsteinson, S., Bedard, D., Cotton, B., Zee, R., "Canadian Ground Based Optical observations of the CanX-7 Drag Sail Deployment" Canadian Aeronautics and Space Institute ASTRO 2018, Quebec, QC.

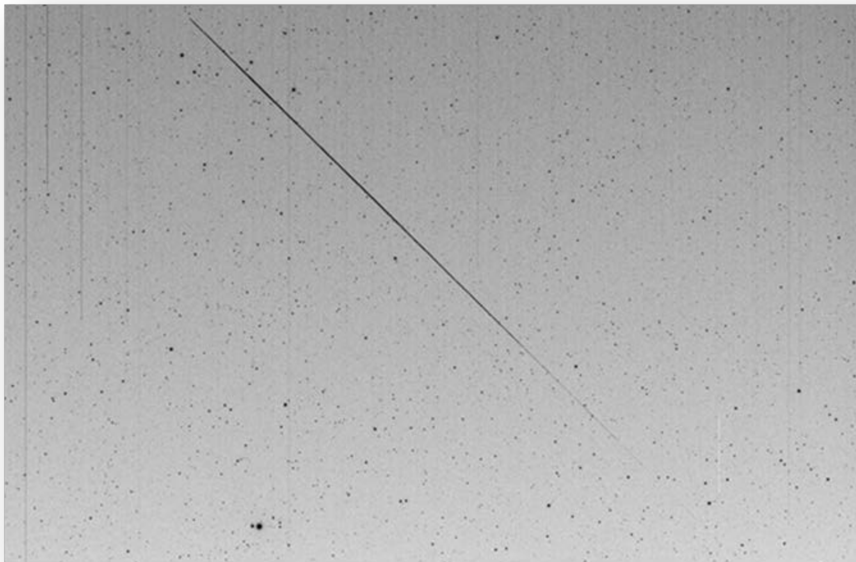

Figure 6: Image from iTelescope system captured after the CanX-7 de-orbit sail deployment. Image courtesy of BAE Systems Ltd.

CanX-7 is still decaying from its initial orbit and is expected to renter in the next 3-4 years. Analysis is ongoing on data collected from the observation period, including orbit determination processes. Initial findings suggest that more work is required to account for high drag and non-conservative forces within dynamical models to enable the future position of targets with drag sails to be effectively monitored.

At the time of publication initial planning is underway for the deployment of the Icarus sail on Carbonite-1, expected to occur late-2018.

3.5 REMOVE-DEBRIS EXPERIMENT

Background
RemoveDebris is a UK-led space debris mitigation technology demonstration small satellite deployed from the ISS in June 2018. The microsatellite will test a variety of space debris mitigation technologies by deploying sub-satellites from the main satellite bus to test a) an optical spacecraft orientation experiment, b) space debris capture net, c) a debris capturing harpoon test and d) a drag sail. In addition to the main technical findings that RemoveDebris offers, the sub satellite deployments, capture net experiment and drag sail unfurling offer unique characterization opportunities for the SSA research community.

Status
In preparation for the in-orbit trials, researchers have begun observing RemoveDebris' photometric characteristics in order to establish a comparison baseline. Figure 3 shows the detected photometric attributes of RemoveDebris as detected by the Ground Based Optical telescope in Ottawa, Ontario, Canada. Preliminary characterization observations helps communicate sensitivity requirements to other observers so that they can properly configure their instruments prior to observation and aids observers during the experiments to make comparisons with the in-orbit experiments with the initial baseline. This helps build collective understanding of the space objects prior to performing the in-orbit experiments.

It is noticeable in Figure 7 that there can be a large brightness change of RemoveDebris during a relatively constant phase angle pass. The light curve shows relatively monotonic changes in brightness and there is an absence of oscillation in the light curve. This preliminary data indicates that the satellite is stabilized during its pass relative to the ground telescopes. Sample imagery of RemoveDebris as observed by Ottawa is shown in Figure 8.

