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Demonstration of a Heterogeneous Satellite Architecture during RIMPAC 2018

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ABSTRACT

The Micro-Satellite Military Utility (MSMU) Project Arrangement (PA) is an agreement under the Responsive Space Capabilities (RSC) Memorandum of Understanding (MOU) involving the Departments and Ministries of Defence of Australia, Canada, Germany, Italy, Netherlands, New Zealand, Norway, United Kingdom and United States. MSMU's charter is to inform a space enterprise that provides military users with reliable access to a broad spectrum of information in an opportunistic environment.

The MSMU community participated on a non-interference basis in the biennial Rim of the Pacific (RIMPAC) exercise from 26 June to 2 August 2018. This provided an opportunity to explore the military utility of a heterogeneous space architecture of satellites including traditional government and commercial satellites, as well as micro-satellites and nanosatellites associated with the "new space" paradigm. The objective was to test the hypothesis that a heterogeneous space architecture, mostly composed of small satellites, can bring significant value to the operational theatre.

This paper describes the results from the MSMU experiment, outlines the lessons learned in terms of the infrastructure required to support such an experiment, and offers insights into the military utility of the heterogeneous space architecture. It concludes that a cooperative heterogeneous space architecture does have advantages and value, and that micro-satellites and nanosatellites contribute significant capability.

INTRODUCTION

This paper presents the results of the experiment conducted during the Rim of the Pacific (RIMPAC) 2018 exercise in the frame of the Responsive Space Capabilities (RSC) Memorandum of Understanding (MOU) by the Micro-satellite Military Utility Project Arrangement (MSMU PA).

The overall objective of the RSC MOU is to define and establish the general principles that will apply to the initiation, conduct, and management of Research, Development, Test and Evaluation (RDT&E) cooperation projects detailed in separate Project Arrangements (PAs) under the RSC MOU. Additionally, the MOU allows the exchange of information for the purpose of harmonizing the participants' military requirements to assist in defining potential cooperative efforts under this MOU.

Within the RSC MOU, the MSMU PA is aimed at developing a blueprint for a Multinational Heterogeneous Space Enterprise. The MSMU PA Technical Working Group (WG) brings together defence scientists and engineers from Australia (AUS), Canada (CAN), Germany (DEU), Great Britain (GBR), Italy (ITA), Netherlands (NLD), New Zealand (NZ), Norway (NOR) and the United States (USA).

Heterogeneous Space Architecture Concept

A heterogeneous space architecture is defined as a coalition of government-owned (military and civil), allied and commercial satellites. This architecture can span all government space capabilities including missile warning, weather, ISR (intelligence, surveillance and reconnaissance), space situational awareness and communications. The instantiation of the heterogeneous space architecture explored in this paper is focused on ISR capabilities. That architecture contains satellites equipped with different phenomenologies and is capable of collecting the ISR data needed to produce the common intelligence picture required to assist in the decision-making process.

The MSMU PA hypothesis is that micro-satellites bring significant value and capability to the heterogeneous space architecture.

RIMPAC 2018

The RIMPAC 2018 exercise was chosen to anchor modelling, simulation, and value-based metrics with real world data. Leveraging an existing exercise allowed the use of exercise scenarios to validate hypotheses of the heterogeneous space architecture. The team focused on high level questions about the heterogeneous space architecture in addition to exploring the architecture's capability to respond to specific exercise Priority Intelligence Requirements (PIRs).

During RIMPAC 2018, the MSMU PA member nations tasked and exploited a multinational hybrid constellation constructed of dedicated[1] and contributing[2] space-based ISR sensors, comprised of commercial and government owned satellites, including micro-satellites.

In addition to developing Tactics, Techniques, and Procedures (TTPs) critical for the operation of a multinational ISR constellation, this experiment also allowed the trialing and dissemination of advanced mission planning, data fusion and analysis applications to provide a multinational fused ISR product.

The MSMU PA fused ISR products were based on a globally distributed 72-hour Tasking, Collection, Processing, Exploitation and Dissemination (TCPED) cycle, with a goal of significantly reducing that cycle through the use of advanced/automated applications.

The MSMU PA participants concurrently used advanced modelling and simulation capabilities to assess mission planning options during RIMPAC 2018. They performed analysis (during and post-RIMPAC 2018) of the collected ISR data with the objective of improving the automated tools, reducing the time necessary to complete the TCPED cycle, improving the effectiveness of multinational efforts in space-based ISR collection, and documenting other key lessons learned.

The MSMU PA RIMPAC 2018 Experiment constellation operated on a non-interference basis with the conduct of the RIMPAC exercise, but with a view to forming an active component of the heterogeneous ISR architecture to support follow-on experiments.

