

# **PHANTOM ECHOES: A Five-Eyes SDA Experiment to Examine GEO Rendezvous and Proximity Operations**

**Simon George, Andrew Ash**

*Defence Science & Technology Laboratory, UK*

**Travis Bessell**

*Defence Science and Technology Group, Australia*

**James Frith**

*Air Force Research Laboratory, US*

**Lauchie Scott**

*Defence R&D Canada, Canada*

**Jovan Skuljan**

*Defence Technology Agency, New Zealand*

**Roberto Furfaro, Vishnu Reddy**

*University of Arizona, US*

## **ABSTRACT**

In February 2020, two spacecraft conducted the first commercial, satellite-servicing rendezvous and docking in Geostationary Earth Orbit (GEO), offering unique opportunities to understand the vehicles' dynamics and observe such activities using ground- and space-based sensors. As part of a wider activity to demonstrate how allied sensors and processing tools can be integrated within a cloud-based, federated processing workflow to improve space safety for allied spacecraft in GEO, both the servicer and client vehicles were observed as surrogate targets within a constrained observation campaign conducted by the Five-Eyes (FVEYs) nations' defence Science & Technology (S&T) organisations. This experimental campaign, known as "PHANTOM ECHOES", brought together capability from across the UK, USA, Canada, Australia and New Zealand through research activity performed under The Technical Cooperation Program (TTCP).

In this paper, an overview is presented of the activity conducted within Phase I of the PHANTOM ECHOES campaign; describing progress in development and integration of FVEYs Space Domain Awareness (SDA) tools within a data processing cyberinfrastructure, as well as outcomes from real-world and simulated observations of the Mission Extension Vehicle-1 (MEV-1) from launch through to its successful docking with Intelsat-901 on 25<sup>th</sup> February 2020. The paper also introduces Phase II of the PHANTOM ECHOES experiment, which is currently underway in line with the Mission Extension Vehicle-2 (MEV-2) mission, and for which the FVEYs SDA S&T community is using to build on experiences and explore alternative surrogate targets in Deep Space which present mission profiles of relevance to the protection of allied spacecraft in GEO.

## **1. INTRODUCTION**

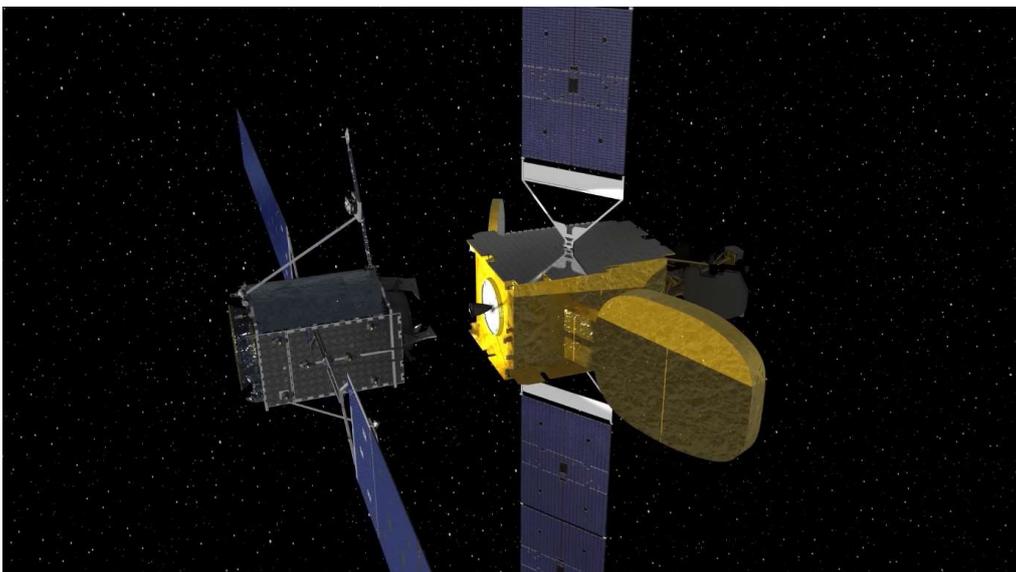
The Geostationary Earth Orbit (GEO) regime is occupied by a wide variety of coalition space vehicles which deliver crucial services for communication, surveillance and navigation for both civil and military purposes. Whilst the GEO regime has consistently been prized for its unique orbital geometry, the growing population of resident space objects (RSOs) in GEO have associated impacts on safety-of-flight and protection of critical, high-value assets (HVAs). Alongside the increase in population density in this region, capabilities for intentional close-proximity activities are becoming increasingly mature. Furthermore, advances in propulsion and autonomy capabilities are also

motivating changing modes of operation for assets in Deep Space, exemplified by new levels of manoeuvrability. These typically comprise of complex, dynamical trajectories, for which legacy models are not best-suited [1].

The emergence of increasing capabilities for conduct of rendezvous & proximity operations (RPO), on-orbit servicing (OOS) and life extension missions in Deep Space are, perhaps, indicative of the increasing threats to critical GEO space assets from uncooperative, adversarial interference. Such interference may comprise of close-proximity inspection of HVAs, physical or electromagnetic interaction or damage, attachment of foreign devices of unknown function or purpose, or the potential abduction and relocation of an allied space asset. In step with the “New Space” agenda, a range of OOS technologies are beginning to appear as viable technical options for the commercial servicing of satellites in Earth orbit, of interest to extend the lifetimes of allied spacecraft. As an increased number of spacefaring nations develop mature RPO capabilities, their operations present further SDA challenges with respect to mission assurance of high-value military spacecraft.

In response to these development, the defence science and technology (S&T) laboratories of the Five-Eyes (FVEYs) nations (the UK, US, AUS, CAN and NZ) are currently collaborating towards a series of coalition Space Domain Awareness (SDA) experiments [entitled “PHANTOM ECHOES”] to examine how S&T can counter these emerging challenges and explore real-world cases to help inform future operational architectures. These activities have been led by the Defence Science & Technology Laboratory (Dstl, UK), the Air Force Research Laboratory (AFRL, US), Defence Research & Development Canada (DRDC, Canada), the Defence Science & Technology Group (DST Group, Australia) and the Defence Technology Agency (DTA, New Zealand); building on the heritage of previous Five-Eyes S&T SDA experiments undertaken since 2014 [2]. Through this collaborative arrangement, additional academic & industry involvement has been afforded through engagement via the participating national laboratories.

In 2019, the opportunity emerged for this community to collaboratively observe a space mission performing the first commercial servicing of a geostationary satellite, aligning with research requirements identified by each nation towards RPO in GEO and the tracking custody of vehicles exhibiting constant-thrust manoeuvres in Deep Space. The Mission Extension Vehicle-1 (MEV-1) was constructed by Northrop Grumman Space Logistics, and launched in October 2019 into a super-synchronous transfer orbit which, over the course of the following four months, conducted a long-duration, low-thrust manoeuvre trajectory to GEO. In February 2020, MEV-1 began an approach towards Intelsat-901 in a GEO graveyard orbit (+300 km above GEO), before conducting rendezvous and docking with its client; marking success of the first, commercial OOS mission in GEO.



**Fig. 1. MEV-1 docking with Intelsat-901 (artist's impression), coincident with Phase I of the PHANTOM ECHOES observation campaign.**

Image Credit: Northrop Grumman / Space Logistics

During late 2019 and early 2020, an observation campaign was undertaken by a multi-national team of researchers using both ground- and space-based sensors, and which formally concluded in March 2020 following successful re-initiation of Intelsat-901's communication service at 27.5° W. This paper provides a summary of the outcomes of that campaign; describing work undertaken by the FVEYs SDA S&T community to date towards development of distributed, coalition data processing architecture for SDA experimentation ["VerSSA"] and in leveraging these prototype capabilities within the first phase of the PHANTOM ECHOES experiment surrounding the MEV-1 mission.

## 2. BACKGROUND: FVEYs S&T EXPERIMENTATION IN SPACE DOMAIN AWARENESS

Since 2014, the FVEYs SDA research community have conducted a series of collaborative experiments under S&T agreements, seeking to improve coalition SDA capability in the area and prototyping future techniques of utility to the Combined Space Operations (CSpO) initiative [3]. These activities have been conducted under the Memorandum of Understanding (MOU) of The Technical Cooperation Program (TTCP) [4], with SDA research activities contributing to TTCP via the ISTAR TP1 CP03 technical panel.

