An Update on SSA in Australia

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ABSTRACT

At AMOS 2008 the first author presented a review of surveillance of space activities in Australia up to that date: this paper reviews significant initiatives and events that have taken place since then. In summary some major policy commitments to Space Situational Awareness (SSA) have been made and some sizeable new R&D programs have been launched to develop nascent Australian SSA capabilities. Australia has still to settle on its national requirements for SSA and space generally, however, so these initiatives have yet to evolve into substantial, enduring programs of record.

In more detail, the communiqués issued at the annual Australian-US ministerial consultations in November 2010 announced an in-principle commitment to Defence collaboration on SSA and to establishing a joint space tracking facility in Western Australia: Defence in Australia is now working through setting up this facility and how it will move into SSA generally. These are part of a larger national re-engagement with space: in particular in 2009 Australia committed to developing a national space policy and allocated A$40 million of funding to a new Australian Space Research Program (ASRP) to boost space research. Over $5 million from this program has been awarded to projects centred on SSA, primarily to enhance EOS' satellite laser tracking system. In addition to these projects, the partners in an allied Defence R&D agreement that includes DSTO have agreed to a joint experiment that will fly a small formation of suitably instrumented CubeSats with the aim of, inter alia, providing ground truth for testing SSA capabilities. More generally DSTO has been supporting various aspects of Defence's engagement with SSA, including identification of S&T in which Australia has particular expertise that could be deployed on SSA given the necessary direction. The paper outlines these recent developments, reviews relevant Australian expertise in one particular field, tracking and sensor fusion (the second author leads DSTO's research program in this area), and canvasses some possible future programs and relationships.

1. INTRODUCTION AND OVERVIEW

In [1] the first author reviewed the history of surveillance of space and SSA in Australia up to that point. This had been rather a mixed bag: there has been strong interest and activity due to Australia's unique geolocation, some significant achievements and creation of enduring facilities, but also missed opportunities and the rundown of activity and expertise due primarily to the lack of a declared national interest in space. Nevertheless the paper ended on a note of hope, citing the existence of some significant, if mainly niche or latent, Australian SSA capabilities and also the stirrings of a renewed national interest in space.

The history of SSA in Australia since has been definitely more positive, albeit still a mixed bag. 2009 did indeed usher in major new national initiatives on space and SSA. In particular the government commissioned the development of a national space policy[1] and in the interim took some initial practical steps towards greater engagement with space that included establishing the Australian Space Research Program (ASRP) [2]; ~A$5 million of the A$40 million in grants since awarded though this program have gone to SSA. Moreover the year also saw the appearance of the 2009 Defence White Paper[2] [3] that explicitly acknowledged Australia's dependence on space and on alliances to deliver space-based capabilities, along with its need to do more to ensure continued to access to these capabilities. The White Paper identified SSA as a priority capability for further development: this was confirmed at the 2010 annual AUSMIN meeting [4] when the US Secretaries of Defence and State and the

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[1] This and other space-related government developments in Australia can be tracked through the new Australian Government Space Portal [5].

[2] Within Australia's Westminster system of government white papers are major reviews of departments or government responsibilities that are carried out roughly once a decade.

Australian Ministers of Defence and Foreign Affairs announced a new partnership on space security and the intention to set up jointly operated surveillance of space facilities in Australia.

These high level initiatives have certainly boosted interest and activity in SSA, both within Defence and beyond. Since the main impetus in Australia for improved SSA is coming from Defence, DSTO (the authors' parent agency) has taken a leading role in coordinating S&T development in support of SSA. Current DSTO activities in SSA include: providing advice on S&T aspects of SSA initiatives to Defence and government; mustering latent or nascent SSA R&D and S&T capabilities both within the organization itself and in the wider community; and guiding, reinforcing and participating in new SSA R&D programs. These are described in more detail in the remainder of the paper; suffice it to say here that ~A$5 million of the available ASRP funds have gone into new civil SSA R&D programs along with a further ~A$4 million of Defence funding, and that DSTO is playing an important role in informing, participating in and enhancing these programs, in particular by providing them with an otherwise unavailable path to space. In playing this role, though, it must be acknowledged that DSTO relies heavily on formal and informal exchanges of information and collaborations with elements in the US, in particular AFRL, and elsewhere.