EXPERIMENT DESCRIPTION

The objectives for the MSMU PA RIMPAC 2018 Experiment were agreed as follows:

- Examine the capability of dedicated mission planning tools to task a multinational hybrid constellation constructed of dedicated and contributing ISR space-based sensors, based on commercial and government owned satellites, including micro-satellites.
- Examine the capability of the hybrid constellation to collect ISR data.
- Examine the capability of dedicated and contributing processing and exploitation tools to:
    - Examine the final resolution and quality of the fused product provided by the contributing satellites in the network.
    - Determine the ability to discriminate among and identify targets included in the product.
- Examine the capability of the heterogeneous space architecture to disseminate the fused product resulting from processing and exploitation.
- Examine the effectiveness of the heterogeneous space architecture, the TTPs for experimentation, and operations.
- Examine the cost benefit of the heterogeneous space architecture.

The experiment was conducted using three incremental steps overs a period of six weeks, see Figure 1.

Figure 2[3] shows the satellites and tools used during the experiment. Approximately 185 commercial and government owned operational satellites (from a total of 248 on-orbit) made up the MSMU constellation and were exploited or tasked to collect during RIMPAC 2018. Participating nations retained national control and tasking authority over their collection assets throughout the experiment.

The experiment execution process as based on a modified version of the Intelligence Requirements Management and Collection Management (IRMCM) process used by NATO and which was the cornerstone of the RIMPAC 2018 experimental framework, see Figure 3.

[1] Dedicated assets are those satellites specifically designed by and for government use.

[2] Contributing assets are satellites not specifically designed for government use, e.g. commercially owned satellites.

[3] Graphic of Carbonite-2 courtesy of Surrey Satellite Technology Limited

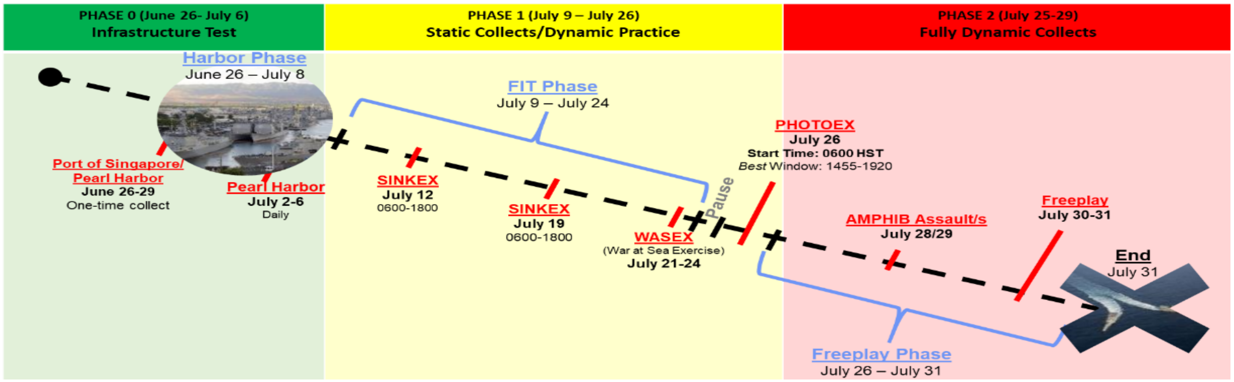

Figure 1: MSMU RIMPAC 2018 Experiment Approach

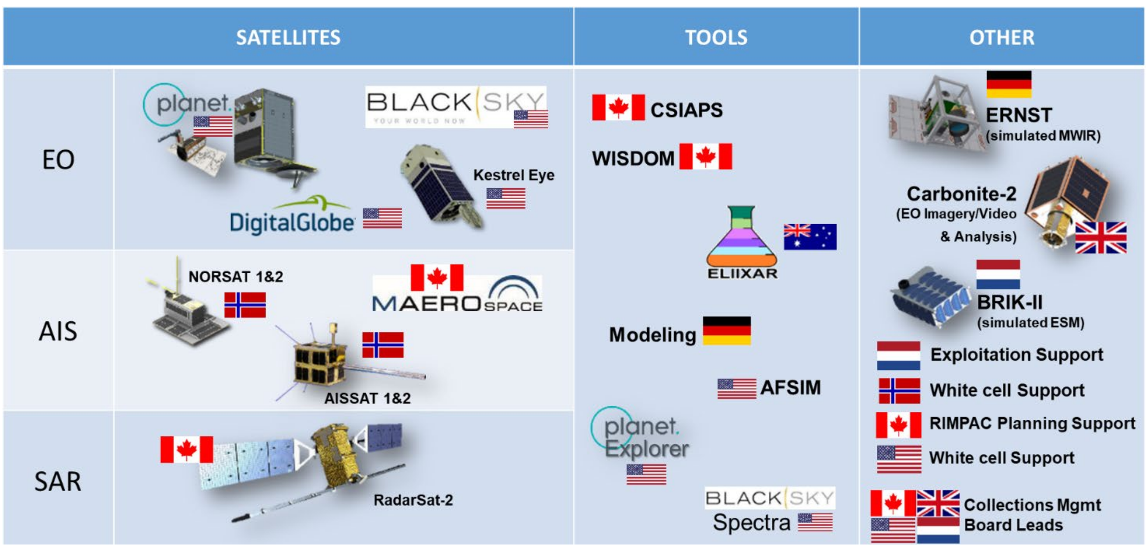

Figure 2: MSMU RIMPAC 2018 National Contributions

Being at the center of the Intelligence Cycle, the IRMCM process ensured that the Intelligence Requirements (IR) were answered and the intelligence assets available were focused and prioritized. The IRMCM was broken down into two main parts:

- Intelligence Requirements Management (IRM) Sub-Process: For the RIMPAC 2018 MSMU Experiment, the IRM sub-process remained relatively static as the Intelligence Collection Plan (ICP) did not change significantly.
- Collection Management (CM) Sub-Process based on the NATO TCPED Cycle: For the RIMPAC 2018 MSMU Experiment, the Collection Management sub-process focused on space-based single-source intelligence collection for Geospatial Intelligence (GEOINT).