Through previous experiment themes such as the Automated Transfer Vehicle-5 (ATV-5) re-entry campaign, the Skynet Observation & Relocation Experiment (SORE) and the Daedalus series of activities associated with observation of de-orbit sail dynamics [2], these endeavours have contributed to improvements in SDA capability across the coalition and have helped to advise operational units across CSpO on future investments and capability needs. Within these experiments, the FVEYs SDA S&T community have successfully demonstrated that national data and processing software can be collaboratively leveraged in support of "real-world" observation campaigns on surrogate targets, and that combined analysis of results could be conducted at various levels of classification.

Based on previous findings and on wider coalition needs for improved sharing of research SDA data, an emergent requirement was identified in the form of a federated solution for data fusion and distribution to enable efficient conduct of future S&T campaigns. Previous experiments, such as those listed above, were constrained in their ability to exchange data between participants; relying mostly on manual processes (e.g. via email and/or File Transfer Protocol) over relatively relaxed timescales. These campaigns also involved little to no exchange of software or tools between participants due to the complexities associated with international release processes & handover mechanisms: hence, data processing was primarily conducted "offline" by individual agencies using nationally-owned systems and tools. Whilst these conditions were adequate to explore a number of SDA-related issues across a small number of events occurring over relatively protracted timescales, they were often impractical for study of more demanding scenarios.

Based on the shared interest of all FVEYs partners in protection of allied assets in Deep Space, in 2018 a distinct series of experiments were postulated by the group to study proximity operations in GEO. These research activities aimed at improving allied capability for the assessment of threats to HVAs and the generation of suitable operator indicators & warnings (I&Ws) via a "federated" coalition data processing architecture solution. This series was predominantly structured around the use of the Northrop Grumman Mission Extension Vehicle (MEV) fleet of commercial life-extension spacecraft as surrogate targets through which to better understand a number of core SDA principles and research challenges associated with manoeuvring & close-proximity space vehicles: space object tracking & cataloguing, fundamental astrodynamics, space object characterisation and novel sensor architectures. This contextual foundation hence framed development of a specific distributed, data fusion architecture as an enabler for a subsequent series of real-world data collection campaigns on the MEV-1 and MEV-2 spacecraft and their designated clients.

Planning for the PHANTOM ECHOES series of activities formally began in early 2019; identifying two, distinct data collection and analysis campaigns coinciding with the life-extension missions of MEV-1 (2019/20) and MEV-2 (2020/21). As an outline, these experiments possessed the following primary aims:

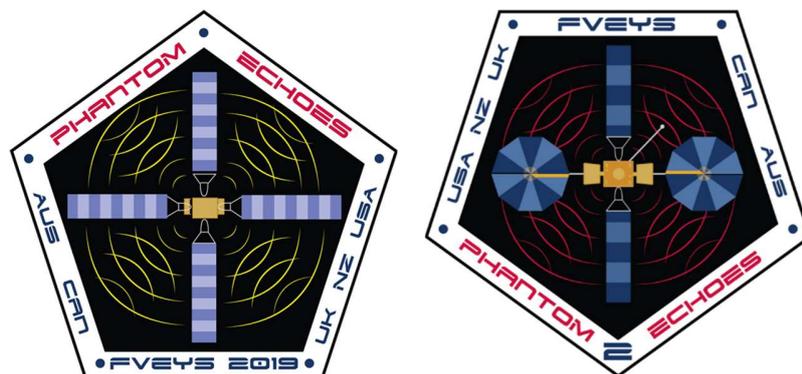
1. Demonstrate ability to integrate SDA capabilities (software and sensor data) across FVEYs community into a single framework that enables joint operations and analysis of high-interest events to enhance coalition SDA

2. Investigate use of allied analysis tools to enhance generation of I&Ws within a GEO proximity-operations case study
3. Explore the use of non-traditional sensors to support GEO SDA missions; notably, electro-optical (EO) astronomical assets and radio frequency (RF) sensors
4. Conduct real-world and simulated observations on targets demonstrating constant-thrust manoeuvre and GEO rendezvous dynamics using FVEYs R&D sensors to understand future operational challenges and possible solutions

The wider experiment was hence divided into two principal phases of activity; both aligning with a discrete data collection and analysis campaign on real-world mission targets:

*Phase I* (“PHANTOM ECHOES”) of the experiment was structured around MEV-1 and its servicing mission towards Intelsat-901. A FVEYs campaign began in October 2019 and concluded in March 2020, exploiting initial progress made by the community towards development of a common data distribution and processing capability formed from a federated suite of tools contributed from across the coalition.

*Phase II*, aligned with the similar activities associated with MEV-2 with Intelsat 10-02, began in August 2020 through a follow-on campaign (“PHANTOM ECHOES 2.0”): this activity is currently underway, and looks to build on the experiences gained during Phase I and to apply ‘lessons learned’ from the MEV-1 event. Current progress within this phase of the experiment is summarised in §5.



**Fig. 2. Unofficial “mission patches” for the PHANTOM ECHOES series of SDA experiments.**  
Image Credit: University of Arizona

### 3. DEVELOPMENT OF A DISTRIBUTED COALITION DATA FUSION ARCHITECTURE (VERSSA)

As a result of experiences captured during previous SDA experiments, the community sought to identify methods to improve the capacity to share sensor data and processing software/capabilities across an allied network. In particular, solutions to enable closer experimental collaboration were desired; particularly to enable study of more demanding and/or dynamic scenarios – for example, associated with more rapid/emerging tempos of a particular event (for example, a predicted conjunction between two objects), inclusion of an elevated number of multi-lateral participants in data collection & analysis, or through the need for real-time elements such as rapid sensor tasking and re-tasking. In line with this, the FVEYs SDA community conducted a review of previous experimental shortcomings associated with software and data exchange, in order to identify requirements for a novel, federated solution capable of supporting future S&T campaigns. A comprehensive list of findings from previous coalition SDA experiments, and their role in informing the direction of the PHANTOM ECHOES activity, is presented in Table 1.

**Table 1. Summary of previous coalition FVEYs SDA S&T experiments (2014-2020) and performance of their associated data distribution architectures.**

Activity (Year)	Data Distribution Method(s)	Findings
<b>AAMOST #1 (2014)</b> LEO custody experiment [UK-AUS]	Email used to coordinate collection and task sensors (cues); File Transfer Protocol (FTP) for exchange of data. No exchange of software between participants	Methods suitable to retain custody on small (~10) number of targets, but highly manual in nature. Methods not optimised for real-time or automated exchanges
<b>ATV-5 (2015)</b> Re-entry coordinated international experiment [UK-AUS-CAN-NZ-US]	Email/FTP for data exchange. Verbal communications used for time offset relay between sensors. Limited near-real-time data transfer into UK Space Operations & Coordination Centre (UK SpOCC), air-gapped (via optical disc) to/from sensors and between systems	Successfully observed event; however, stressing demands on manpower collocated at sensor to perform OD, cueing and data collection. UNITY system demonstrated ability to get collected data into UK SpOCC in non-real-time for single event
<b>SKYNET Observation and Relocation Experiment [SORE] (2015)</b> GEO HVA custody during relocation [UK-CAN-AUS-US]	Emails to coordinate collection and task sensors (cues); FTP used for exchange of data. No real-time sensor tasking required	Non-real-time methods worked reasonably well for this event, due to its relatively “sedate” nature (GEO relocation over ~2 months). Observation gaps during daylight hours used to perform analysis for (optical) data collection during night [5]
<b>EUSST “Pipe-Cleaner” Campaign (2016)</b> Preparation and verification for delivery of sensor data to EUSST [UK]	Emails for tasking of sensors (tasking form) and for return of data files. No explicit format standard or ICD for sensor data; however, broad compatibility with CCSDS formats. Data ingest into UK SpOCC via unclassified internet, air-gapped (via optical disc) to other systems	Heavy burden on manpower at UK SpOCC for ingest of data and re-tasking of sensors. Daily tasking cycle suitable for optical sensors, using daylight hours to schedule night tasking. “Dynamic” tasking prototyped based on emerging events (e.g. conjunctions, re-entries) but non-real-time
<b>Daedalus (2017-2019)</b> De-orbit sail deployment [UK-CAN-US]	Emails to coordinate collection, with FTP for exchange of data. No explicit tasking or cueing of sensors by central source; external (Space-Track.org) TLEs used under “best efforts” basis	Mechanisms largely suitable to enable events taking place over (relatively) sedate timescales and where no centralised coordination was required. All data fed centrally to Dstl. Connectivity to UK sensors sub-optimal for transfer of data at Classified-level
<b>UNITY (2015, 2017-2020)</b> Variety of experiments [UK-US]	Virtual Private Network (VPN) and testbed system established at unclassified level between government secure networks (US, UK); application of “pub/sub” service with a disclosure diode between clients. No joint space Command & Control (C2) tools developed due to delays in testbed establishment & resources	Establishing equivalency of security accreditation/body of evidence critical to enabling this VPN to be established. Networking and integration process complex and time-consuming due to bespoke architecture. Experimentation and testing of space C2 tools was achieved, although this largely occurred outside the confines of the testbed
<b>AAMOST #2 (2018)</b> LEO cataloguing experiment [UK-AUS]	CyVerse chosen for data exchange, with FTP as a backup and communications via email. Generation of centralised tasking list using Dstl OD software, distributed by email and CyVerse. Decentralised scheduling of sensors (performed at sensor site). No singular data format(s): different sites used their own unique data formats. No exchange of software	OD computation and manual cataloguing process highly resource-intensive, significantly reducing capacity of target list. Lack of common formats (both for data and orbits) and no automated parsers added additional burden. CyVerse initially found cumbersome and slow to upload, download, and delete data; experiment reverted to backup FTP method during execution
<b>Argus (2018-2019); Argus II (2020)</b> “Citizen Science” amateur SSA [UK]	Emails to coordinate collection and task sensors (cues); email and FTP for return of data from observers. No specific data format, no real-time tasking of sensors	Pace of events & quantity of observation data outstripped capacity to process data. Data flow largely one-way from sensors, with OD/analysis performed in slow-time centrally by Dstl. Use of inconsistent data formats considerably slowed down execution (various proprietary camera formats required special consideration)

