PHANTOM ECHOES 2: A Five-Eyes SDA Experiment on GEO Proximity Operations

Simon George, Alexander Agathanggelou, Grant Privett, Philippa Halpin, William Feline, Andrew Ash
Defence Science & Technology Laboratory, UK

Paul Chote
University of Warwick, UK

Lauchie Scott
Defence R&D Canada, Canada

Jovan Skuljan
Defence Technology Agency, New Zealand

Jason Alvino
Defence Science and Technology Group, Australia

James Frith
Air Force Research Laboratory, US

ABSTRACT

On 12th April 2021, Mission Extension Vehicle-2 (MEV-2) conducted rendezvous and docking with INTELSAT 10-02 as part of a commercial life-extension mission in Geostationary Earth Orbit (GEO). The defence science and technology (S&T) agencies of the Five-Eyes (FVEY) nations – the United Kingdom, United States, Australia, Canada and New Zealand – exploited this opportunity to successfully pursue a coordinated Space Domain Awareness (SDA) experiment, observing and scrutinising the dynamics and behaviours of the two satellites to improve allied capabilities for protection of allied spacecraft in GEO. This experiment, known as "PHANTOM ECHOES 2" (PE2), followed-on from an initial campaign undertaken in 2020 on the MEV-1 mission [1] and forms Phase II of a series of collaborative SDA activities conducted by the FVEY SDA S&T community on GEO proximity operations. These activities have been performed under The Technical Cooperation Program (TTCP), as part of a wider research initiative named "PHANTOM ECHOES".

In this paper, an overview of activity conducted within *Phase II* of the PHANTOM ECHOES experiment is presented; describing application of a FVEY SDA S&T sensor and processing architecture in observing the activities of MEV-2 from launch through to successful docking with INTELSAT 10-02. The paper first introduces the wider PHANTOM ECHOES initiative and the motivations for collection of real-world data on surrogate targets in Deep Space, before proceeding to provide an outline summary of specific observation campaigns conducted on orbital transfer and proximity docking phases of the MEV-2 mission. Preliminary data and results from these campaigns are then provided, highlighting where the FVEY SDA S&T community is exploring the challenges associated with flight safety of allied spacecraft in Geostationary Earth Orbit (GEO) and is identifying potential solutions.

1. INTRODUCTION

As technologies mature within the commercial sector for applications such as satellite life extension, on-orbit servicing and active debris removal, the space domain is witnessing a rapid growth in capability for satellites to interact and operate in close proximity in Deep Space. These developments are indicative of the increasing threat to critical space assets in GEO from uncooperative, adversarial interference: as an increased number of spacefaring nations develop mature capabilities for rendezvous and proximity operations (RPO), their operations present challenges to flight safety and mission assurance of high-value military spacecraft.

In response to this, since 2019, the defence S&T laboratories of the FVEY nations have collaborated on a series of coalition Space Domain Awareness (SDA) experiments [entitled "PHANTOM ECHOES"] to understand how novel solutions arising from within S&T may help to counter these emerging challenges [1]. These experiments have been conducted under the Memorandum of Understanding (MOU) of The Technical Cooperation Program (TTCP) [2], building on the heritage of previous FVEY SDA S&T experiments undertaken since 2014. Through collaborative arrangements with the leading national laboratories, additional academic and industry involvement has been afforded to enable conduct of a multi-faceted SDA experiment to be undertaken on real-world targets of interest aligned with these objectives.

For PHANTOM ECHOES, the Northrop Grumman Mission Extension Vehicle (MEV) fleet of commercial life-extension spacecraft were adopted as surrogate observation targets to enable a better understanding of the operational challenges associated with manoeuvring and close-proximity space vehicles. Efforts were divided into two principal phases of activity; both associated with discrete phases of data collection and analysis:

> *Phase I* ("PHANTOM ECHOES") was structured around Mission Extension Vehicle-1 (MEV-1), whereby a FVEY SDA S&T observation campaign was conducted between October 2019 and March 2020 on MEV-1 and its client, INTELSAT-901. This campaign exploited 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. Details and findings from this phase of the experiment were presented at AMOS 2020 [1].
>
> *Phase II*, ("PHANTOM ECHOES 2") sought to replicate the approach; this time, focussing on observation activities associated with MEV-2 with INTELSAT 10-02 and exploiting the tool suite developed within Phase I as part of a real-time use case. Data collection efforts on these targets began in August 2020 upon launch of MEV-2, and were progressed via a series a short-duration "sprint"-like campaigns conducted sporadically until final docking of the two objects in April 2021.

During late 2019 and early 2020, *Phase I* of the PHANTOM ECHOES experiment was undertaken on MEV-1; observing its orbital transfer, GEO motion, client approach and rendezvous and docking with INTELSAT-901 using a variety of ground- and space-based sensors. During the follow-on campaign of PHANTOM ECHOES 2 [*Phase II*] undertaken between August 2020 and April 2021, the procedure was repeated using MEV-2; expanding the scope of the experiment and applying "lessons learned" from the first phase. Tracking and observation activities were undertaken by the international team throughout key phases of the MEV-2 mission: during the long-duration, electric-thrust orbit circularisation (August 2020 to January 2021); throughout its approach, rendezvous and docking to its mission client INTELSAT 10-02 (February 2021 to April 2021); and once operating as a Combined Vehicle Stack (CVS) with INTELSAT 10-02 (April 2021+).

Overall, these two phases of experimentation were conducted with the following principle aims, supporting S&T research requirements developed in collaboration with the Combined Space Operations (CSpO) initiative [3]:

1. Demonstrate ability to integrate SDA capabilities (software and sensor data) across FVEY 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 indicators and warnings (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 FVEY SDA S&T sensors to understand future operational challenges and possible solutions

The remainder of this paper is dedicated to providing a summary of the PHANTOM ECHOES 2 (PE2) experiment, presentation of initial results, and outline of future steps anticipated within the analysis phase of the experiment.

2. COALITION OBSERVATION AND ANALYSIS CAMPAIGN (PHANTOM ECHOES 2)

MEV-2 [SSN ID #46113, 2020-056B] was constructed by Northrop Grumman / Space Logistics LLC and launched from Guiana Space Centre (French Guiana) on 15th August 2020. The spacecraft is structurally identical to its predecessor, MEV-1 [SSN ID #44625, 2019-067B], and has been designed to conduct life extension of commercial spacecraft in GEO by attaching to the rear (zenith-pointing) face of the client and providing augmented propulsion capabilities on behalf of the client for station-keeping and post-mission disposal. Whilst its predecessor was the first spacecraft to conduct commercial rendezvous and docking on a satellite in the GEO graveyard, MEV-2 was the first to attempt such a procedure on an operational spacecraft directly on-station at GEO altitude and in relative proximity of other operational spacecraft. As such, collection of real-world data on MEV-2 and its client offered a unique opportunity to address the SDA challenges of tracking of electric-thrust objects in transit to GEO, and the dynamics and detectability of proximity operations in GEO using ground and space-based sensors.

Following insertion into an elliptical, "Geostationary Transfer Orbit [GTO]-like" initial orbit (~ 4300 km x 35700 km), MEV-2 undertook a four-month orbit circularisation process to transit to geosynchronous orbit. At the end of January 2021, MEV-2 undertook an Easterly drift around GEO to approach a longitude of 1°W and begin co-location with its mission client, INTELSAT 10-02 (IS10-02) [SSN ID #28358, 2004-022A]. After an extended period of RPO activities and payload calibration, MEV-2 successfully docked with INTELSAT 10-02 on 12 April 2021, with its client directly on-station and operational at 1°W and without interruption to its client's communications services [4]. By providing its client with an augmented manoeuvre capability for routine station-keeping, MEV-2 is planned to extend INTELSAT 10-02's operational lifetime by a further five years. Circa 2026, MEV-2 will then conduct an end-of-life disposal manoeuvre on IS10-02, before detaching and undertaking a similar mission for a future client vehicle.