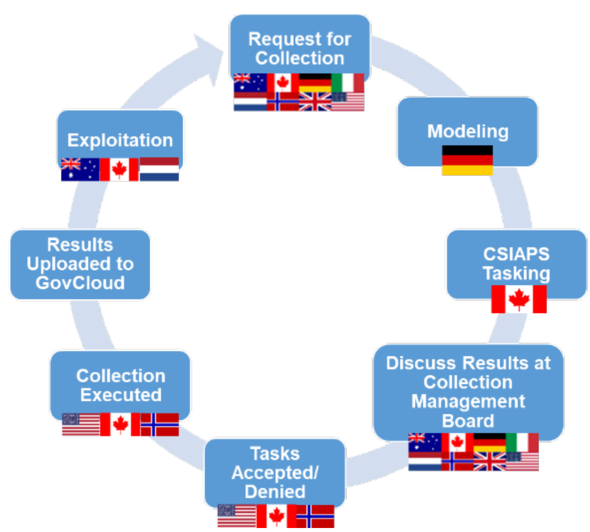

Figure 3: MSMU RIMPAC 2018 Execution Process

In order to execute the Tasking step, a Collection Management Board (CMB) chaired by a designated nation was formed and met daily to review, validate and prioritize all received Requests for Collection (RFC). The CMB discussed collection opportunities based on the RApid Sensor Contact Assessment Tool (RASCAT) (DEU) and the Commercial Satellite Imagery Acquisition Planning System (CSIAPS) (CAN). A single-source collection task list was subsequently produced and used to assign collection tasks to satellites whenever feasible.

In order to attempt to compress the Exploitation step, the intelligence production support system prototype and sensemaking tool WISDOM (CAN) and the Evolutionary Layered ISR Integration eXemplar Architecture (ELIIXAR) (AUS) were used to conduct some of the exploitation, analysis and fusion required to meet the requirements of the PIRs and the Specific Intelligence Requirements (SIRs).

RESULTS

Potential Sensor Availability Analysis

RASCAT assessed the sensor availability for the on-orbit satellites with Electro Optic (EO), Automatic Identification System (AIS), radar, as well as simulated sensors. Optimal radar and EO sensor accesses were selected and the respective satellites forwarded to CSIAPS for a refined collection simulation.

Figure 4 provides a representative example of the RASCAT analysis. In this example, RFC CAN 102 was submitted to collect EO/IR imagery of an airfield at Barking Sands in support of RADARSAT-2 collection. The main task was to detect aircraft on land, such as combat jets (e.g., F-18) or larger.

RASCAT provided a quick overview in increments of 10 minutes of the space asset availability over the Pacific Missile Range Facility (PMRF). RASCAT delivered clear and precise visualizations identifying a primary collection window from 1000 hours to 1215 hours and a secondary one from 1315 hours to 1545 hours. RASCAT effectively minimized the computational effort required to run subsequent advanced mission planning options using CSIAPS.

In the CSIAPS software, over 70 different parameters were captured for each satellite to characterize its operation and capabilities. The parameters recorded included information on the sensor type, the aperture angles associated with each sensor mode, and the resolution of the image products that each satellite could generate. These parameters were organized into a graph-based knowledge ontology.

CSIAPS was used to generate collection opportunities for each mission. Each opportunity consisted of a satellite name, a sensor mode, a target imaging location (latitude and longitude), as well as a time interval during which the satellite would be able image the target. Criteria such as the elevation angle of the satellite were used to select an initial list of prospective collection opportunities, which were presented to the MSMU Collection Management Board (CMB) in daily meetings. The collection opportunities approved by the CMB were then forwarded to the satellite providers for tasking.

Force Buildup – Ship Count

The task was to count the number of ships in the vicinity of Pearl Harbour obtained from multiple phenomenologies (SAR, AIS and EO). RASCAT reporting identified compatible accesses at 1030-1200 Hawaii Standard Time (HST) and 1400-1500 HST. TTPs were still in the practice stages during Phase 0, Stage 1 so RFC submissions were sometimes inconsistent at this early stage in the experiment. All assets were instructed to collect over Pearl Harbour for