Successful international engagements, exchanges and collaborations will be crucial to Australia establishing an effective SSA program. High level defence-related initiatives, such as the possible siting of a Space Fence node in Australia or the establishment of a coalition Combined Space Operations Centre, look likely to continue to set the immediate agenda for SSA: Australia's ability to respond effectively to these will depend very much on information exchanges and collaborations at lower levels that strengthen local knowledge and expertise. Moreover responsible use of space is an international issue with implications that go well beyond Defence; Australia is still coming to grips with how best to muster national resources to address this problem and will be looking to more experienced players in space for models or initiatives that help the country play a more effective role in doing so.

The remainder of the paper is structured as follows. The next section reviews current SSA programs and capabilities in Australia: these can be broken down into new research initiatives spurred by the ASRP, new defence capabilities driven by the recognition of a shared interest in space security, and some significant latent capabilities (mainly in the astronomical community) that have yet to be mustered in support of SSA. Section 3 then reviews in more detail another of these latent capabilities, the tracking and sensor fusion research program within DSTO: the authors' expectation is that at some point in the not too distant future this program will start to undertake SSA related work.

2. PROGRAMS AND CAPABILITIES IN AUSTRALIA

At present SSA capability development in Australia is driven by two main forces: the boost to space-related research provided by the ASRP; and increased coalition concerns about space security. A number of other latent SSA capabilities can be readily identified that presently lie outside the domains defined by the drivers above; national SSA requirements will need to be consolidated and expanded, however, before these are likely to be developed to their full potential.

New R&D initiatives

As might be expected, the Australian Space Research Program has a broad mandate to support new projects in space science and education. Nevertheless SSA is one of the program's seven listed priorities; of the fourteen grants awarded over the last two years, one "Automated Laser Tracking of Space Debris" is completely devoted to SSA, while another "Platform Technologies for Space Atmosphere and Climate" includes several SSA related work packages. The main grant is for just over A$4 million and was awarded to EOS[3] to expand the capability of their precision satellite laser tracking system and assess its performance in the context of likely Defence requirements. Defence has recently supplemented this project by awarding EOS a further CTD contract of A$3 million: this will focus more on how the laser tracking system might best be integrated with other components, e.g. surveillance radars, of a larger surveillance of space system. DSTO is directly involved in this project through provision of information on defence's surveillance of space requirements and participating in the assessment program.

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[3] EOS [6], formally known as Electro-Optic Systems, is a Canberra based SME that was originally spun out of GeoSciences Australia's participation in the international satellite laser ranging program. As well as laser tracking systems it also makes telescopes and enclosures.

Perhaps more importantly, DSTO has found a way to leverage this work by linking it with a couple of other ASRP projects, in particular the “SAR Formation Flying” grant awarded to a consortium headed by the University of New South Wales to study precision flying of small constellations that would enable new SAR systems, and leveraging them all by providing them with a path to space that they otherwise lack. Discussions in a multi-lateral defence R&D program involving Australia, Canada, the UK and the US identified an opportunity to run a small satellite experiment that would provide a real system to exercise the technologies being developed in the ASRP grants. The result is Project Biarri, a 3 ball CubeSat mission in which the US will provide the CubeSat platforms, system integration and launch, the UK a communications package, and Australia the GPS-based precision navigation systems. The mission should provide an ideal target for testing and validating surveillance of space systems: launch is currently scheduled for mid 2013.

Finally DSTO is also a participant in a number of other ASRP grants and is seeking other linkages between any or all them that might be leveraged in a similar fashion.

New requirements

As noted above, the 2009 White Paper and the 2010 AUSMIN discussions have identified a common interest in improved SSA and made joint commitments towards achieving it. For Defence in Australia the first priority is to make better use of the space situational awareness information to which it has access but hitherto not made much use. Up until recently no regional power had any significant space assets and none of Australia’s military deployments to date have included space-capable adversaries. Therefore, unlike the NATO partners, Australia has not had to seriously consider space situational awareness in planning and operations. This situation no longer holds, consequently the Australian Defence Force (ADF) has recently stood up a Joint Space Operations Cell within HQJOC, started allocating responsibilities for operating proposed new surveillance of space systems to existing units, and is reviewing the wider structures, architectures and information flows that will link these units with their ADF customers and allied partners. DSTO’s Joint Operations Division has been assisting the ADF with this process of defining requirements, structures and processes associated with the new mission.