To identify options for a suitable data fusion architecture solution to support further coalition SDA experiments, several face-to-face, collaborative workshops were conducted during 2018 and 2019 at various international venues. These discussions drew experience from the outcomes of previous experimental activities conducted by the group (as listed in Table 1), as well as recently-initiated projects from across the coalition. These discussions considered the utility of leveraging existing R&D solutions, developing a bespoke research architecture specifically for coalition SDA experimentation from the ground-up, or implementing hybrid approaches which utilising, existing general-purpose infrastructures but are steered towards specific SDA application. Factors which were evaluated included the technical capability and relative maturity of each proposed solution, their security and Intellectual Property (IP)-handling aspects, individual processing performance, accessibility and (international) releasability.

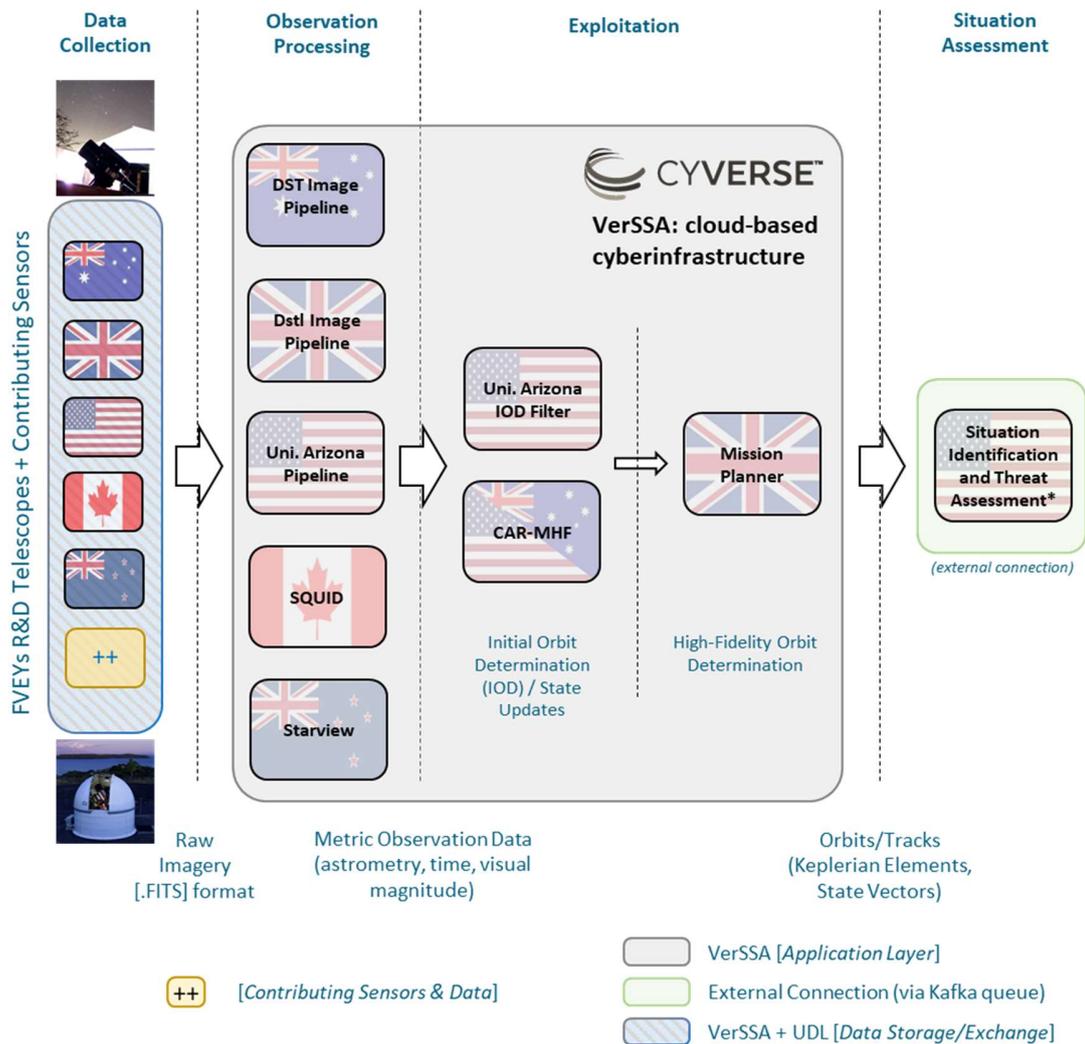
Based on these considerations, a decision was made to adopt a “hybrid” approach; specifically, to develop and deploy a federated architecture of SDA processing tools contributed from across the FVEYs S&T community, using a distributed cyberinfrastructure to host them within an application transport layer. As a capable solution, and based on trial usage during a FVEYs experiment in mid-2018, the University of Arizona’s CyVerse [6] computational infrastructure was selected: this choice was based on its capability to host and execute software & tools within a distributed environment, its capacity to store and process large capacities of data, and legacy advantages in terms of existing compatibility with US release processes & infrastructure. Through inspection and testing of this functionality at research and development (R&D) level, the community sought to construct evidence which could help inform future CSPO and national SDA processing architectures.

A branch of CyVerse was created by the University of Arizona, entitled “VerSSA”, tailored specifically for SSA/SDA experimentation amongst the FVEYs S&T community: the platform consists of a generalised data storage facility and a web-based interface (‘Discovery Environment’ [DE]), driven by a cloud-based cyberinfrastructure which accesses remote servers for the execution of software processes & data analysis tools. Based on these factors, VerSSA was chosen to act as the foundation for a transport layer in which a shared set coalition SDA processing tools could be deployed and executed. It was also identified as a partial data repository solution for the storage of observation & analysis data, although the FVEYs S&T community also sought to utilise the Unified Data Library (UDL) platform [7] for storage and exchange. Shared electro-optical data was stored and processed as Flexible Image Transport System (.FITS)-formatted files within VerSSA and handled as unclassified information resource among the partners for the purposes of processing and analysis.

To support active experimentation within the remit of PHANTOM ECHOES, effort was undertaken by the FVEYs S&T community to establish a “federated” suite of SDA data processing capabilities which would be capable of supporting data collection and analysis activities. An audit of allied tools & software was conducted via an open call for relevant capabilities possessed by each nation against a number of generalised categories: *scheduling, data collection, observation processing, exploitation and situation assessment*. This audit captured a number of potential tools (across FVEYs government, industry and academia) which could be candidates for integration into the VerSSA framework, subject to contractual and external release perspectives. A schematic overview of the full FVEYs VerSSA toolset (as of August 2020) is presented in Fig. 3; summary details are listed in Table 2.