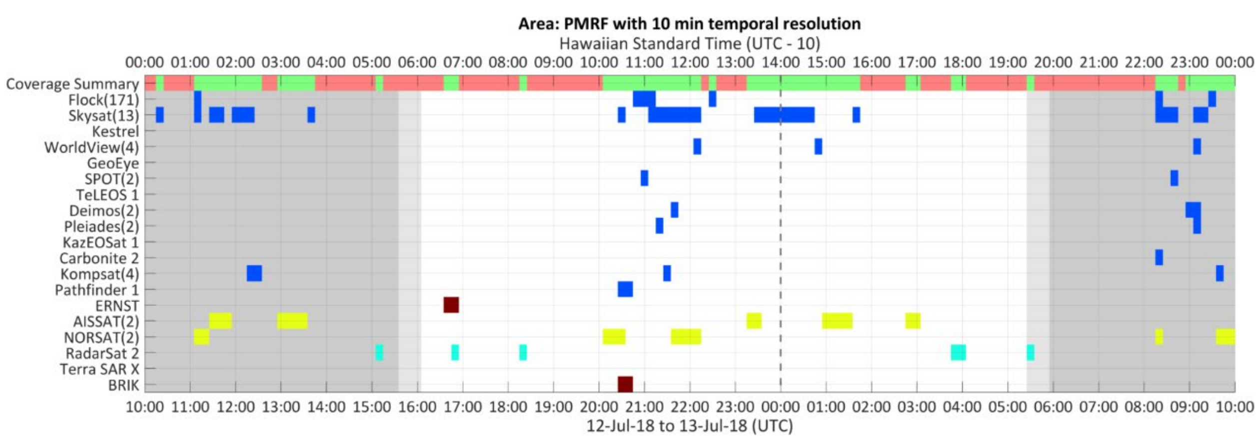

Figure 4: MSMU RIMPAC 2018 Example Access Report

each day during the phase.

Each provider was instructed to perform ship counts from successful collections during the previously mentioned time windows. The WISDOM team emphasized the need for bounding boxes for ship count comparisons, so small, medium, large, and extra-large boxes were defined. The aim was to compare collected data over the specified areas (S, M, L, XL boxes) encompassing Pearl Harbour during the identified compatible access windows. The main task was to perform ship counts, identify discrepancies, and draw conclusions on RIMPAC activity to inform the common intelligence picture.

Table 1 summarizes the ship count results.

The ship count discrepancies confirmed that (1) not all ships were transmitting AIS, (2) AIS messaging is inconsistent (affects counting parameters for exploitation), and (3) there was a significant force build-up at Pearl Harbour, see Figure 5.

Table 1: RIMPAC 2018 Experiment - Ship Count

Box Size	WISDOM (Maero-space data)	ELIIXAR(NOR AIS data)	NLD (NOR AIS, only A-class vessels)	USA (Dove imagery)
Small 10x10km	16	15	15	50
Medium 20x20km	21	19	19	
Large 100x30km	63	67	64	
Extra Large 300x300km		88	83	

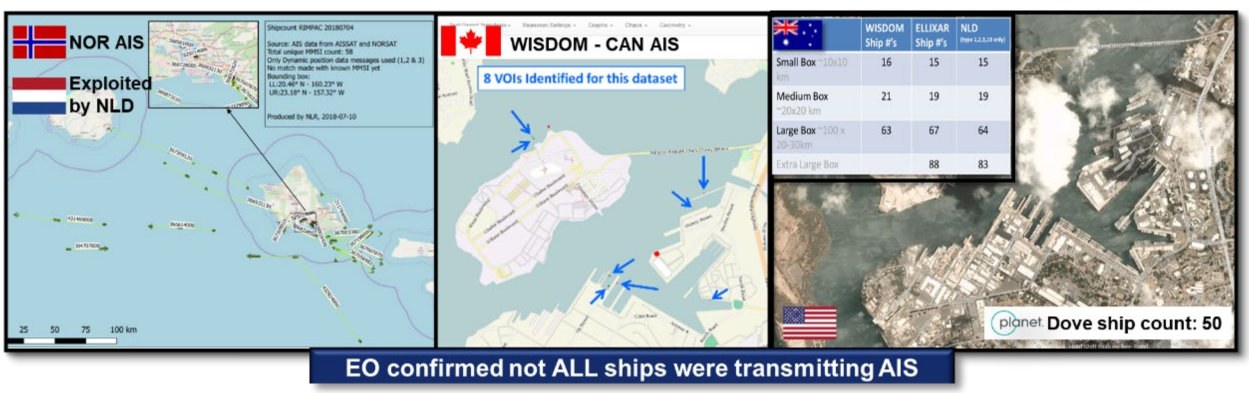

Figure 5: Verified Force Build-up at Pearl Harbour[4]

[4] PlanetScope © 2018 Planet Labs Inc

Fusion of Multiple Data Sets

Phase 0 identified a need for additional exploitation support to test the fusion of multiple data sets in order to identify targets, validate results, or identify discrepancies. Figure 6 shows two examples (Phase 0: Pearl Harbour and Phase 1: SINKEX) of exploitation capability by fusing commercial EO imagery with AIS data for ship detection and identification.