Throughout its mission from launch until docking, MEV-2 was the focus of an extended data collection experiment. This effort was sequenced against two principal segments of the MEV-2 mission, with specific observations campaigns conducted within each. These were:

(1) Tracking and orbit determination of MEV-2 during orbit circularisation and GEO transfer [August 2020 to January 2021] – ***PE2 Electric Propulsion Orbit-Raising (EPOR) Campaign***
(2) Observation of proximity operations of MEV-2 with INTELSAT 10-02, and subsequent docking [February 2021 to April 2021] – ***PE2 Rendezvous and Proximity Operations (RPO) Campaign***

Within these segments, several discrete, short-duration campaigns of data collection and processing were undertaken using a mix of sensors and processing tools across S&T, academia and industry. During each campaign, observers collected metric (position, time) and signal (e.g. photometric brightness) measurements on both MEV-2 and IS10-02 under "best efforts" according to weather, sensor availability and personnel constraints, and shared this data with the contributing group of researchers. Measurement data was handled and exchanged as unclassified imagery and data; shared, stored and processed using the experimental 'CyVerse/VerSSA' platform [6][7] developed by the FVEY SDA S&T community during *Phase I*. A timeline of the data collection campaigns undertaken by this community during the PE2 experiment is presented in Table 1.

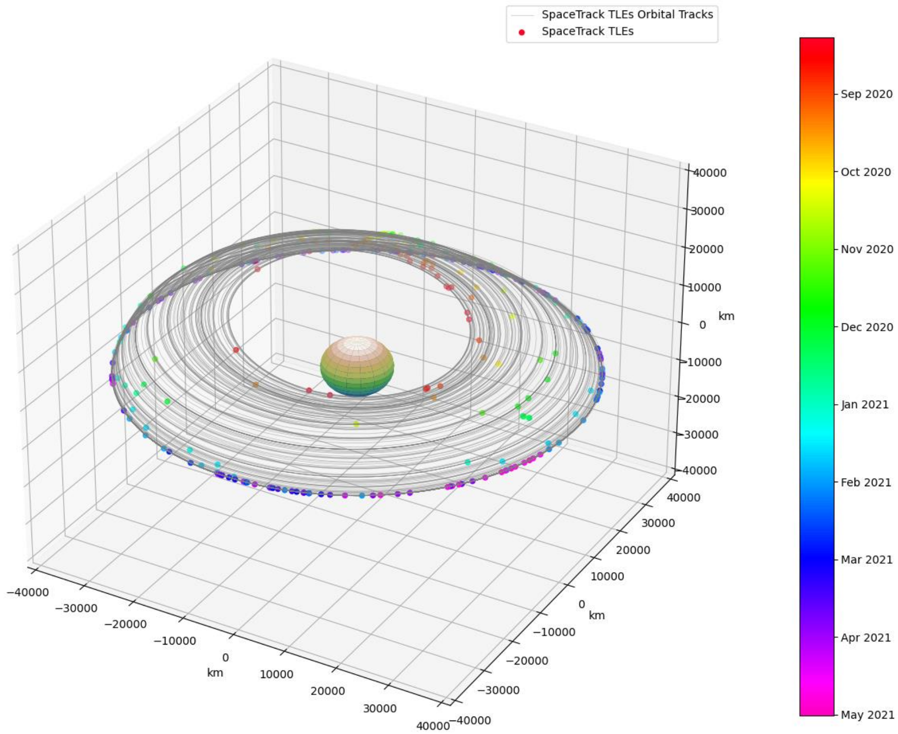

Fig. 2. Evolution of the orbital position of MEV-2 over the duration of the PE2 experiment.
Each TLE published by Space-Track.org [5] between August 2020 and May 2021 has been colour-coded and positioned according to epoch, then has been propagated for one orbit (grey) to demonstrate the evolution.

Table 1. Timeline of observation campaigns undertaken during the PHANTOM ECHOES 2 experiment.

Date(s)	**Campaign**	**Description**
01 Jun 2020	*Experiment Start*	Beginning of background data collection on IS10-02
14 Jul 2020 – 31 Jul 2020	**De-Risk Campaign**	Testing of VerSSA and custody maintenance activities in preparation for EPOR Campaign
28 Sep 2020 – 09 Oct 2020	**EPOR Campaign #1**	Observation and tracking experiment undertaken on MEV-2's orbit-raising mission segment (Weeks One and Two)
16 Nov 2020 – 22 Nov 2020	**EPOR Campaign #2**	Observation and tracking experiment undertaken on MEV-2's electric orbit-raising mission segment (Week Three), sequenced to coincide with SACT 20-3
25 Jan 2021 – 25 Apr 2021	**RPO Campaign**	Observation campaign surrounding MEV-2 docking
01 May 2021	*Experiment Finish*	Cessation of data collection

The contributing observing network comprised of both research-grade sensors, academic and industry capabilities and, when available, operational SDA capabilities. Coordination of observation tasks between sensors was performed on an “open-loop” basis, conducted via Unclassified email and based upon public orbit data from Space-Track.org [5] (augmented by additional information provided by industry sources, where available) to cue sensors onto MEV-2 and INTELSAT 10-02. Schematic diagrams of the network of sensors employed during each discrete campaign are presented in Fig. 4 (PE2 EPOR campaign) and Fig. 8 (PE2 RPO campaign), and details of each sensor are provided in Table 2. A “de-risk” campaign was conducted during July 2020 to validate performance of the sensor and data processing architecture in preparation for formal data collection activities.

The national lead organizations coordinated contributions from a variety of academic, industry, and commercial partners in their respective countries:

- Airbus Defence and Space
- Basingstoke Astronomical Society (BAS)
- Beechleaf Consulting Ltd.
- Bluestaq LLC
- Canadian Space Agency (CSA)
- Cubica Technology Ltd.
- Deimos Space UK
- Department of National Defence, Canada (DND)
- ExoAnalytic Solutions
- Goonhilly Earth Station (GES)
- iTelescope.NET
- Liverpool John Moores University (JMU)
- Northrop Grumman / Space Logistics LLC
- Numerica Corporation
- Safran Data Systems
- Space Insight Ltd.
- Tamworth Regional Astronomy Club (TRAC)
- UK Space Geodesy Facility (SGF)
- UK Space Operations Centre (UK SpOC)
- University of Arizona
- University of Auckland
- University of Kent
- University of Liverpool
- University of Texas at Austin
- University of Warwick (UoW)

Table 2. Overview of S&T network utilised during the PHANTOM ECHOES 2 experiment.
Contributing sensors (from academia, industry and the amateur community) are noted with an asterisk (*).