For the US, with its very much larger and much more mature space operations program, the immediate priority has been expanding the Space Surveillance Network to handle the increased demands placed on it by the increasing numbers of both functional satellites and inert objects in orbit. Australia’s geolocation and long-standing alliance with the US make it a natural choice to host new surveillance systems that improve the geographic spread of the network. However, while there has been a fair amount of speculation in the specialist press about what sensors might be located in Australia, to date the only surveillance of space systems actually deployed in Australia in recent times have been two small experimental Raven telescopes that are an extension of AFRL’s HANDS system [7]. These were installed at the Ionospheric Prediction Service’s station at Learmonth in Western Australia in 2009. Negotiations on an agreement to relocate an operational AN/FPQ-14 C-band tracking radar from Antigua to the Harold E Holt base near Learmonth are quite far advanced but still to be finalised. And while other proposals have been floated or canvassed, in particular that Australia host a node of the new Space Fence system, as far as the authors are aware none of these are yet under serious, detailed negotiation: given the time needed to sort through sovereignty and other issues associated with such installations, expectations of their rapid deployment would be optimistic.

DSTO’s immediate role in the hosting of new surveillance sensors is to provide advice of the technical capabilities of the sensors, and on technical issues concerned with their establishment, maintenance and operation. Both the government and the ADF want a clear understanding of any new sensors’ capability and cost of operation, especially if Australia is to jointly operate and support them. DSTO also has a longer-term mandate to seek out ways in which any new sensors could be integrated in some way with existing Australian systems, or in which Australia could add value by associating new indigenous capabilities with such sensors that might not otherwise be developed or deployed. Examples of the latter include collocating EOS’ precision laser tracking system or an interferometric radar with a Space Fence node.

Perhaps the main challenge DSTO faces in fulfilling these roles is understanding the operations of surveillance of space systems and the priorities and requirements that determine these. The component technologies (radar, electro-optics) are generally mature enough to be well understood, but Australia has had no experience in the systems’ mission. This is a particular problem when advising on whether and in what indigenous systems Australia might best invest in order to add significant extra capability to a future joint system for surveillance of space.

Finally in the longer term the greatest influence on the development of SSA capabilities in Australia may well be the US proposal to establish a Combined Space Operations Centre.

Other potential resources

The Australian astronomical community is a substantial, but as yet still largely untapped, potential resource of new SSA capability. The community has a high international reputation and a long history of success in getting big grants out of government for large facilities and programs. Currently it is a significant partner in the two major international telescope programs, the Square Kilometre Array (SKA) and the Giant Magellan Telescope (GMT), having received ~A$200 million in government grants for the former and ~$A90 million for the latter. The SKA holds particular promise for SSA in Australia; with 36 12m dishes the precursor radio telescope being built under Australian SKA Pathfinder program [8] will be an impressive instrument in its own right, while if Australia and New Zealand's bid to host the full SKA succeeds, the local academic and industry base supporting radio astronomy, radar and related technologies will receive a very substantial boost.

On the down side, SSA is not currently a significant interest or priority for the astronomical community. Neither of the Australian SKA or GMT programs include an explicit SSA component, and while individual groups have undertaken some specific SSA activities (e.g. the University of Western Australia's collaboration with CNES in the French TAROT program [9]) these have been independent and relatively small scale initiatives lacking national coordination or backing. Indeed the current Australian astronomical program likely to be of greatest direct value to SSA, the star survey of the southern skies being carried out under Australian National University's SkyMapper project[4], does not even note this application of its work [10]. In general near space is of little intrinsic interest to the local astronomical community, while there have been no national or defence space programs seeking (and funding) their efforts in connection with it. Indeed in the absence of national partners and drivers, the community has increasingly focused on international programs such as the SKA: the international dimension to these engagements makes any new interest in them shown by Defence and other parts of government as much a problem as an opportunity. There is still much to be done to build in Australia the broad-based technical and national communities of interest in SSA that exist elsewhere.

While Australian astronomers may not be that interested in near space, the radar and physics research communities are doing significant work on the ionosphere and related phenomena such as the influx of micro-meteorites. To date the main applications of this work have been to the Ionospheric Prediction Service's space weather and communications advisory reports and to Australia's over-the-horizon radar program: they could be expanded to include SSA if suitable tasking can be identified and funded.