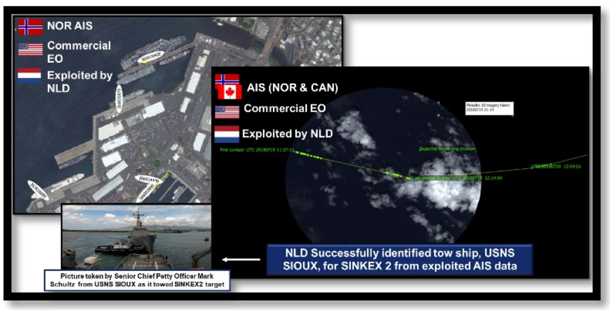

Figure 6: Fusion of Commercial EO Imagery[5] [6] with AIS Data

Figure 7 shows the process of successfully identifying an unknown ship in EO imagery. Dove images contained unknown ships. The CSIAPS team stepped in as exploitation support and compared the imagery with Maerospace AIS and were able to successfully identify one of the two ships. Ship 2 is Maritime Mobile Service Identity (MMSI) 316030879, the CAN ship ASTERIX. The length is reported as 182.46 m.

Exploitation of the fused ISR data led to the successful identification of the Auxiliary Oiler Replenishment (AOR) vessel ASTERIX. Open source imagery taken during RIMPAC 2018 also confirmed the identity of the ASTERIX and that the MMSI reported by AIS was accurate and not spoofed.

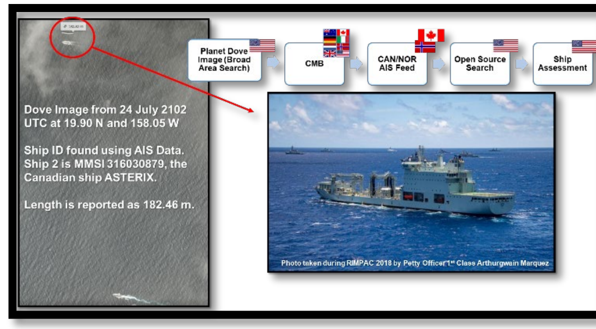

Figure 7: Ship Fusion of Planet[7] Image with Maerospace AIS and Open Source Data

Tracking of Uninvited Vessel

The Exercise Coordination Cell (White cell) based in Pearl Harbour reported that an uninvited vessel, referred to as the "Auxiliary General Intelligence (AGI) vessel", was shadowing the USS CARL VINSON (aircraft carrier). The CMB determined that it was of interest to obtain ISR data and information about this vessel. An RFC was subsequently submitted, see Figure 8 for a timeline of events.

The AGI vessel was not transmitting AIS. Hence, it was not straightforward for the MSMU community to detect, recognize, and identify the vessel.

It was quite possible that RADARSAT-2 would eventually capture images containing the AGI vessel. Such images can be processed with the OceanSuite application in CAN (DRDC Ottawa) to generate Near-Real-Time Ship Detection Reports (NRTSDR). Unfortunately, as the AGI vessel was not transmitting AIS, the SAR-AIS Association System (SAAS) application at DRDC Ottawa could not correlate the ship detections with an AIS report to generate Enhanced Near-Real-Time Ship Detection Reports (ENRTSDR).

In summary, it is possible that the AGI vessel was reported as a ship detection report, but there is no way to know among a set of such NRTSDRs which one actually corresponded to the AGI vessel.

The proposed solution was to exploit the known information that the AGI vessel was shadowing the USS CARL VINSON. The idea was to consider a set of ship detection reports at a given time, and then try to

[5] SkySat imagery © 2018 Planet Labs Inc

[6] PLEIADES ©CNES 2018, Distribution Airbus DS

[7] PlanetScope © 2018 Planet Labs Inc

locate the aircraft carrier using AIS data. Afterwards, if a RADARSAT-2 ship detection report was found in close proximity to the USS CARL VINSON, it would likely originate from the AGI vessel. The proposed solution was implemented as a series of steps as follows:

- Select a dataset of ship detection reports (NRTSDRs) made available by DRDC Ottawa (exploiting the OceanSuite application with RADARSAT-2 data).
- Ingest the NRTSDR dataset as a set of propositions in WISDOM.
- Find the AIS dataset(s) available around the time reported for the NRTSDR dataset.
- Ingest the relevant AIS dataset(s) found as a set of propositions in WISDOM.
- Working with the ingested propositions, use the rule-based reasoning capability of WISDOM to check if the USS CARL VINSON is reported in the ingested AIS data.
- If the USS CARL VINSON is reported in the AIS data, then find the AIS contact from the carrier that has its timestamp the closest to the time of the ship detection data.
- Use the kinematics and geospatial analysis capability of WISDOM to compute the proximity of each ship detection report from the relevant USS CARL VINSON AIS contact found.
- Find the ship detection report that has a proximity value to the USS CARL VINSON contact that would make it a good candidate to likely be the AGI vessel of interest.
- Report the location and time of the ship detection report as a potential, hypothesized location of the AGI vessel.

The hypothesized location of the AGI vessel could be used to search the image repository to look for images that would have been generated in the same area and around the same time. If such images were found, then image processing could be performed to detect the AGI vessel and estimate some of its attributes. If the latency for the process described above is low, then the hypothesized location and temporal information about the AGI could be used in tipping and cueing activities (in the form of requests for collection).