Sensor	Organisation	Site	Description
*BAS observers	BAS	Hampshire, UK	3 x ~25 cm optical telescopes
*Beacon Observatory	Univ. Kent	Kent, UK	43 cm optical telescope
*Deimos Sky Survey	Deimos Space UK	Ciudad Real, ESP	40 cm optical telescope
DST Observatory	DST Group	Adelaide, AUS	20 cm and 50 cm optical telescopes
Dstl Observatory	Dstl	Wiltshire, UK	12 cm and 28 cm optical telescopes
DTA Observatory	DTA	Auckland, NZ	28 cm optical telescope
DRDC Observatory	DRDC	Ottawa, CAN	15 cm optical telescope
*GHY-3 antenna	GES / Airbus	Cornwall, UK	30 m X/S-Band RF receiver
*GEOF Herstmonceux	UK SGF	Sussex, UK	40 cm optical telescope
*GOTO-N prototype	GOTO Collab. (via Univ. Warwick)	La Palma, ESP	(4 x 40 cm) telescope array
*iTelescope network	iTelescope.NET	(multiple, global)	~10-15 cm optical telescopes
*Liverpool Telescope	Liverpool JMU	La Palma, ESP	2 m astronomical telescope
NEOSSAT	DRDC / CSA	LEO (~800 km)	Space-based optical system
*Newfoundland Observatory	DRDC	St. John's, CAN	13 cm optical telescope
*Numerica network	Numerica Corp.	(multiple, global)	~30-50 cm optical telescopes
*SAFRAN WeTrack	Safran Group	(multiple, global)	RF receiver network (France)
SAPPHIRE	DND	LEO (~800 km)	Space-based optical system
Starbrook	Space Insight Ltd.	Troodos, CYP	15 cm optical telescope
*SuperWASP	Univ. Warwick	La Palma, ESP	(8 x 12 cm) telescope array
*TRAC observers	TRAC	Tamworth, AUS	2 x ~20 cm optical telescopes
*Univ. Arizona Observatory	Univ. Arizona	Tucson, US	50 cm and 60 cm optical telescopes
*UoW CMOS test telescope	Univ. Warwick	La Palma, ESP	18 cm optical telescope

3. THE PE2 ELECTRIC PROPULSION ORBIT-RAISING (EPOR) CAMPAIGN

3.1 Campaign Execution

A key finding from the Phase I activity [1] surrounded the relative difficulty in tracking MEV-1 during its long-duration orbit-raising phase: publicly-available tracking data (TLEs) were often only sufficient to maintain coarse tracking for a limited period of time, and the true position of the vehicle would rapidly diverge from Keplerian estimates due to its application of long-duration electric thrust. In response to this challenge, two distinct observation campaigns (each of one- to two-week duration) were planned to investigate the capability to track and maintain custody of vehicles equipped with constant-thrust electric propulsion (EP) for transfer to GEO.

These campaigns were conducted during September 2020 and November 2020 (see Table 1) and utilised the VerSSA software architecture developed during Phase I [1] alongside electro-optical sensors (both ground- and space-based) from across the FVEY SDA S&T network outlined in Table 2. The aim of each campaign was to demonstrate a full end-to-end tracking and catalogue maintenance process; enabling custody of the target vehicle(s) to be maintained for the duration of each week-long "cycle". The campaigns also sought to demonstrate prototype techniques for tipping-and-cueing other sensors using the VerSSA framework using internally-derived orbit estimates. To this end, a Concept-of-Operations (CONOPs) flow was defined to handle tracking and handover between sensors and using VerSSA; shown schematically in Fig 3. Since MEV-2 resided in an elliptical orbit during this time, it could be observed from all longitudes during these campaigns.

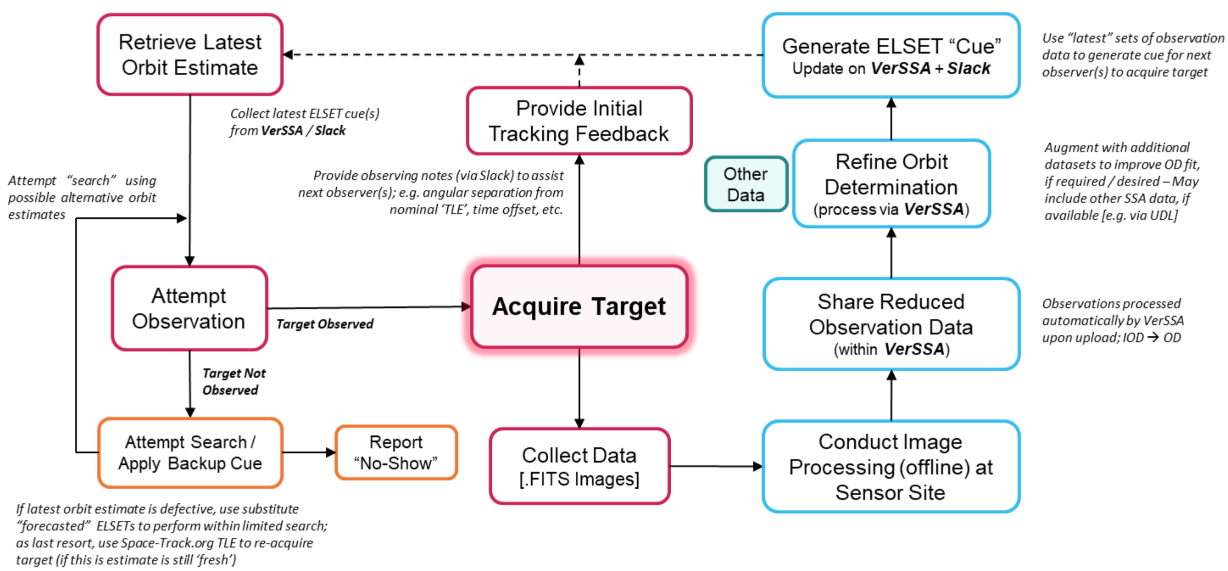

Fig. 3. Schematic describing the CONOPs implemented during the PE2 EPOR Campaign.

To enable this, improvements to the baseline VerSSA toolset implemented from [1] were made by the University of Arizona team within CyVerse to improve and expand the level of automation and enable a rapid sequence of data processing to be initiated upon receipt of new data. This enabled a federated SDA processing workflow, performing data reduction, astrometric processing, and Initial [IOD] and high-fidelity Orbit Determination [OD], to rapidly process tracking data and provide target acquisition cues (in the form of synthetic TLEs derived using only data and tools from within the network) to elsewhere in the observing network in pseudo- real-time. This architecture was coupled with use of an agile chat and communications channel using the Slack platform [8] for exchange of rapid feedback amongst sensor operators.

Weeks One and Two (28 September 2020 to 09 October 2020) of the campaign were conducted under trial conditions to refine the identified CONOPs using exemplar targets [NAVSTAR75 and NAVSTAR77], and to acquire exemplar data on MEV-2 for test purposes. Week Three (16 November 2020 to 22 November 2020) of the campaign was subsequently undertaken under "quasi-operational" conditions; tracking MEV-2 across the FVEY SDA S&T sensor network and applying the CONOPs described in Fig. 3. This campaign was sequenced to coincide with the SACT 20-3 (Sprint Advanced Concepts Training) exercise, allowing PE2-related orbital estimates to be provided to the SACT community and to exploit commercial SDA data on MEV-2 from the Numerica Telescope Network [9] made available by Numerica via the Unified Data Library (UDL) [10]. A full schematic of the sensors which were involved in the PE2 EPOR campaign is shown in Fig. 4.