**Table 2. Software applications currently integrated within VerSSA**  
An asterisk (\*) denotes software which is partially, or wholly, contractor-owned.

Nation	Tool / Capability	Application
AUS	DST Image Pipeline	Observation Processing (astrometry)
CAN	SQUID [Semi Quick Intelligent Detector]	Observation Processing (astrometry, photometry)
NZ	Starview	Observation Processing (astrometry, photometry)
UK	Dstl Image Pipeline	Observation Processing (astrometry)
UK	Mission Planner	Exploitation (orbit determination)
US	CAR-MHF [Constrained Admissible Region Multiple Hypothesis Filter]	Exploitation (initial orbit determination)
US*	SITA [Situation Identification and Threat Assessment]	Situation Assessment
US	Uni. Arizona (UA) IOD Filter	Exploitation (initial orbit determination)
US	Uni. Arizona (UA) Pipeline	Observation Processing (astrometry, photometry)



**Fig. 3. Workflow of tools implemented within VerSSA as of August 2020.**  
Image Credits: {Dstl, DTA}

A significant capability enabled by VerSSA is the functionality to containerise software applications [“apps”] and execute them within a virtual infrastructure. Application containerisation was a crucial enabler for the sharing of tools between the participating nations, since applications could be delivered as pre-compiled, executable packages which hence retain all national IP associated with underlying processes and algorithms. Preparation of individual software applications for integration into VerSSA principally consisted of tailoring each piece of software to be placed in a containerised form (using Docker [8]) to subsequently be installed into the VerSSA environment. Such a process could then enable the application to be executed by CyVerse’s remote servers.

Software could be delivered either as interpreted language or as compiled code, and the transfer process was conducted by each nation individually in collaboration with the University of Arizona (UA): source code and/or executable files were passed to UA software engineers, who undertook the containerisation process through dialogue with the originating national representative. Interface Control Documents (ICDs) were developed by UA in discussion with individual nations to establish the number(s) and type(s) of input/output files used by specific apps, and how to translate these into formats for use downstream.

With each individual tool integrated in a containerised form, they can be called and executed within CyVerse by accessing each app's associated Application Programming Interface (API) using a script/language that can handle http(s):// requests (for example, Python). This approach allows individual instances of each app to each run on a new (remote) server; effectively copying an image of the "master" version of each app onto a new processor. Multiple users can call or run each tool simultaneously in parallel, or execute multiple processes concurrently.

As of August 2020, a prototype SDA toolset has been formed within VerSSA from national software tools from across the coalition, designed specifically to enable experimentation by the FVEYs SDA S&T community. Testing has been undertaken on each individual application to verify that performance matches results produced when executed on the source code against a test dataset. As an aid to the user, a comprehensive suite of online documentation was developed by UA, housing a wiki encyclopaedia, data formats & ICDs, and video tutorials on the use of VerSSA [9].

The current VerSSA toolset enables a semi-automated workflow to be created within the CyVerse environment for the processing of SDA data, comprising the following sub-steps: 1) astrometric processing of raw EO imagery to extract satellite position(s) and time(s); 2) tagging of objects and formation of tracklets; 3) generation of initial orbit estimates via Initial Orbit Determination (IOD); and 4) conduct of a full, Special Perturbations (SP) Orbit Determination (OD) based on initial state vector estimates and processed observation data. An optional final step, whereby orbit solutions can be compared for close-approach and proximity-threats, can then be conducted via interface with external tool(s).

The work undertaken on VerSSA alongside the PHANTOM ECHOES initiative has shown that cloud-based data processing & storage solutions display considerable promise for meeting the needs of an R&D architecture tailored towards allied SDA experimentation. This judgement is based on the achievements to date by the FVEYs SDA S&T community to construct a centralised SDA storage and processing framework (at Unclassified level), accessible from multiple, distributed sites. This framework is planned to be leveraged within future S&T experiments and could act as a template for future, operational coalition architectures. An exemplar, demonstration workflow is currently functional within VerSSA in preparation for data collection within PHANTOM ECHOES 2, allowing a full process of data analysis to be initiated autonomously upon upload of new observation data.

## **4. COALITION OBSERVATION & ANALYSIS CAMPAIGN (PHANTOM ECHOES)**

### **4.1 Overview**

Mission Extension Vehicle-1 (MEV-1) was designed by Space Logistics LLC, a subsidiary of Northrop Grumman Corporation, and launched from Baikonur Cosmodrome (Kazakhstan) on 9<sup>th</sup> October 2019. Following insertion into a highly-eccentric, super-synchronous transfer orbit, MEV-1 performed a 4-month circularisation procedure where four Hall-effect thrusters burned near-continuously to conduct a long-duration transfer to geosynchronous orbit. In February 2020, MEV-1 entered rendezvous with Intelsat-901 in the GEO graveyard orbit, before docking with it and assuming full control of Intelsat-901's orbital and attitude control. Following docking of the two vehicles, the resulting combined vehicle drifted back toward its operational longitude at 27.5 degrees West, where Intelsat-901 resumed its communications services for customers in March 2020. By providing its client with augmented manoeuvre capability for routine station-keeping and end-of-life disposal, MEV-1 is expected to extend Intelsat-901's operational lifetime by a further five years (to 2025), before detaching and undertaking a similar mission for a future client vehicle.

A data collection campaign, formed around utilisation of an R&D network of sensors across the PHANTOM ECHOES network and beta-testing of the data processing functionality within VerSSA, was sequenced against two principal segments of the MEV-1 mission of relevance to multi-lateral research interests. These were:

- (1) Tracking and orbit determination of MEV-1 during orbit circularisation and GEO transfer [Oct 2019 to Jan 2020]
- (2) Observation of rendezvous & proximity operations of MEV-1 with Intelsat-901, and subsequent docking [Jan 2020 to Feb 2020]

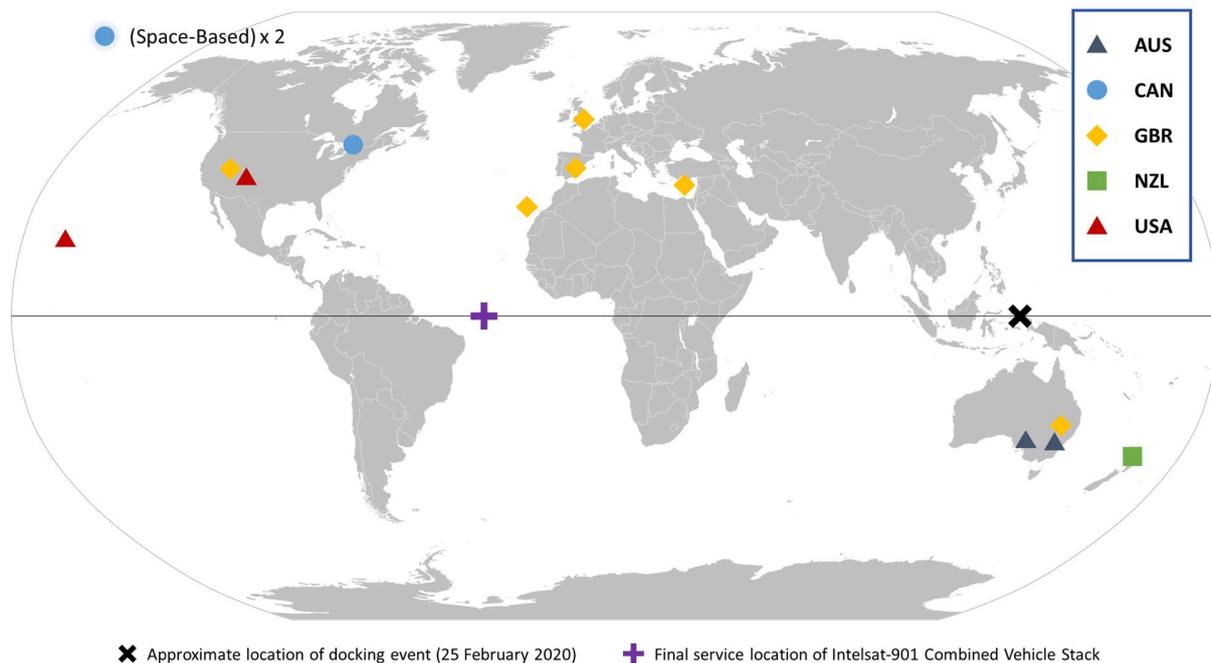
During this campaign, observers from Dstl, AFRL, DRDC, DST, DTA and the University of Arizona performed optical tracking of both MEV-1 and Intelsat-901, collecting astrometric and photometric measurements from ground and space under “best efforts” according to weather, sensor availability and personnel constraints. A combination of research sensors and, when available, operational SDA capabilities accessible by the group, were used to collaboratively observe the satellite pair. A number of ad-hoc, academic observations also contributed from the academic community within the FVEYs nations, including other data types and phenomenologies. An overview of the sensor network utilised within Phase I is described in Table 3, and shown geographically in Fig. 5.