The timeline in Figure 8 shows the actual series of events that led to a dynamic tasking of an EO collect in an attempt to capture an image of the AGI. The image did not capture the AGI, but it did confirm that it was no longer trailing the Carl Vinson.

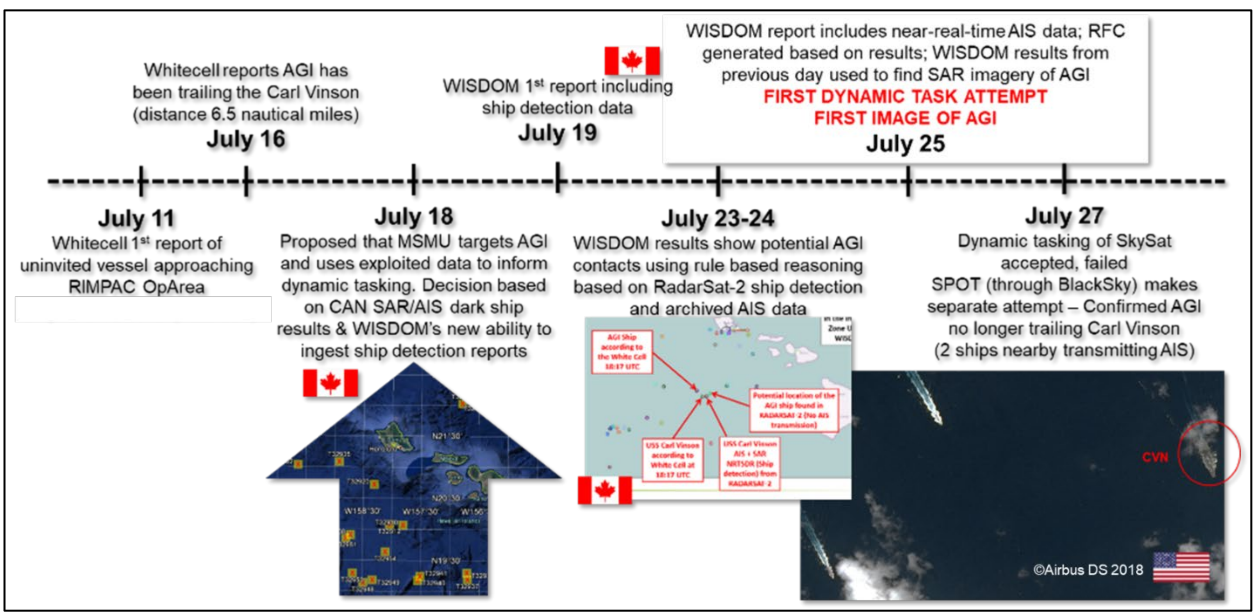

Figure 8: Dynamic Tasking of SPOT imagery collect for the AGI Vessel[8]

[8] SPOT image ©Airbus DS 2018

Multi-National Tasking

CAN RFC 102 was submitted to collect an Electro Optic (EO)/ Infra Red (IR) image in support of previously-requested RADARSAT-2 data, to determine the presence and composition of the Coalition Air Division at the Pacific Missile Range Facility (PMRF)/Barking Sands airbase. A task was assigned to Planet to collect EO/IR imagery of the airfield at PMRF with a view to detecting the presence of military aircraft; specifically to assess whether the airbase at PMRF/Barking Sands was in use by the Coalition Air Division, and if so, whether there were aircraft present similar in size to a combat jet (e.g., F-18) or larger. Figure 9 shows the relative placement and area coverage of the SkySat and RADARSAT-2 images of PMRF. North is to the top, and the imagery is in a Universal Transverse Mercator (UTM) projection. Note that land areas in the SkySat image are saturated in order to show the full coverage area. The range (R) and azimuth (A) directions for the RADARSAT-2 image are indicated by the R and A arrows.

Depending on meteorological conditions, the airfield may be obscured by clouds in EO/IR imagery. Synthetic Aperture Radar (SAR) imagery can penetrate clouds (if present); the SAR imagery can be used to detect aircraft, and the SAR data can provide additional complementary information to the EO/IR imagery.

The proposed solution was to collect both EO/IR and SAR imagery as close to concurrently as possible, analyze both EO/IR and SAR imagery, and create a fused image product to provide additional insight.

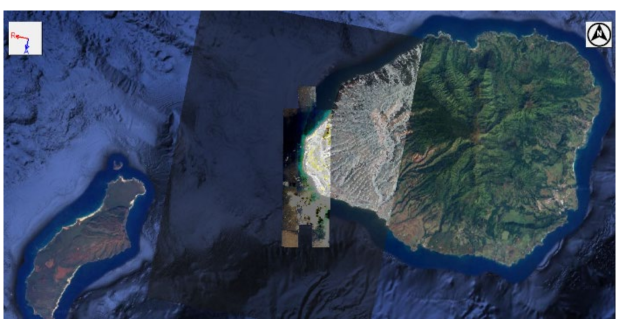

Figure 9: Relative placement and coverage of SkySat[9] (narrower swath) and RADARSAT-2 (wider swath) images acquired over PMRF[10] and overlaid on imagery from Google Earth