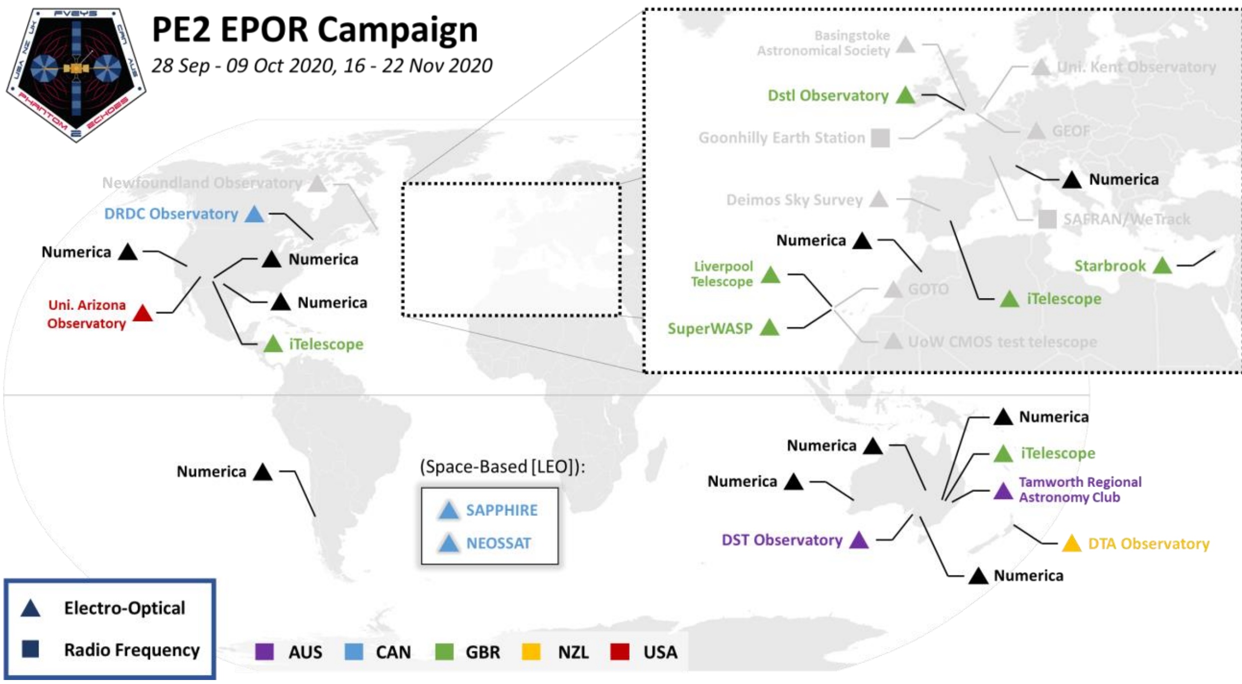

Fig. 4. Geographical distribution of S&T sensors network utilised during the PE2 EPOR Campaign. Where data has been obtained from commercial SDA data sources, these sensors are marked with (▲)

3.2 RESULTS: Tracking and Custody of MEV-2 during Constant-Thrust Orbit-Raising Activities

Using the described architecture of sensors/data and tools within VerSSA, the team successfully retained full orbit custody of MEV-2 throughout Week Three using only optical data from S&T and commercial sources and internally-derived orbit estimates for subsequent re-acquisition. Through use of the trial CONOPs shown in Fig. 3, the upload of new astrometric tracking data from a sensor site would trigger an automated process conducting IOD (using a prototype IOD routine developed by the University of Arizona) and, subsequently, OD (using Dstl's Mission Planner software) to form a new special perturbations orbit solution for MEV-2 based upon the latest data. In turn, this was converted into a "FVEY-generated" element set (ELSET) and shared across the wider sensor network (via both VerSSA and Slack) to enable re-acquisition of the vehicle using other telescopes. Through this, it was possible to retain full custody of MEV-2 despite gaps in availability of public (Space-Track.org [5]) orbit data and without use of *a priori* knowledge, such that there was no loss of custody of the vehicle during this tracking cycle.

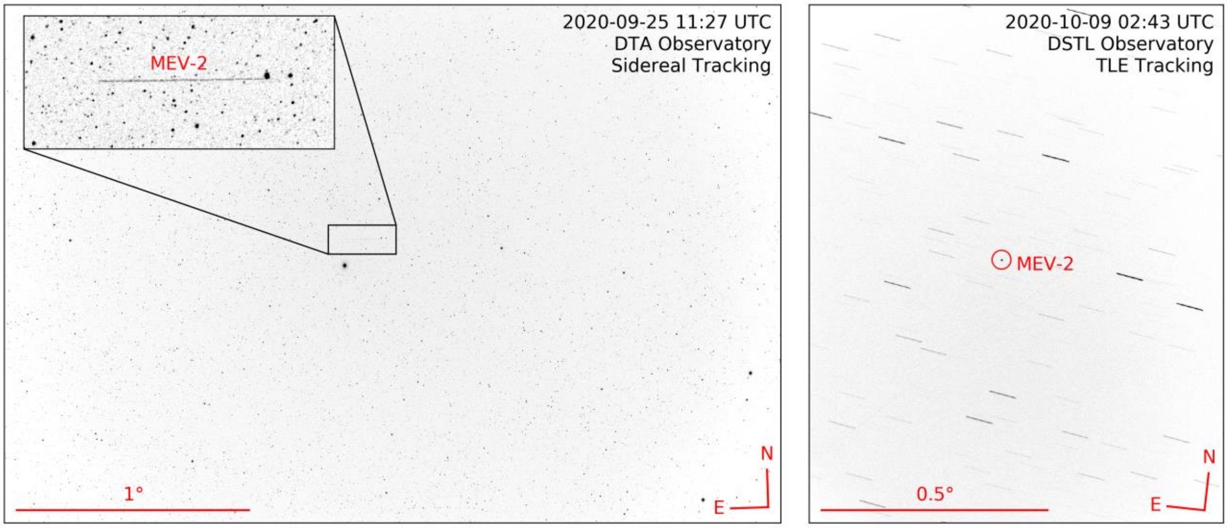

Fig. 5. Example observations of MEV-2 from the PE2 EPOR Campaign:
(left) DTA Observatory, 26 September 2020. (right) Dstl Observatory, 09 October 2020.

During the campaign, techniques were also prototyped for short-term "forecasting" of MEV-2's future motions and the predicted deviation from Keplerian dynamics, to improve capability to acquire the target using narrow-field sensors. Recognising the limitations of TLE data for representation of continuous-thrust orbits, several prototype experimental routines were developed by a FVEY tiger team (comprised of researchers at Dstl, DTA and DST Group) to conduct linear regression and/or machine learning on MEV-2's orbital history; capturing trends which could be used to inform future behaviour. These processes identified trends in five of MEV-2's six Keplerian elements (mean motion, inclination, eccentricity, right ascension of the ascending node and argument of perigee) along with a prediction of mean anomaly based upon mean motion trends. A propagation routine was used to project these to future epochs and form "experimental", predictive ELSETs which could be used for future observation scheduling.

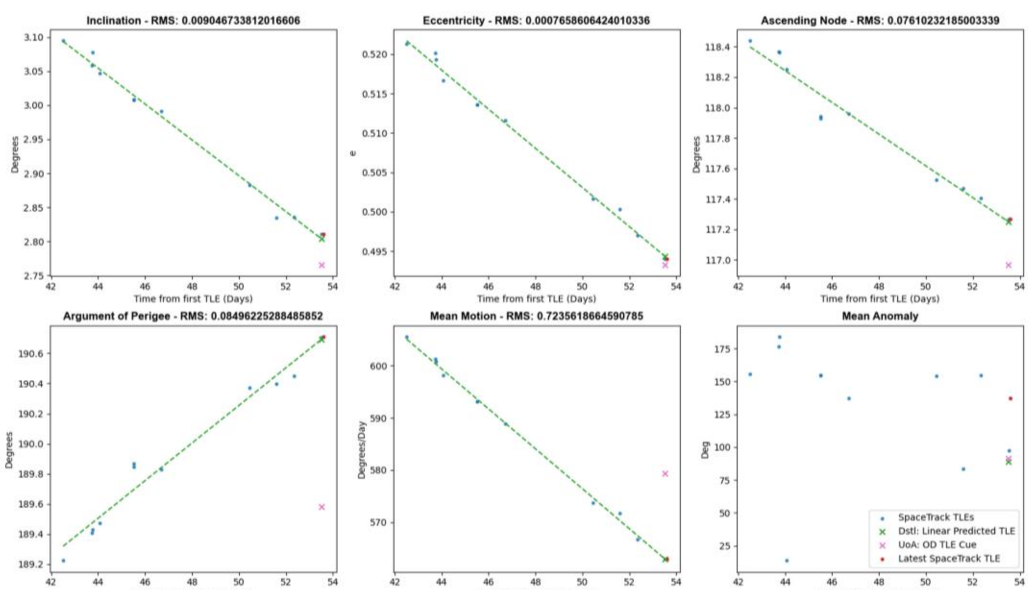

Fig. 6. Variation in MEV-2 TLE data witnessed 28 September 2020 to 10 October 2020.
The charts have been overlaid with a linear regression model which was used to create FVEY-generated predicted ELSETs. The associated root mean square (RMS) error of the model listed for each orbital element.