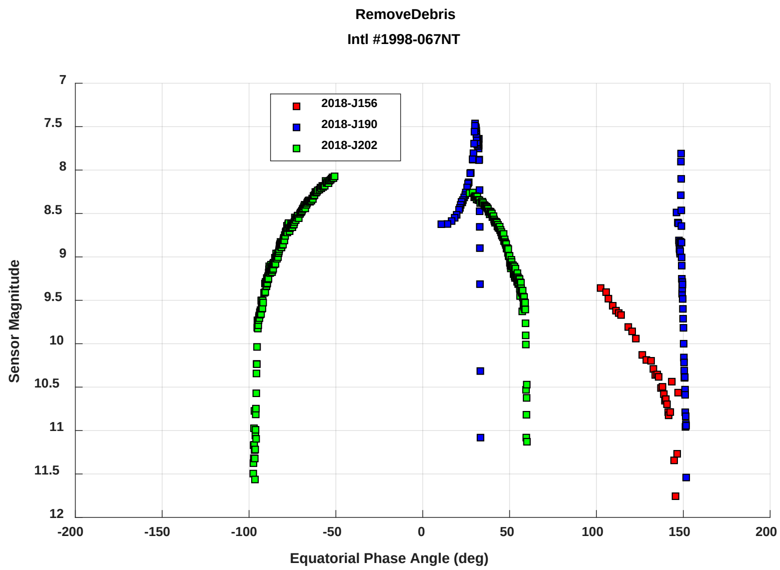

Figure 7: Baseline photometry of the RemoveDebris satellite

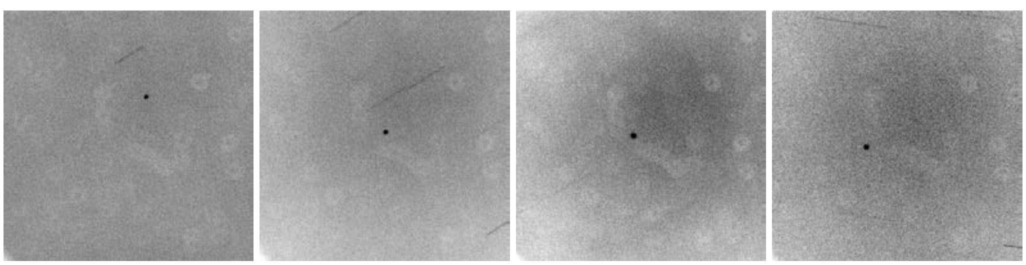

Figure 8: Time series of imagery of RemoveDebris during a pass over the Ottawa ground sensor (2018-J202)

Status

At the time of reporting Dstl are engaging with Surray Space Centre (SSC) to plan for the observations of RemoveDebris Satellite as it tests its various ADR systems; this is expected to occur late-2018.

4. 5-EYES JOINT SSA OBJECTIVES

In 2018 representatives from the 5-eyes S&T organisations (UK Dstl, US AFRL, NZ DTA, AUS DSTG and CAN DRDC) undertook an exercise to capture top-level research priorities based on national SSA requirements; this encapsulated the experiences from the series of experiments to-date as detailed above. A set of 12 research requirements were articulated against 5 themes; represented pictorially in Figure 9;