A RADARSAT-2 Wide UltraFine mode image was acquired on a descending orbit with HH polarization, covering an area of approximately 50 km x 50 km. The Planet SkySat image was collected on a descending orbit and it covered a narrower swath sweeping north to south across the PMRF airfield. The temporal match (4.5 days between image collections) was poor. As a result of this four-day separation, the two images do not necessarily capture the same objects/activity, although the infrastructure will most likely be unchanged. The image absolute geolocation did not match, but a rough co-registration of the two images was achieved with a simple translation of about 10 m applied to the RADARSAT-2 image. The RADARSAT-2 image allowed imaging of ground areas that were obscured by clouds in the SkySat image, and it provided other additional information over and above that from the SkySat image. In Figure 10, the upper panel shows a SkySat pan-sharpened image chip, the middle panel shows a RADARSAT-2 image chip, while the lower panel shows a blended SAR-EO/IR image chip showing site information in clouded areas. For scale, it is about 1.2 km east-west across this image chip. The GEO point (yellow cross) is located at 22.026596 N, 159.782768 W.

In Figure 11, the upper panel shows a SkySat pan-sharpened image chip with two possible helicopters (inside purple circle), while the lower panel shows a RADARSAT-2 image chip of the same area showing no evidence of the two possible helicopters. For scale, it is about 500 m East-West across this image chip.

In addition to the two possible helicopters visible in the SkySat image (Figure 11), there are some aircraft support equipment at other locations. The RADARSAT-2 image shows the presence of runway infrastructure (e.g., arrestor cable) at a location that matches paint markings visible in the SkySat image.

Potential Further Exploitation of the Results

This multi-phenomenology data exploitation was completed by a scientist at DRDC Ottawa Research Centre and would benefit from further analysis by a trained military Image Analyst (IA).

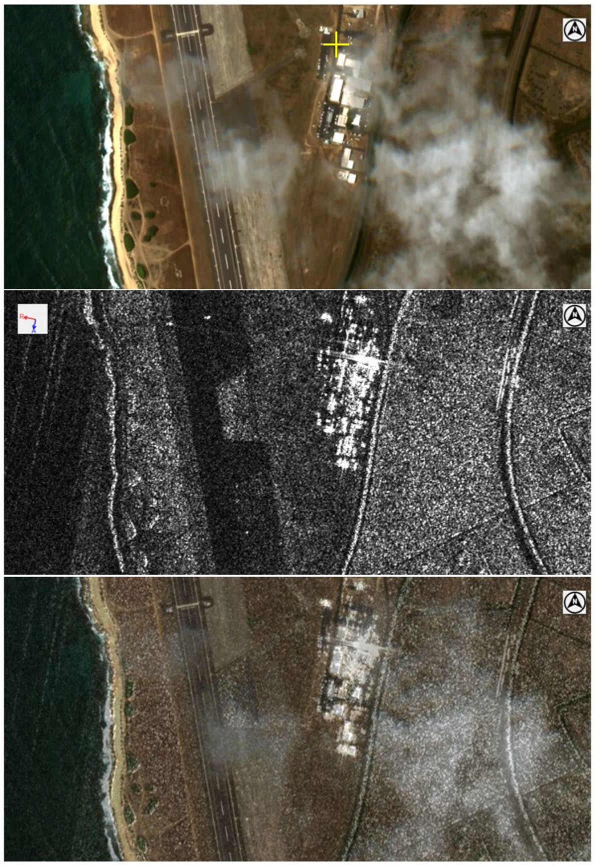

Figure 10: SkySat[11] and RADARSAT-2 image chips showing an area that crosses the main PMRF runway.

WISDOM Interfacing with ELIIXAR

Achieving machine-to-machine exchange of data/information/knowledge is an objective of the MSMU PA. Machine-to-machine exchange from WISDOM to ELIIXAR was achieved during the MSMU RIMPAC 2018 Experiment. WISDOM propositions were exported in eXtensible Markup Language (XML) format and then imported into ELIIXAR and parsed using Java code supplied by Canada. Figure 12 shows a WISDOM proposition that was ingested and displayed in ELIIXAR indicating the location of a vessel that was to be sunk as part of the exercise. Intelligence analysts could potentially use ELIIXAR to view the proposition, fuse it with other information, and derive new intelligence products.