**Fig. 4. Intelsat-901 and MEV-1 Combined Vehicle Stack (CVS), artist's impression.**  
Image Credit: Northrop Grumman / Space Logistics

**Table 3. Overview of R&D network utilized during Phase I of the PHANTOM ECHOES experiment.**  
Contributing sensors (from academia/industry) are noted in with an asterisk (\*).

	Sensor	Organisation	Site	Description
AUS	DST Observatory	DST	Adelaide, AUS	2 x Ground-based optical telescope
AUS*	EOS Space Systems	EOS	Canberra, AUS	Ground-based optical telescopes
CAN	GBO-Ottawa	DRDC	Ottawa, CAN	Ground-based optical telescope
CAN	<i>NEOSSat</i>	DND/DRDC	LEO (~800 km)	Space-based optical system
CAN	<i>Sapphire</i>	DND	LEO (~800 km)	Space-based optical system
NZ	DTA Observatory	DTA	Auckland, NZ	2 x ground-based optical telescopes
UK	Dstl Observatory	Dstl	Wiltshire, UK	Ground-based optical telescope
UK*	Herstmonceux GEOF	UKRI/NERC	Sussex, UK	Ground-based optical telescope
UK*	iTelescope network	iTelescope.Net	(global)	Astronomical telescopes
UK*	Starbrook	Space Insight	Troodos, Cyprus	Ground-based optical telescopes
UK*	SuperWASP	Uni. Warwick	La Palma, Spain	Ground-based optical telescope
US	Raven Observatory	AFRL	Albuquerque, US	Ground-based optical telescope
US*	UA Observatory	Uni. Arizona	Tucson, US	2 x Ground-based optical telescopes
US*	NASA Infra-Red Telescope	Uni. Hawaii	Hawaii, US	Infra-Red telescope
US*	Large Binocular Telescope	Uni. Arizona	Mt Graham, US	(2x) 8.4 m optical telescope

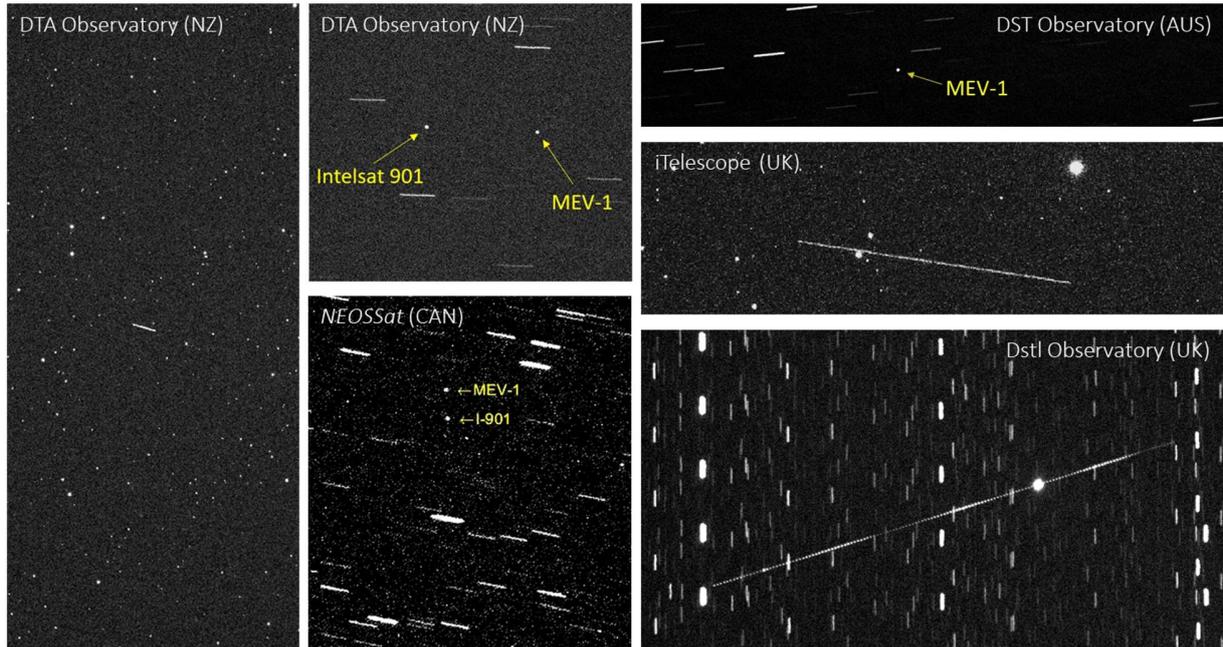


**Fig. 5. Overview of R&D sensor network utilized during PHANTOM ECHOES Campaign. Where multiple sensors are in relative geographical proximity, these have been grouped as a single icon.**

Coalition observation efforts were formally initiated on 11<sup>th</sup> October 2019 following insertion of MEV-1 into an introductory transfer orbit by its Proton launch vehicle. Sensor measurements (including astrometric [position] and photometric [brightness] data) were handled and exchanged amongst the group as unclassified imagery data; stored and processed within VerSSA for subsequent post-event analysis by the group. A representative collage of tracking images from ground- and space-based S&T optical sensors from across the coalition is presented in Fig.6. As well as collecting real-world measurements, simulation work was also performed to generate synthetic data, aligned with similar scenarios of interest associated with GEO proximity events, to test additional components of the VerSSA software toolbox.

Unfortunately, due to limitations on conducting a comprehensive testing process on all applications ahead of the MEV-1 activity, the VerSSA suite of tools was not fully qualified to be deployed as a core part of the experiment at the time of the event: instead, it was exploited in an evaluation capacity during the lifetime of the Phase I campaign. Prior to collection of any observation data on MEV-1, a decision was made to revert to existing implementation of tools (“offline”) in order to fulfil the data processing and analysis needs during the campaign itself, with subsequent post-event analysis to take place using the VerSSA functionality. Coordination of observation tasks between sensors was hence performed on an “open-loop” basis, conducted via Unclassified email and using public orbit data from Space-Track.org [10] (augmented by additional information provided by industry sources) to cue sensors onto MEV-1 and Intelsat-901.

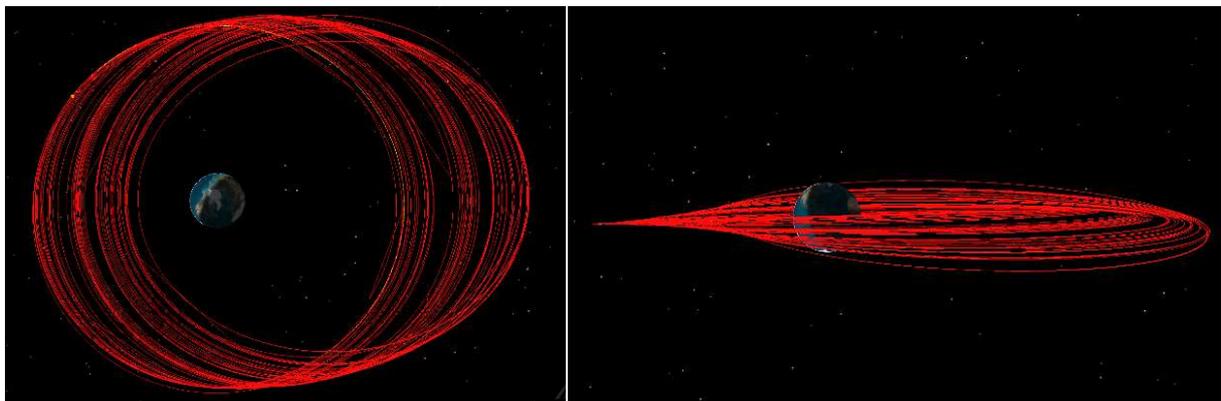
A full analysis of the experimental results is currently underway, and will be complemented by further results following completion of Phase II of the experiment. A full summary of results from both phases of activity will be reported in 2021; however, a number of initial findings are presented in the following sub-sections, based on qualitative experiences from Phase I of the campaign.