- Cataloguing
- Sensors
- Characterisation
- Astrodynamics

- Common Operating Picture (COP), encompassing Human factors

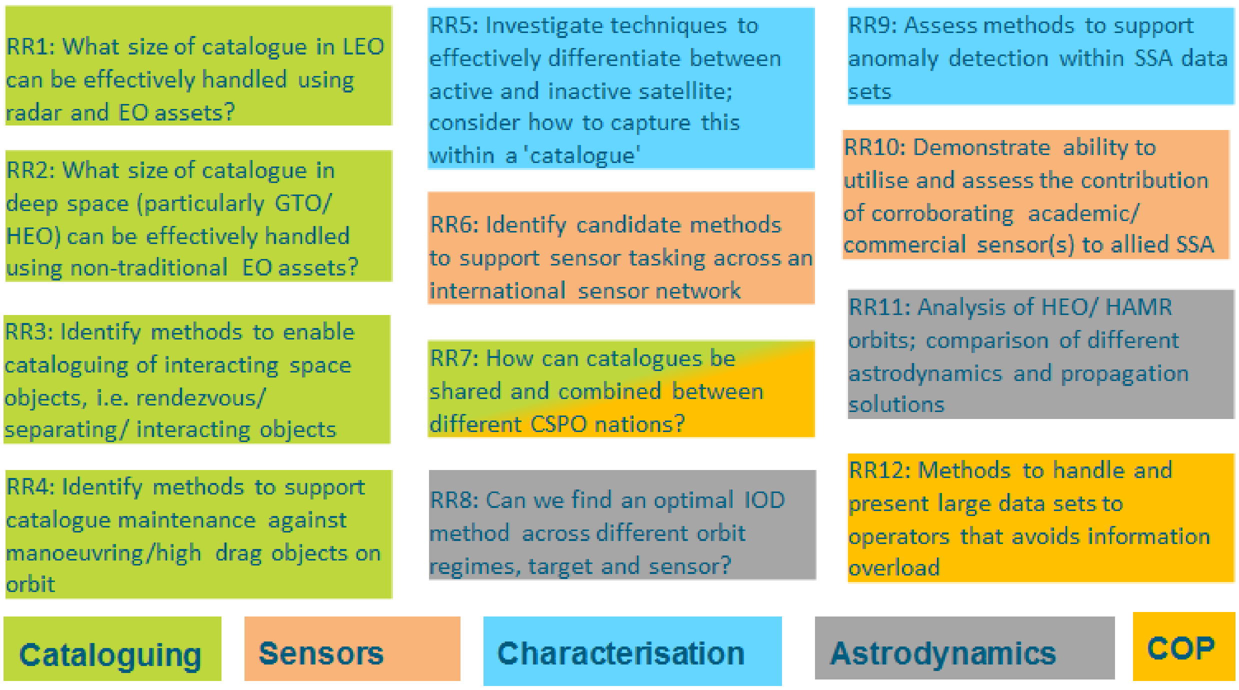

Figure 9: Research Requirements Identified

This set of research requirements has enabled the identification of common needs for R&D whereby IRC could be leveraged to enhance the output of the work. In terms of priority, the group have identified the following set of common requirement that have high relevance and alignment with national research activities:

- RR2: What size of catalogue in deep space (particularly GTO/ HEO) can be effectively handled using non-traditional EO assets?
- RR3: Identify methods to enable cataloguing of interacting space objects, i.e. rendezvous/ separating/ interacting objects
- RR4: Identify methods to support catalogue maintenance against manoeuvring/high drag objects on orbit

These research requirements form the basis of our short-term IRC goals. As part of this process we are shifting to a new paradigm whereby our research is structured around an agreed set of topic areas with work packages designated to each of the participants, in contrast to the previous campaigns that were larger driven by events of opportunity. This accounts for the interests and capabilities of each entity so that we exploit expertise where is best resides across our research community.

5. FUTURE PLANS

In addition to continuing support for the Daedalus and RemoveDebris Satellite experiments already underway, the 5-eyes group is designing a package of work to explore how SSA can support the military in understanding threats and hazards for allied assets located in GEO. This work is being conducted under TTCP MOU, with each nation assigned a specific lead activity:

- Observations, target selection & timeline – CAN
- Data simulation – US
- Vignettes and threat definition – UK
- Processing and analysis – AUS
- Observation support – NZ

To support investigation of the three high priority research areas a set of real and simulated targets are being defined that comprise the relevant challenges; namely debris objects in GTO that pose a collision risk, targets that exhibit formation flying in GEO (e.g. SATCOM clusters) and objects that manoeuvre (such as SATCOM relocation). A series of analyses will be conducted that pool together prototype capabilities from the 5-eyes S&T community to assess their utility in support of deep space cataloguing against these challenging targets.

The authors are exploring ways to further engage with S&T suppliers both within the 5-eyes nations and potentially wider international community (noting the constraints imposed by the use of TTCP MOU to conduct this work). We encourage interested parties to contact the authors to explore this further.

6. REFERENCES

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