[11] SkySat image © 2018 Planet Labs Inc

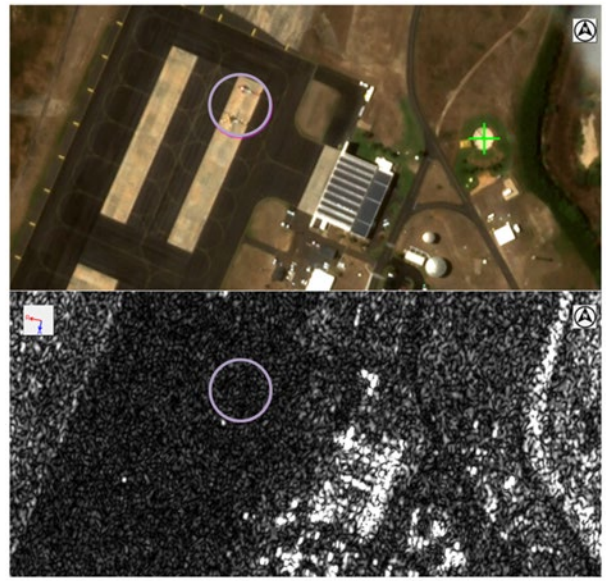

Figure 11: SkySat and RADARSAT-2 image chips showing an area that crosses the PMRF helicopter landing pad[12]

KEY FINDINGS

The MSMU RIMPAC 2018 Experiment was a valuable activity in terms of advancing our understanding of micro-satellites and the significant value and capability they bring to the heterogeneous space architecture. The experiment also provided an opportunity to test promising prototypes which may contribute to automating or compressing key steps of the TCPED cycle.

The RIMPAC 2018 Experiment revealed that a cooperative heterogeneous space architecture does have advantages and value, and that micro-satellites and nanosatellites contribute significant capability.

The exercise execution highlighted a diverse set of insights that ranged from individual sensors and toolsets to architectural implications. All findings emphasized the need for significant infrastructure enhancements for improved collection planning, decreased TCPED latencies, expansion of exploitation toolsets, and collection management support.

[12] Original RADARSAT-2 Data and Products © MacDONALD, DETTWILER AND ASSOCIATES LTD. (2018) – All Rights Reserved. RADARSAT is an official mark of the Canadian Space Agency

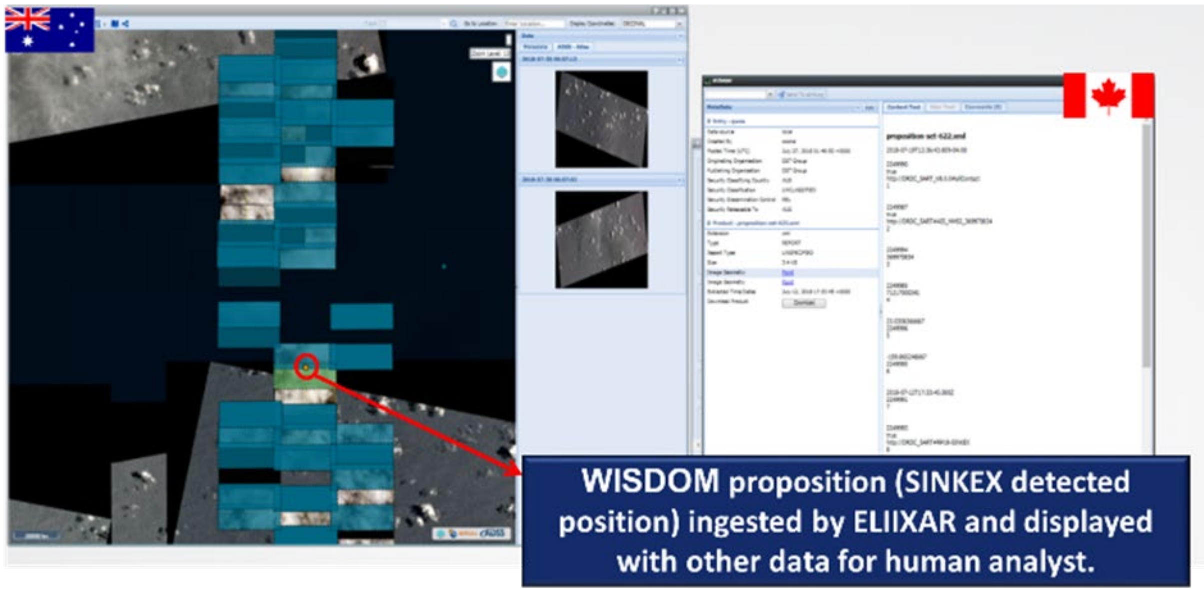

Figure 12: WISDOM Proposition (SINKEX) Ingested by ELIIXAR

CONCLUSIONS

The exploration of tasking and exploitation of a multinational hybrid constellation constructed of dedicated and contributing ISR space-based sensors and based on commercial and government owned micro-satellites, is a difficult problem which requires significant investment in time and effort to prepare, execute, learn, train, and repeat. Under the RSC MOU, the MSMU was able to build a multinational constellation with global coverage, and create an initial blueprint of the heterogeneous space architecture.

The findings of the RIMPAC 2018 exercise set a baseline for the MSMU capability and acted as an initial step to set guidelines and requirements for future cooperative micro-satellite missions to enhance military utility.

Acknowledgments

This international cooperative experiment was made possible by all the groups involved in the RIMPAC planning process, specifically the Trident Warrior Experiment team, who were flexible and supportive despite our limited involvement due to early stages of development. As part of the Trident Warrior team Richard Weiss, Steve Burchard, and Ellen Sherif offered support with the development of a data collection management plan and helped identify activities that would align with MSMU's experiment needs. Their efforts were fundamental in our success.

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