**Fig. 6. Post-launch tracking of MEV-1 (collage).**  
Image Credits: {Dstl, DTA, DST, DRDC}

#### 4.2 Tracking and Custody of MEV-1 during Constant-Thrust Activities

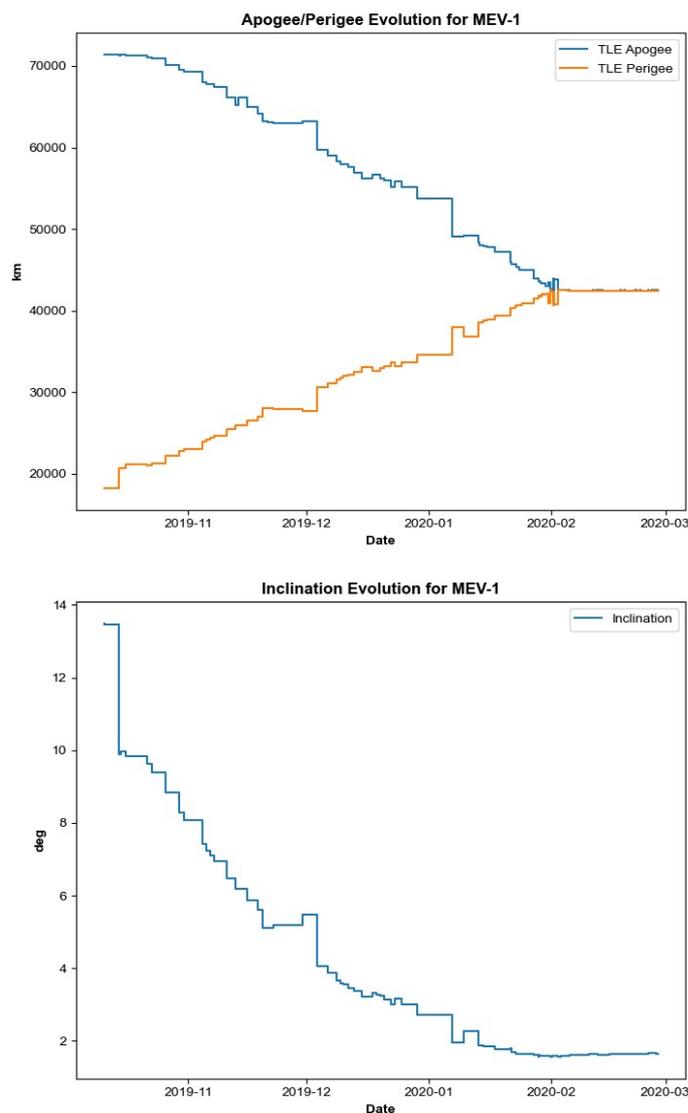
MEV-1 was initially injected into a 71,417 x 18,265 km eccentric orbit at an inclination of 13.5°. Over a ~97-day period, this orbit was circularised via long-duration actuation of its electric thrusters to reduce its orbital eccentricity and inclination, creating rapidly-evolving changes to MEV-1's orbital trajectory; this profile is depicted in Fig. 7. MEV-1 continued to conduct circularisation manoeuvres until February 2020, whereby the vehicle reached a near-circular orbit at an altitude of +300 km above GEO to later conduct RPO activities with IntelSAT-901 whilst geographically positioned over the Pacific Ocean. A three-dimensional profile of MEV-1's long-duration dynamics is shown in Fig. 7 in terms of the orbital evolution of semi-major axis and inclination, based on public Two-Line Element (TLE) data from Space-Track.org [10]. Evolution of the orbital apogee, perigee and inclination over the same duration are presented in Fig. 8.



**Fig. 7. (left) Semi-major axis evolution of MEV-1 from October 2019 to January 2020. (right) Inclination pull-down from a 13.5° to 0° inclination.**

Figure Credit: DRDC

MEV-1's initial orbital geometry at commencement of its constant-thrust activities presented a number of tracking and custody challenges for the utilised R&D network: owing to the observing and illumination geometry, at some stages of the mission, (5-7) day gaps in visibility could be witnessed from a single geographical site. These constraints were augmented further by daylight and illumination restrictions for optical instruments: MEV-1's orbital geometry sought to maximise the time spent in Sunlit conditions (likely to assist with power generation for use of its electric thrusters), minimising the time spent in eclipse. For ground-based, optical sensors, this limited opportunities to observe the vehicle during local night-time, as well as placing limits on the available resource to conduct "search" and/or reacquisition techniques. The ability to maintain uninterrupted custody would likely require a global sensor network (ideally, with multiple sensors for additional redundancy and handover processes), utilising remote operation and autonomy with resources dedicated to specific tracking of the vehicle. Options for persistent observation & tracking, for example through reception of RF emissions irrespective of solar illumination condition or terrestrial weather, could be explored to mitigate optical observation gaps and full loss of custody of the vehicle.

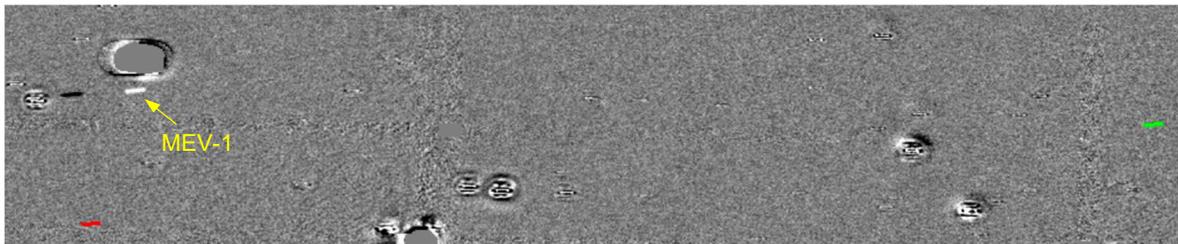


**Fig. 8. Evolution of MEV-1 (Keplerian) orbital parameters based on public Two-Line Element (TLE) data from Space-Track.org [10]. (top) Apogee & perigee. (bottom) Inclination.**

Figure Credit: Dstl

Beyond simple geometrical access limitations, MEV-1's constant-thrust system (and overarching electric propulsion orbit-raising procedure) introduced constraints for ground-based observers to maintain orbit custody when relying on public information and when taking only ad-hoc observations. Satellites applying non-impulsive (and non-conservative) forces cannot be adequately represented by simple Keplerian elements, since such trajectories are effectively non-Keplerian and present varying thrust magnitude and geometry over long durations. Simple mean element cues from public sources (for example, TLEs available from Space-Track.org [10]) were only sufficient to maintain a coarse track on MEV-1 for a limited period of time and would rapidly diverge from true position of the vehicle, particularly when updates to these cues were sparse. Once the vehicle was rendered "lost" due to imprecise cueing information, reacquisition typically required the application of wide-field or surveillance sensors which could operate with coarse orbit/cueing information.

A particular example of the utility of such sensors was demonstrated by complementary involvement of the wide-field SuperWASP telescope (approx.  $480 \text{ deg}^2$ ;  $15.5^\circ \times 31^\circ$ ) in the campaign, operated by the University of Warwick (UK) at Roque de los Muchachos Observatory on La Palma. During MEV-1's early orbit-raising period, angular offsets on the order of 4-5 degrees (or more) could be encountered against the nominal position predicted by a 1.5 day-old TLE solution; for example, as illustrated in Fig. 9. Where SuperWASP was able to detect the vehicle with a relatively coarse pointing cue, routine acquisition of the vehicle by the primary R&D observing team operating narrower-field (typically  $< 1^\circ$ ) optical telescopes was more challenging and led to a greater frequency of missed detections of the vehicle during this segment of the mission. To maintain full custody of such objects with narrow instruments and without reliance on external cues, a significant sensor resource is likely required to (semi-) persistently observe the vehicle from multiple sites and conduct estimation of non-conservative forces using tracking and filtering methods in order to schedule later collection attempts.