These cues were circulated via unclassified email on a daily basis to the observing S&T sensor network as a forecast of predictive ELSETs at 15-minute intervals covering the following 24 hours. These element sets were often valid for only a short window of time, beyond which their quality would rapidly degrade: optimal performance was therefore witnessed when selecting ELSETs closest to the time of planned observation in order to avoid any accumulation of positional errors. During Week Three of the campaign, FVEY-generated predicted ELSETs were provided to the SACT community and successfully used by commercial SDA vendors to acquire the vehicle. The method was found to be effective over short timescales, particularly during periods where MEV-2 was applying a consistent control schema to its EPOR thrust performance. This was operated successfully to cue narrow-field, large-aperture telescopes (such as the Liverpool Telescope image shown in Fig. 7) onto MEV-2. Since ELSETs available from Space-Track.org [5] were found to quickly degrade due to MEV-2's thrust dynamics, the technique was used to collect data which could not have been captured if using public orbit information only.

However, whilst it was employed effectively during this campaign, the method was found to be less suitable in the event of a change in control law on MEV-2's orbit-raising cycle; for example, a cessation of EPOR thrusting or a variable burn profile. This situation occurred periodically during the orbit-raising process, whereby the vehicle entered a "coast" period for several orbits before re-engaging the EP system. In these situations, rudimentary sensor search patterns (using synthetic ELSETs which could accounting for possible uncertainties in the vehicle's orbit) were required to recover the vehicle and track it on its new trajectory. The operation of extremely wide-field telescopes such as SuperWASP (15 x 15 degree field of view) also demonstrated capability to rapidly survey along the expected orbital track and to recover the vehicle, building on previous trials on this topic [1][11].

Through conduct of this pseudo- "live" exercise, the campaign has proven the utility of VerSSA platform for the sharing of data and for conducting semi-automated data processing workflow suitable for a pseudo-cataloguing mission, and a methodology for tipping-and-cueing of optical sensors against vehicles under near-constant electric thrust. From the valuable lessons learned during Weeks One and Two of the activity, improvements were made towards the consistent formatting and content of data and the requirements for automated data processing, such that it was possible to deliver at-pace processing (through VerSSA) during the successful Week Three event. Furthermore, improvements in VerSSA capability were undertaken by the University of Arizona team to improve connectivity of the platform with UDL and for real-time alerts to be shared with a dedicated communications channel operated using Slack.

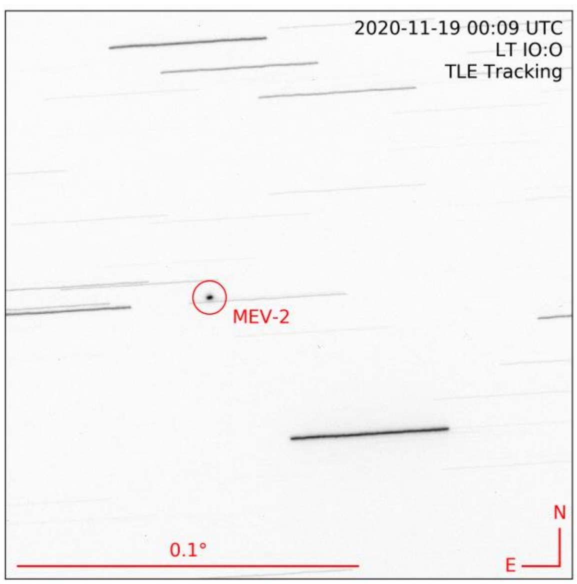

Fig. 7. MEV-2, observed by the Liverpool Telescope on 19 November 2020 using a FVEY-generated ELSET.
Image Credit: University of Liverpool, Cubica Technology Ltd., Liverpool John Moores University

4. THE PE2 RENDEZVOUS AND PROXIMITY OPERATIONS (RPO) CAMPAIGN

4.1 Campaign Execution

For space safety precautions, the docking procedure conducted by MEV-1 and its client in February 2020 was wholly conducted at an altitude approximately 300 km above the GEO belt (in the so-called GEO "graveyard" orbit), at a longitude of ~132°E [12]. Whilst it was possible to collect an amount of observation and tracking data during the Phase I experiment on the two objects during their proximity operations (over the one month prior to the docking), this was limited by sensor coverage, sensor availability, and weather issues. For the Phase II campaign, the favourable geography offered by operation of the client at 1°W enabled a range of sensors sited across Europe (and a limited number of other longitudes) to observe this event and collect real-world data. As such, an extended observation campaign was prepared to span the duration of proximity operations activity between the two spacecraft; initially planned for a duration of three weeks, but eventually spanning three months due to changes made to the operator's mission plan once on-orbit.

The campaign primarily targeted the collection of a diverse library of real-world SDA data on this unique event using a variety of sensor phenomenologies; expanding on the "optical-only" data which had been collected during Phase I. A key objective was therefore to acquire data which may help to evaluate the utility of differing sensor types/capabilities for these kinds of scenarios, as well as the gathering of real-world data to support post-event analysis and development to tactics, techniques and procedures (TTPs) for GEO flight safety. Data collection commenced on 25 January 2021 as MEV-2 finalised its orbit circularisation activities and began approach to its client's position at 1°W; finally concluding on 25 April 2021, two weeks after the successful docking event.

This contributing sensor network included a wide variety of ground- and space-based sensors with varying capabilities, and across optical and RF phenomenologies: a schematic of the sensors involved in this campaign is shown in Fig. 8. To simplify data collection requirements and expectations, sensor pointing and tasking was decentralised to the sensor operators, and data returned through a variety of mechanisms in non- real-time under "best efforts". All data processing was conducted in offline (batch) mode by individual participants, using relevant internal tools outside of the VerSSA architecture due to the less stringent processing requirements.

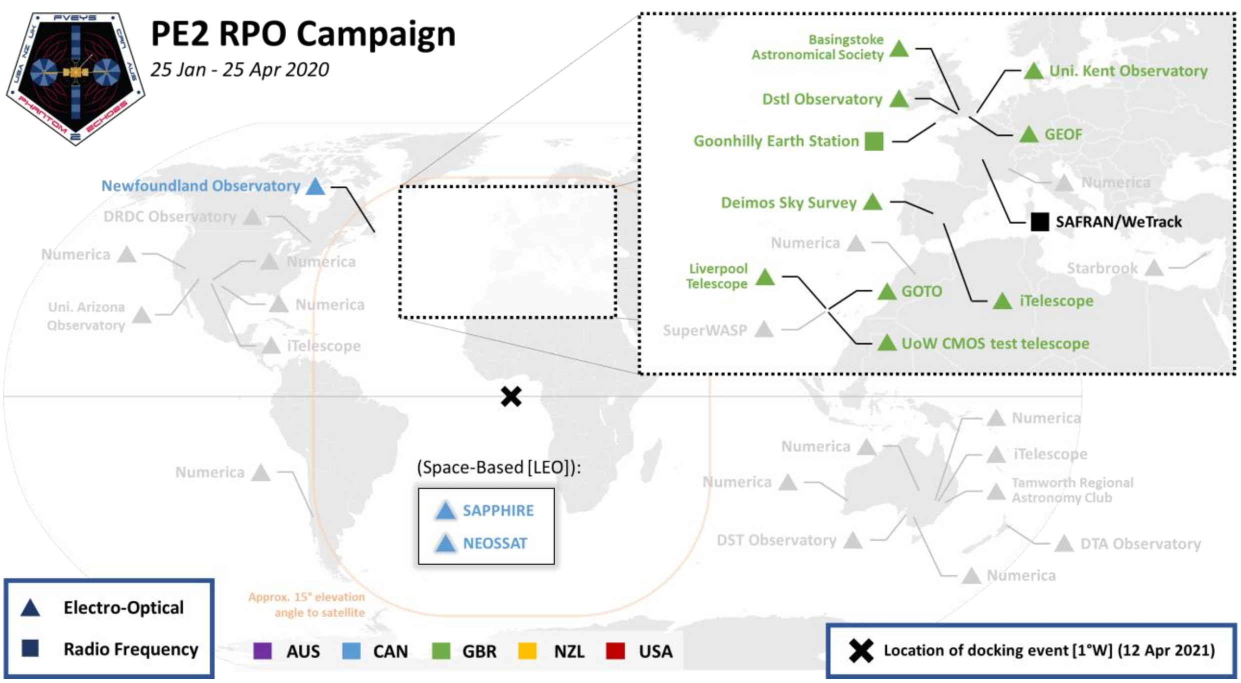

Fig. 8. Geographical distribution of S&T sensors network utilised during the PE2 RPO Campaign. Where data has been obtained from commercial SDA data sources, these sensors are marked with (■)