3. TRACKING AND SENSOR FUSION RESEARCH

Tracking and sensor fusion algorithms for automatic data processing are at the core of surveillance applications. At DSTO we have a research group which is a centre for expertise in low-level data fusion, especially in the creation, association and fusion of tracks. The team has substantial practical expertise in multi-sensor, multi-target tracking and various aspects of multi-sensor fusion, including fusion architectures and bias compensation. In this section we give a brief overview of a selection of the group's research of relevance to the SSA problem.

Nonlinear and non-Gaussian dynamic estimation

Whilst the Kalman filter has been at the core of recursive Bayesian estimation (tracking) for over 40 years it has well known restrictions and limitations when dealing with nonlinear and non-Gaussian systems. One of the most popular methods for dealing more effectively with these issues is the particle filter (or sequential Monte Carlo methods). DSTO has been at the forefront of the development of these methods and has applied them to a wide range of tracking problems with great success. Many of these applications are documented in the text books [11, 12].

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[4] The first author would like to thank Dave Monet for bringing SkyMapper to his attention at AMOS 2008.

Track before detect (TkBD)

Under conventional target tracking, sensor data is sequentially processed by data conditioning algorithms, a single-scan detector, and a tracker. The single-scan detector transforms the sensor data into a collection of point-measurements and applies a threshold. The tracker then associates together measurements from a common target and estimates that target's parameters. TkBD is a tracking paradigm that removes the single-scan detector and provides the whole sensor image as the tracker input. This allows the TkBD tracker to accumulate sensor data and to use the target dynamics model to improve the detection decision. TkBD has been shown to significantly improve sensitivity to low Signal-to-Noise-Ratio (SNR) targets. The term TkBD describes the measurement and decision models: there are many alternative algorithms.

DSTO's research program in TkBD has made contributions in two complementary areas: firstly in the advances of specific algorithms, in particular the particle filter and histogram probabilistic multi-hypothesis tracker; and secondly in the understanding of the relative merits of the many methods through detailed statistical comparisons and study of the fundamental limits of TkBD performance.

The particle filter is a general estimation framework for nonlinear non-Gaussian problems, and TkBD is one such problem. The original work on particle filtering TkBD assumed a continually present target with known amplitude in either Rayleigh or Gaussian noise. DSTO's research has extended the particle filter target model to include a target existence model that allows for targets that appear or disappear, enabling simultaneous target state estimation and target detection [13]. The research has also extended the measurement models to allow for fluctuating unknown target amplitude [14] and for different types of sensors including models of colour video [15, 16], arrays of acoustic sensors [17], and sensors with complex valued data (such as radar) [18]. The particle filter TkBD method has been applied to multi-sensor problems and was demonstrated to be able to exploit complementary sensors well beyond their current useable range [19].

An alternative algorithm for TkBD is the Histogram Probabilistic Multi-Hypothesis Tracker (H-PMHT). This algorithm models the sensor image as an observation of a mixture model and uses expectation-maximisation to fit the mixture components, which correspond to targets. DSTO's research has extended the H-PMHT to deal with nonlinear target dynamics and non-Gaussian target signatures within the sensor image frame [20].The assumption of a known target signature has also been relaxed by allowing the algorithm to learn the sensor's response to the target from the data itself [21].

In addition to this algorithm development, research on algorithm performance assessment has been undertaken. This research has examined performance both at a relative level, comparing alternative TkBD methods [22, 18], and at a fundamental absolute level, determining analytic bounds for performance. Since TkBD combines estimation and detection, these bounds describe both the best achievable estimation accuracy [23] and the lowest detectable target SNR [24]. Much of this performance assessment will appear as part of a graduate text [25].

Sensor management

DSTO has developed significant capabilities in sensor resource management for adaptive radar systems. Our work has been born out of experience with the practical challenges in the newly acquired AEW&C system. In the future, our experimental phased array radar (XPAR) system will provide a closed loop test bed for trialing new algorithms.

Specific experience includes:

- *Information theoretic approaches to sensor management for track maintenance.* White and Williams have both experimented with myopic approaches utilising mutual information as a criterion. Williams developed performance bounds for myopic information theoretic methods, showing that these are guaranteed to obtain at least half of the optimal reward [26, 27]. Algorithms were also developed to improve upon this in the case involving many independent targets (and encompassing cases to which the guarantees do not apply) [26, 28]. Additional work considered the specific case of sensor networks [26, 29].
- *Search theory approaches to detection of new targets.* Recently, Williams extended the traditional search theory formulation to solve the problem of determining optimal radar time allocations for the problem of searching for new targets. Based on a combination of coordinate descent and interior point optimisation, the method is easily extensible to multiple sensors and/or multiple time steps [30].