**Fig. 9. Difference-image between two frames collected by the SuperWASP telescope on 9<sup>th</sup> November 2019 at approximately 0230 UTC. The predicted streak position of MEV-1, based on a TLE at epoch of 7<sup>th</sup> November 2019 / 1500 UTC, is shown in green, whilst the true (detected) position of MEV-1 is highlighted by the yellow marker. Angular separation between the "predicted" and "true" positions is approximately  $3.5^\circ$ ; for illustration, the equivalent position of the same TLE, but with a 9-minute offset applied, is highlighted in red.**

Figure Credit: University of Warwick

A number of sparse, research-grade observations were collected by the R&D team during MEV-1's orbit-raising segment, but a focused campaign of data collection and custody maintenance was not pursued. The latency and "freshness" of publicly-available TLE data presented obstacles for scheduling frequent observation windows with up-to-date orbit cues, further constrained by personnel limitations for undertaking routine (e.g. daily) tracking. Of the sparse datasets collected from these efforts, these were typically of limited density, span and/or cadence to fully analyse the thrust dynamics and resulting orbit solution in isolation: dense, sustained tracks of data are required in order to improve success of the subsequent orbit determination steps and for associated estimation of non-conservative forces.

This shortfall has informed plans for an improved data collection campaign to be undertaken during Phase II of the activity; specifically considering custody maintenance and orbit determination perspectives surrounding constant-thrust missions, and MEV-2 in particular.

### 4.3 MEV-1 / Intelsat-901 GEO Rendezvous and Docking

Upon entering proximity to Intelsat-901, MEV-1 initiated a series of (2 x 1) km Clohessy-Wiltshire relative motion circumnavigations to inspect the client and for testing of its proximity sensors & navigation solution prior to making a docking approach. Upon verification of satisfactory performance, MEV-1 then approached Intelsat-901 from the zenith direction, and began a process to dock with the Liquid Apogee Engine assembly by using a probe device to clamp onto the client. Successful coupling of the two vehicles took place on 25<sup>th</sup> February 2020 at an approximate Earth longitude of 130° E, and at an altitude ~300 km above the GEO protected region in order to mitigate risk of generating unwanted space debris due to a collision or other mishap.

During this period, astrometric, photometric and spectrometric observations were collected by the PHANTOM ECHOES team from New Zealand, Australia and the United States whereby the two vehicles would appear in close proximity; for example, as shown in the sequence of images from the DTA Observatory in Auckland, New Zealand, in Fig. 10.

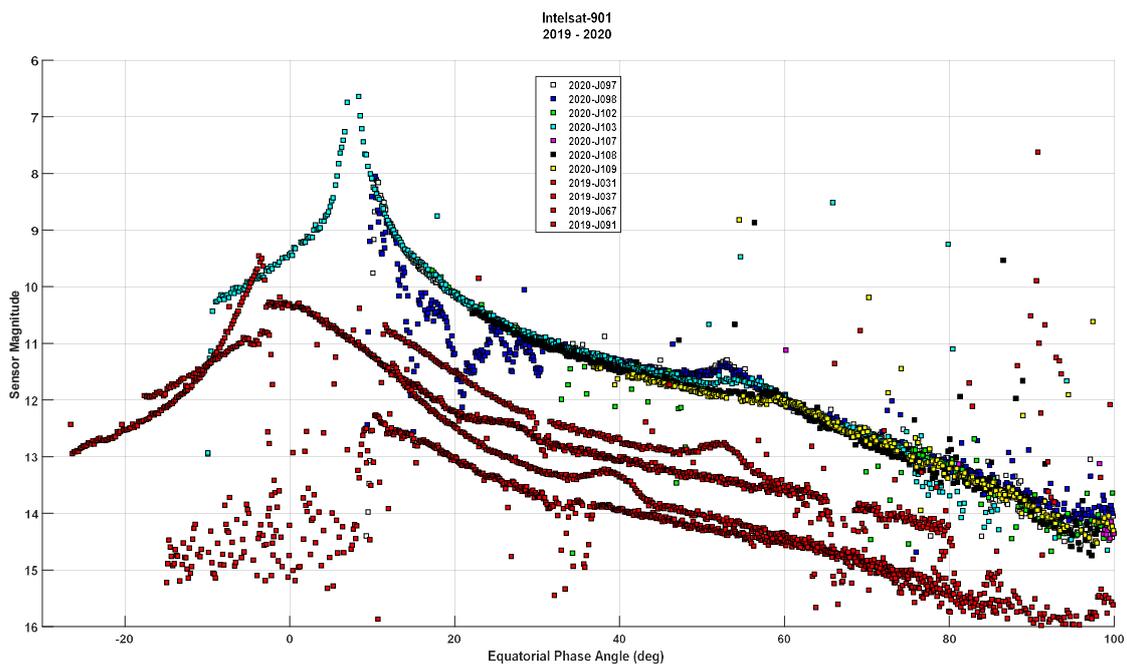


**Fig. 10. Sequence of observations of MEV-1 and Intelsat-901 captured on 5<sup>th</sup> February 2020 from Auckland, New Zealand at approximately 30-minute intervals. Angular separation of the objects is around 1 arcmin, with Intelsat-901 appearing on the left and MEV-1 on the right within each frame.**

Figure Credit: DTA

During the proximity segment, both satellites performed periodic attitude and orbital manoeuvres which made external (TLE) orbit data unreliable as an identification aid, notwithstanding any inherent unreliability of such data owing to cross-tagging issues. In some cases, relative brightness could be used as an indicator to differentiate (the larger) Intelsat-901 from (the smaller) MEV-1, although this was often an unreliable metric due to frequent attitude changes being made by both vehicles which modified their apparent visual magnitude; as evidenced in Fig. 10. The undertaking of orbital manoeuvre (translational) and attitude (rotational) changes by both vehicles led to further tracking impediments due unknown dynamics which were not accurately modelled.

Ground- and space-based photometry was examined as a method for the discrimination and identification of individual spacecraft when jointly in the sensor field-of-view. Based on observations of Intelsat-901 and MEV-1 prior to docking, there is some evidence that objects could be distinguished from their apparent phase curves, arising from the different engineering geometry and different morphology and glint profile when stable (tumble-free): this can be interpreted within the pre- and post-docking photometric curves displayed in Fig. 11. These results could be partially corroborated across multiple sensors/observers; however, full verification remains inconclusive at this time – this performance will be considered further during Phase II of the experiment. Similarly, data collected using spectroscopy sensors operated by the University of Arizona indicated that the resulting spectral profiles could be of utility to augment the process for discrimination and identification; however, this requires more study in order to draw a comprehensive set of conclusions.



**Fig. 11. Photometric measurements from the Ottawa ground-based observatory against the Combined Vehicle Stack (multi-color) and pre-docking photometry of Intelsat-901 (red light curves).**

Figure Credit: DRDC

Once the pair had docked, the resulting Combined Vehicle Stack (CVS) formed a cruciform pattern with solar arrays perpendicular to one another (as displayed in Fig. 4). Following successful shakedown to affirm that systems were performing nominally, the CVS was then manoeuvred to its final operating longitude at 27° W, arriving at this location on 30<sup>th</sup> March 2020. Intelsat-901 formally began resumption of its communications service on 2<sup>nd</sup> April 2020, with MEV-1 assuming orbital and attitude control on behalf of the combined vehicle.

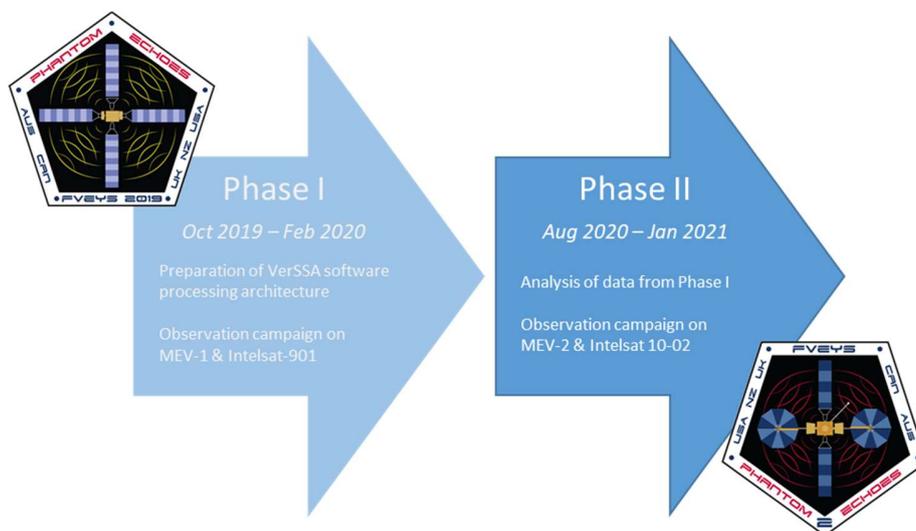
From ground-based optical sensors, an increase in surface geometry of the CVS post-docking could be inferred from relative brightness and photometric measurements: this was witnessed as a 2-3 m<sub>v</sub> increase in general brightness of the singular vehicle, as well as visual changes to the profile of lightcurve morphology and glint pattern. Elements of these features can be observed in pre- and post-docking photometry measurements presented in Fig. 10; however, these results are still under review and will be compared with similar results arising from Phase II of the activity from MEV-2 and its intended client.