The campaign was supported by superb contributions from the diverse sensor and observing team(s) which participated in the event, including the UK Astrodynamics Community of Interest (ACI, an informal group of UK SDA experts), and via a lively chat channel operated using Slack for the sharing of data and ad-hoc analysis around the community. The FVEY SDA S&T activity was also conducted in collaboration with, and in parallel to, a real-world event exercise conducted by the GLOBAL SENTINEL community on MEV-2, led by the UK Space Operations Centre and involving space operations centres of the United States, Australia, Canada, Germany, Spain, France, Italy, Japan and South Korea.

4.2 RESULTS: MEV-2 / INTELSAT 10-02 GEO Rendezvous and Docking

A rich set of observation data was gathered during the three-month campaign; encompassing astrometry, photometry (single- and multi-colour), polarimetry and RF data. Through comparison with known motion and events associated with the MEV-2 mission (as provided by the operator), in addition to commercial SDA data contributed by Safran Data Systems' passive RF WeTrack service [13], this has enabled commencement of a preliminary "forensic" analysis regarding what contextual information could be inferred from ground and space regarding the event. In particular, this has examined the capability to resolve and track objects in close proximity in GEO using various class of sensor, as well as to discriminate possible consequences of a proximity event. This analysis will be undertaken during the remainder of 2021 and into 2022.

Owing to the variety of optical sensors used to observe the two spacecraft during the campaign, it has been possible to begin exploring the relative merits of different classes of instrument for following this type of event. Alongside "traditional" ground-based SDA telescopes and space-based instruments like NEOSSAT and SAPPHIRE, a variety of "non-traditional" assets were used to observe the event: this included publicly-accessible, sidereally-tracked systems (e.g. iTelescope [14]) and academic instruments such as the Liverpool Telescope [15]. Furthermore, an overwhelming amount of amateur-grade data was acquired on MEV-2 and IS10-02 via collaborators within the Basingstoke Astronomical Society [16], helping to demonstrate the ability to resolve the two targets with relatively modest equipment and providing insights towards the practical angular resolution limitations for observing this type of event. A collage of example images captured from the campaign from amateur observers are shown in Fig. 9.

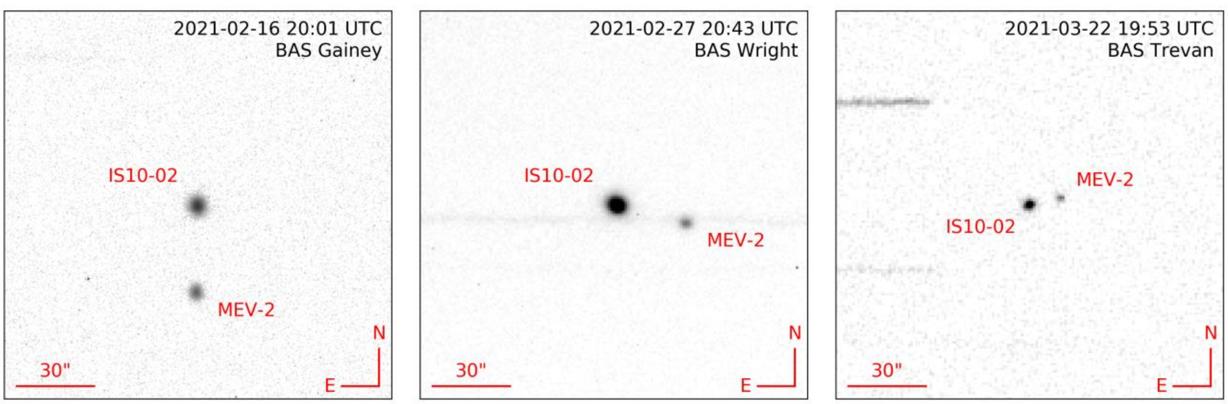

Fig. 9. Example observations of MEV-2 from the PE2 RPO Campaign from "citizen science" observers: (left) BAS-Gainey, 16/02/2021. (centre) BAS-Wright, 27/02/2021. (right) BAS-Trevan, 22/03/2021.
Image Credit: Basingstoke Astronomical Society

Through the involvement of academic and industry contributors (the University of Liverpool, Cubica Technology Ltd. and Liverpool John Moores University), it was possible to examine performance of the 2.0 m-aperture Liverpool Telescope (LT) [15] for these types of scenarios. Several images were obtained using the IO:O optical imaging instrument, which has a 10 x 10 arcminute field of view with ~0.3 arcsecond (binned) pixel resolution. Fig. 10 demonstrates how this capability can augment wide field-of-view instruments in monitoring the vicinity of GEO satellites: in this figure, two frames, collected near-coincidently (simultaneously and within ~250 m in observing location) on MEV-2 and IS10-02 by the UoW test telescope and the LT's IO:O instrument, are shown. The small-aperture, wide field of view Complementary Metal-Oxide-Semiconductor [CMOS] sensor excels at providing a wide situational awareness and high-cadence light curves in the nearby GEO region, but this comes at a sacrifice of fine resolution. The narrow-field Liverpool Telescope can only observe one object at a time, but is able to resolve the arcsecond spatial scales required to differentiate closely-spaced objects.