- *Adaptive balancing of track maintenance and new target search.* White et al demonstrated a system that divides radar time between these two tasks [31]; ongoing work is seeking to adaptively balance them.
- *Information theoretic measures in random finite sets.* Ristic has shown how information theoretic measures such as Renyi divergence can be applied within the random finite set framework to optimise track maintenance and new target search within a unified objective [32, 33]. These ideas have also been applied in observer trajectory planning for bearings only tracking [34] and detection and location of radiation sources [35].

Data association

Over the last two years, we have been continuing work at MIT on graphical models approaches to tracking. To date, work has focused on fundamental combinatorial problems in data association such as multiple dimensional assignment and approximation of matrix permanents. Progress includes:

- *Approximation of marginal association probabilities.* We independently developed a graphical model formulation of the assignment problem (for calculating marginal probabilities and maximum a posteriori solutions) and demonstrated excellent performance in challenging tracking problems [36]. The work on approximation of the marginal probabilities is closely related to emerging work in machine learning, statistical physics and information theory on approximation of the matrix permanent. We subsequently (and in parallel with another author) proved convergence of the method [37]. The approximation dramatically extends the reach of methods that require marginal probabilities (such as JPDA).
- *Random finite set data association.* One extension of the previous topic is algorithms in random finite sets that utilise the approximate marginal association probabilities. Such algorithms have been avoided in this domain due to the high computational complexity of calculating the quantities. The availability of high-quality, low complexity approximations to them may significantly change this situation [38, 39].
- *Alternative Lagrangian relaxation formulations for multiple dimensional assignment.* Our work also provides alternative formulations for solving multiple dimensional assignment problems. We have compared the traditional Lagrangian relaxation approach to approaches based on the recent work on dual decomposition methods by the machine learning community. The new methods appear to improve the speed of convergence significantly. We also compared to a method based on graphical models that is not guaranteed to converge, finding that it converges to the optimal solution in over 99% of problems examined, generally taking far fewer iterations than the traditional methods [40].

Random set theoretic approach to information fusion

Random set theory provides a unifying framework for information fusion (reasoning under uncertainty, estimation, classification and target tracking). This elegant theory, still under intense development, has already produced some remarkable results in target tracking and robust Bayesian estimation. DSTO has developed significant capabilities in this theory.

Specific experience includes:

- *Robust Bayesian estimation & classification.* In many practical applications, the measurement models (i.e. likelihoods) are difficult to specify precisely. In some situations even the measurements can be given only imprecisely (e.g. fuzzy or crisp intervals). Using random set representation of imprecise likelihoods and/or imprecise measurements, we have recently developed robust Bayesian estimation and classification [41, 42], with applications to natural language processing [43], radar [44], epidemics [45].

- *Dynamic multi-object estimation and tracking.* Random finite set theory has made a significant impact on multi-object estimation and tracking. Researchers in DSTO have made important contributions to SMC implementation of PHD and CPHD filters [46], Bernoulli filter and smoother [34, 47] and the development of a proper metric for multi-target tracking performance evaluation [48].

- *Information theoretic measures in random finite sets* (see Sensor Management)

Current work includes (a) hierarchical point processes with applications to joint tracking and sensor registration, and extended target tracking; (b) automatic reasoning and decision making using imprecise, ambiguous, vague and random data (priors and observations).

4. CONCLUDING REMARKS

The paper has described a nascent national SSA program, for which perhaps the biggest challenge (aside, of course, from the ever-present problem of resources) is making smart choices about what to do next. The paper also describes some recent DSTO developments in tracking and sensor fusion which address some of the generic fundamental challenges of surveillance: how to make best use of your sensor resource (sensor management), how to find faint targets (track-before-detect), how to deal with measurements of uncertain target origin (data association) and how to create and propagate a consistent representation of the target track with its associated uncertainty (particle filters and random set based methods). Currently, the most exciting opportunity for Australia is the Biarri mission that promises to link otherwise separate Australian research programs and groups and elevate their activities in a way that would not have been possible without international collaboration. Hopefully other programs will follow in its footsteps.

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