## 5. PHASE II (MEV-2) AND FUTURE WORK

On 15<sup>th</sup> August 2020, a second Northrop Grumman mission (MEV-2) launched from French Guiana onboard Ariane 5 flight VA253 [11] and will, circa January 2021, rendezvous and dock with Intelsat 10-02 to perform life-extension of the client vehicle. Based on the experiences gathered during the initial PHANTOM ECHOES campaign, the FVEYs S&T community will use this opportunity to repeat elements of the campaign undertaken during Phase I, whilst leveraging more of the VerSSA functionality to attempt semi- real-time processing of data collected by S&T sensors on MEV-2 and its client.

The MEV-2 spacecraft is functionally identical to MEV-1 and will follow a broadly-similar set of CONOPs to its predecessor towards rendezvous with its intended client. A notable feature of this follow-up mission is that the principal RPO and docking activity will take place in-situ at geosynchronous altitude, with the client remaining on-station and continuing to deliver its own communications service throughout the docking process. The client, Intelsat 10-02, is currently stationed at a longitude of 1° W alongside a number of other active payloads in its vicinity: as such, this poses a unique opportunity for the FVEYs community to examine concepts associated with GEO rendezvous and protection of active payloads in the Deep Space in a relatively congested region of the GEO belt.

The associated PHANTOM ECHOES 2 experimental activity will, hence, further attempt to understand the capability limitations of long-range SDA sensing capabilities, and resolve deficiencies encountered during the MEV-1 experimentation through use of alternative S&T approaches. An active observation campaign will be conducted by the FVEYs SDA S&T team to track and observe the MEV-2 mission and its dynamics on its journey towards, and around, Intelsat 10-02. A full rationalization of results gathered from PHANTOM ECHOES Phases I & II will hence be conducted following the conclusion of MEV-2 observation activity in Q1 2021, seeking to conduct a thorough analysis of the gathered data and deploy/develop algorithmic approaches which enhance situational I&Ws of utility to allied HVAs in Deep Space.



**Fig. 11. Schematic depicting progression of the PHANTOM ECHOES experiment.**

Figure Credit: Dstl

## 6. SUMMARY

Through the participation of the UK, US, Canadian, Australian and New Zealand defence R&D communities, Phase I of the PHANTOM ECHOES experiment has demonstrated strong progress towards formation of a collaborative sensor and processing architecture for coalition R&D on Space Domain Awareness. During October 2019 and March 2020, a successful observation campaign was executed against the MEV-1 mission, and a repeat campaign will take place on MEV-2 between August 2020 and January 2021.

Preparatory work undertaken by the FVEY's SDA S&T team has yielded significant progress in standing up a single, federated data processing architecture to enable coalition SSA experimentation. Software tools and data from all nation participants have been integrated into a single computational architecture (VerSSA) to derive a methodology for conduct semi-automated, end-to-end processing of raw optical imagery. This capability is structured around the processing of electro-optical data, spanning the processes of feature extraction, astrometric reduction, orbit determination, and culminating in a (partial) capability for generation of GEO proximity threat warnings as an enabler for coalition experimentation.

During the research activity conducted in alignment with the MEV-1 mission, a multi-national sensor architecture of ground and space-based assets was operated on a "best effort" principle to gather tracking and characterisation data during October 2019 and March 2020. At each stage of MEV-1's advance toward Intelsat 901, observers from DSTL, AFRL, UA, DRDC, DST and DTA performed optical characterization of both MEV-1 and Intelsat 901 using both research and, when available, operational SSA capabilities to collaboratively track the satellite pair. Within Phase I of the experiment undertaken so far, nations have worked collaboratively on data collection, processing and analysis for the purposes of further understanding the implications of long-duration electric thrusting and GEO proximity operations on existing astrodynamical models and characterisation capabilities in development within S&T.

Through refinement of the contributing architecture and adaptation of the associated techniques during Phase II of the PHANTOM ECHOES experiment (August 2020 to January 2021), further progress is expected to be made in these areas which can advise future solutions of relevance to the Combined Space Operations community. Comprehensive results from the PHANTOM ECHOES series of activities, combining results from Phase I and Phase II, will be reported in 2021.



**Fig. 12. The PHANTOM ECHOES S&T team at AMOS 2019.**

## ACKNOWLEDGEMENTS

Content includes material subject to © Crown copyright (2020), Dstl. This material is licensed under the terms of the Open Government Licence except where otherwise stated. . To view this licence, visit <http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3> or write to the Information Policy Team, The National Archives, Kew, London TW9 4DU, or email: [psi@nationalarchives.gov.uk](mailto:psi@nationalarchives.gov.uk)

The authors are indebted to the hard work of a number of other individuals and organisations who have contributed to the PHANTOM ECHOES experiment thus far, which stretches far beyond the names listed at the head of this paper. The authors would therefore would like to thank the following personnel for their contribution: Alex Agathangelou, Adam Battle, Donald Bedard, Travis Bessell, Tanner Campbell, Kris Drozd, Will Feline, James Frith, Roberto Furfaro, Joe Gerber, Peter Genovese, Pip Halpin, Nick Harwood, Martyn Hole, Nirav Merchant, Andy Partridge, Grant Privett, Vishnu Reddy, Jared Rieckewald, Lauchie Scott, Edwin Skidmore, Jovan Skuljan, Stefan Thorsteinson, Ramona Walls, Leeha Wood, Virginia Wright.

This material is based upon work supported by the National Science Foundation under Award Numbers DBI-0735191, DBI-1265383, and DBI-1743442. URL: [www.cyverse.org](http://www.cyverse.org)

## REFERENCES

- [1] S. George, A. Ash. Future On-Orbit Spacecraft Technologies and Associated Challenges for Space Situational Awareness, *AMOS 2019 Conference* (17-20 September 2019, Maui HI, USA), 2019.
- [2] A. Ash, J. Skuljan, L. Scott, W. Martin, V. Wright, T. Bessell. A Summary of 5-Eyes Research Collaboration into SSA, *AMOS 2018 Conference* (11-14 September 2018, Maui HI, USA), 2018.
- [3] Memorandum of Understanding among the Australian Department of Defence, the Department of National Defence of Canada, the New Zealand Defence Force, the Secretary of State for Defence of the United Kingdom of Great Britain and Northern Ireland, and the Department of Defence of the United States of America for Combined Space Operations; 01 July 2015.
- [4] Memorandum of Understanding among the Australian Department of Defence and the Department of National Defence of Canada and the New Zealand Defence Force and the Secretary of State for Defence of the United Kingdom of Great Britain and Northern Ireland and the Department of Defence of the United States of America Concerning the Technical Cooperation Program (TTCP) II; April 2018.
- [5] Ash, Scott & Feline (2016), Findings from the UK and Canadian Space Situational Awareness (SSA) Experimentation during the Relocation of SKYNET 5A Satellite; AMOS Conference 2016.
- [6] CyVerse [CyVerse Discovery Environment]. <https://de.cyverse.org/de/> (last accessed: 13 August 2020)
- [7] UDL [Unified Data Library]. <https://unifieddatalibrary.com/> (last accessed: 13 August 2020)
- [8] Docker [software containerisation platform]. <https://www.docker.com/> (last accessed: 13 August 2020)
- [9] Uni. Arizona/Confluence [VerSSA wiki encyclopaedia]. <https://verssa.atlassian.net/wiki/spaces/VA/overview/> (last accessed: 13 August 2020)
- [10] JFCC SPACE/J3 [Space-Track.org orbit data]. <https://www.space-track.org/> (last accessed: 13 August 2020)
- [11] Arianespace [Ariane Flight VA253 mission overview]. <https://www.arianespace.com/mission/ariane-flight-va253/> (last accessed: 13 August 2020)