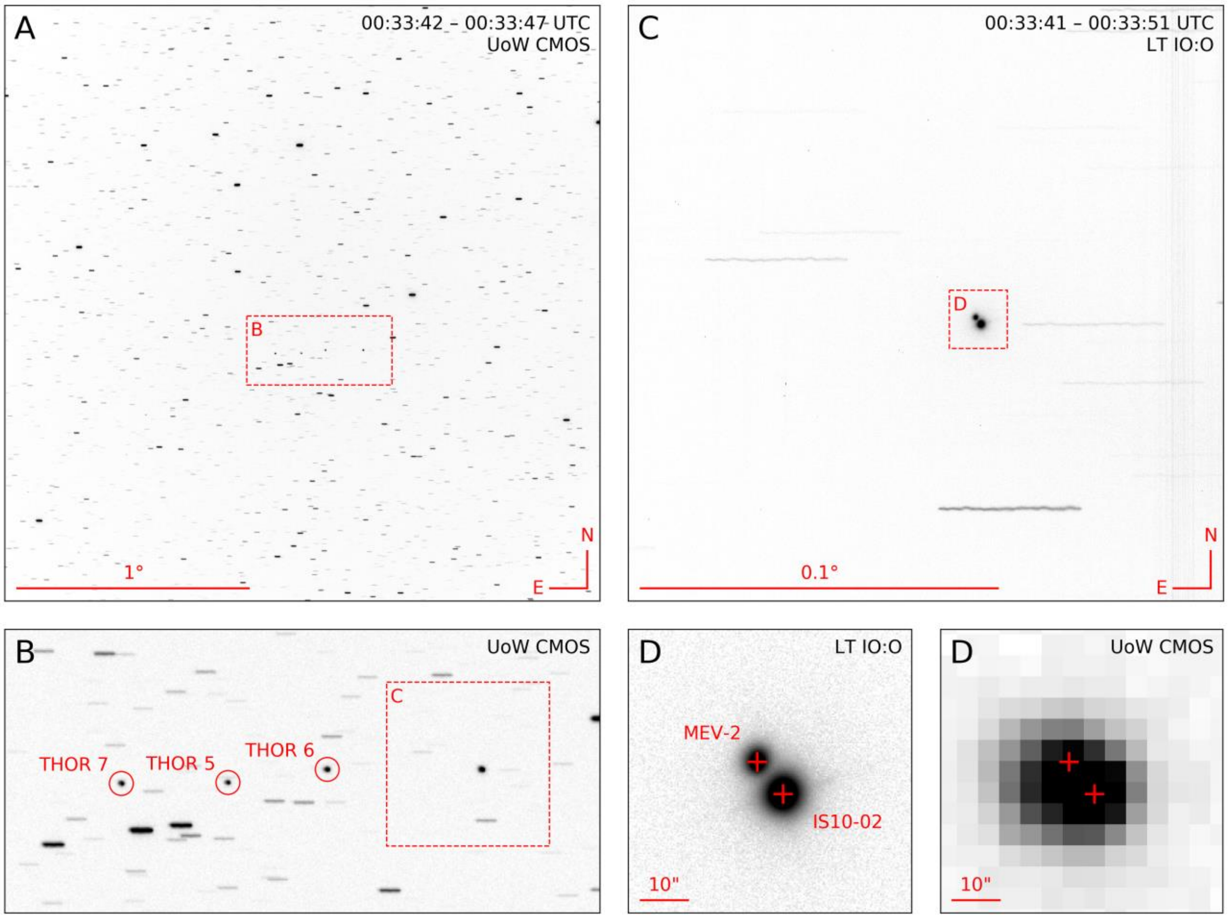

Fig. 10. Simultaneous images obtained with the UoW CMOS telescope and the Liverpool Telescope's IO:O imager, depicting the trade-offs between wide-field survey and narrow-field astronomical telescopes: (a) Full-frame image from the UoW CMOS test telescope. (b) Cut-out focusing on the GEO slot at 1° W. (c) Full-frame image from the IO:O instrument. (d) Cut-outs focusing on IS10-02 and MEV-2 with the two instruments.

Image Credit: Univ. Warwick; Univ. Liverpool / Cubica Technology Ltd. / Liverpool John Moores Univ.

Optical imagery was reduced to astrometric and photometric measurements for onward analysis: the latter has been used to examine the utility of light curve techniques for labelling and assessing stability of GEO spacecraft and for providing independent verification/assessment that a successful GEO docking may have taken place. A comprehensive dataset collected by the UoW test telescope presented opportunities to characterise MEV-2, IS10-02 and the three neighbouring THOR satellites (THOR5, THOR6 and THOR7) over the course of the campaign. Observations of IS10-02 exhibited a consistent phase curve structure, with ability to identify a 15° solar off-pointing bias angle, as well as a feathering offset of its two (N-S) solar arrays. When placed in a "holding" orbit during quiescent periods of activity, MEV-2 would display a smooth, consistent light curve from night-to-night, but would be much more variable in phase when undertaking attitude and translational manoeuvres associated with calibration, inspection and demonstration activities. A full analysis of data collected on all five objects will be presented in a future publication (Chote et al, in preparation).

A record of photometry data collected on IS10-02 by the UoW CMOS test telescope system is shown in Fig. 11: during nights where IS10-02 and MEV-2 could not be spatially resolved, some of the MEV-2's features can be seen 'superimposed' on top of IS10-02's light curve. After docking, the shape, composition and stability of the IS10-02 curve was found to deviate, indicating a change in configuration of the CVS: in particular, displaying an adjustment of the solar offset and feathering of IS10-02's solar arrays, as well as a change in the composition of the peak glint.

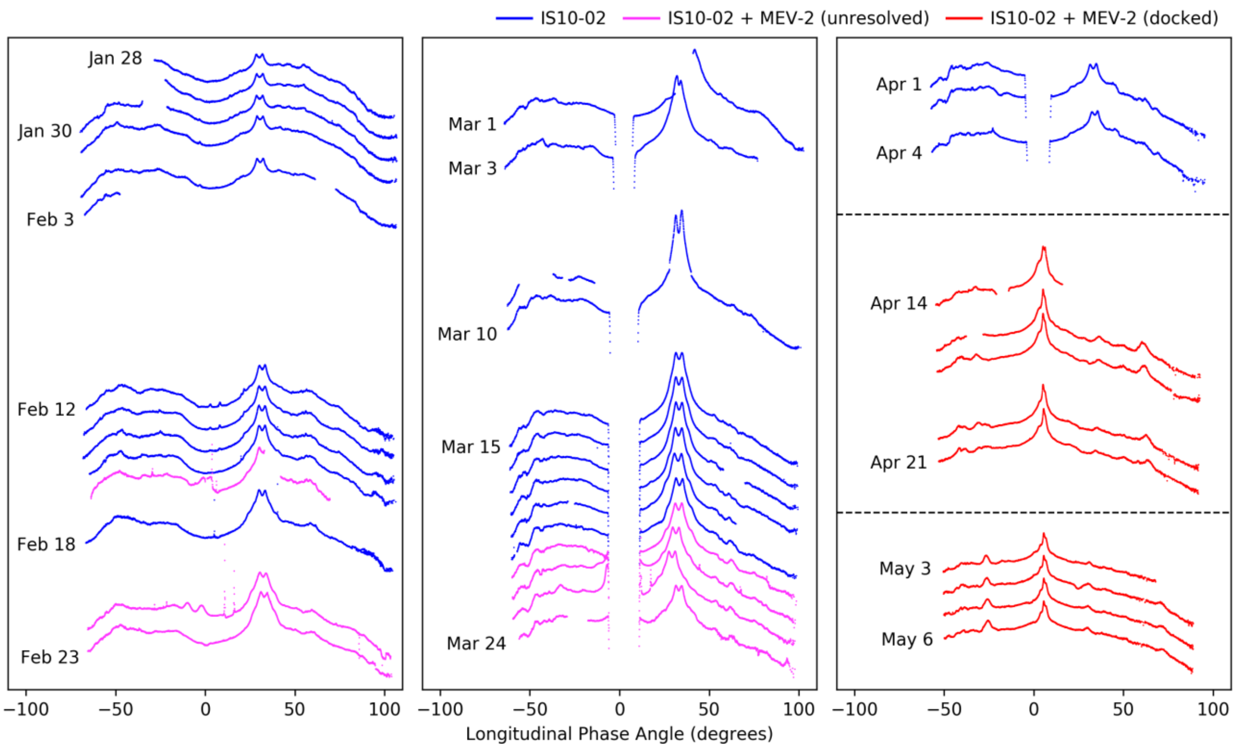

Fig. 11. Broad band optical light curves of IS10-02 observed from La Palma before and after docking with MEV-2. Data are plotted on a shared magnitude scale, stacked with an artificial m_v = 1 offset per night. Image Credit: Univ. Warwick

To examine the utility of spectral data for object identification and tagging, multi-colour photometry was obtained using the Gravitational-wave Optical Transient Observer [17] (GOTO-N) prototype telescope on La Palma. Staggered colour filters were used in overlapping telescopes to collect simultaneous 2- and 3-colour measurements; cycling of these filters enabled acquisition of all colour pairs and for cross-calibration. Regular measurements were obtained over the duration of the RPO campaign, each obtaining ~30 minute light curve segments that were collapsed into mean colour indices and 1-sigma uncertainties. Fig. 12 demonstrates that IS10-02 and MEV-2 each presented distinct colour profiles which were broadly stable over the two months of pre-docking observation for phase angles between -65 and -40 degrees. Following the docking process, the CVS inherited the colour profile of IS10-02 prior to docking, with no measurable change. A full analysis of colour data for IS10-02, MEV-2, and neighbouring spacecraft will be presented in a future publication (Chote et al, in preparation).

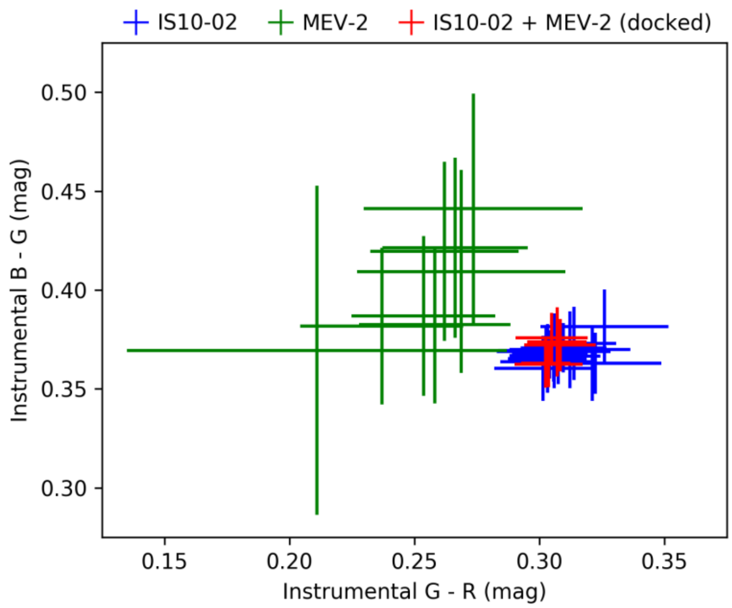

Fig. 12. Individual nightly colour-index measurements of IS10-02 and MEV-2 between January 2021 and April 2021, demonstrating the ability to separate the two spacecraft in colour-space.
Image Credit: Univ. Warwick.

During the campaign, opportunity also arose to test an experimental RF system for bistatic detection of objects in GEO: under this arrangement, a 30 m dish antenna at GES (located at 5° W) was used as a bistatic receiver for skin reflections from GEO satellites from a SATCOM uplink transmitter also located within the UK. Since the nominal ~0.25° TT&C uplink beam for SKYNET-4E (operating at 0.96°W) encompasses the GEO longitude slot at 0.98°W containing IS10-02 (and MEV-2), it was possible to attempt detection of the reflected RF energy from these two objects using a large dish pointed at IS10-02's expected orbital position. Through knowledge of the uplink waveform used for the TT&C link, the Doppler frequency shifts in the received (reflected) signal arising from motion of the IS10-02 could be measured and tracked, as well as the presence of other bodies (e.g. MEV-2) within the narrow ~0.07° receiver beam (approx. 45 km at GEO range).

Using this trial approach, IS10-02 could be routinely detected by the system, enabling tracking of its Doppler motion – it was even possible to identify the Doppler footprint of chemical station-keeping manoeuvres undertaken by IS10-02, such as the one depicted in Fig. 13 and verified using publicly-available ephemeris data [18]. Likely due to its smaller cross-sectional area, MEV-2 could only be detected sporadically by the arrangement; typically when its solar array orientation offered a favourable bistatic angle between transmitter and receiver. This arrangement would occur on a daily basis circa 1200 UTC, where MEV-2's solar arrays were aligned near-tangentially to the Earth and to this bistatic geometry, along with other, more sporadic occasions. Hence, from preliminary data analysed to date, there is evidence to suggest that this technique may be beneficial for tracking and monitoring GEO: a relatively small and low-powered uplink illuminator can be used in conjunction with a large receiver dish to perform surveillance of GEO spacecraft.

Space-based photometric measurements on IS0-02 and MEV-2 were acquired by both SAPPHIRE and NEOSSAT during the final proximity phase between January 2021 and April 2021. Example measurements collected by SAPPHIRE are presented in Figs. 14 and 15, for IS10-02 and MEV-2 respectively.

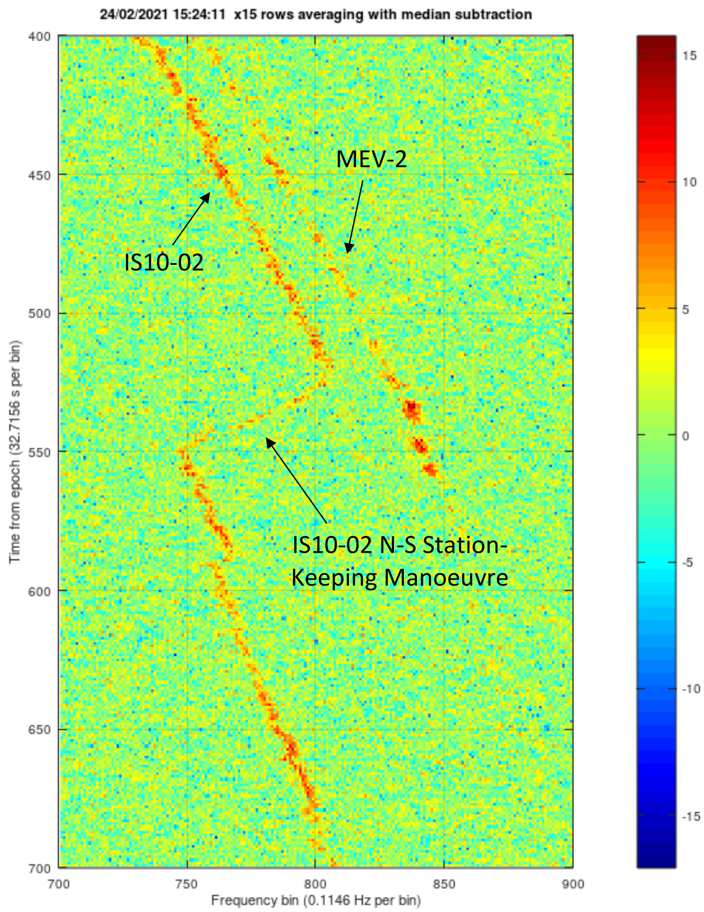

Fig. 13. IS10-02 and MEV-2 detected using bistatic radar geometry on 24 February 2021, including N-S station-keeping manoeuvre undertaken by IS10-02 at 2027 UTC. The colour bar indicates the power per pixel relative to the median value, expressed in dBm.
Image Credit: Goonhilly Earth Station Ltd., Airbus Defence and Space

Considering the photometric response of IS10-02 in SAPPHIRE measurements (Fig. 14) with those acquired by the UoW CMOS test telescope (Fig. 11), much greater variability can be observed in space-based observations as compared with those collected from the ground. This is due to the rapidly-changing viewing geometry witnessed by a space-based observer as compared to that experienced by a ground-based system: SAPPHIRE, in its near polar orbit, observes a GEO object over a variety of viewing angles, spanning target declination angles of ±10° during any given orbit - this effect modulates the detected brightness of a GEO object by 0.2-0.4 magnitudes. In addition, orbital motion can occasionally lead to a space-based instrument transiting through a GEO object's specular glint (or null) geometry, which may show drastic brightness changes during particular seasonal observing geometries. In contrast, a ground-based observer experiences a near-constant declination angle to a GEO target if viewed over an entire night, and more consistent phase angle behaviour. Similarly, MEV-2's measurements (Fig. 15) show a high degree of variability; although to a greater extent than IS10-02 – this is believed to be attributed to both SAPPHIRE's rapidly-changing viewing geometry as well as MEV-2's changing attitude during rendezvous and docking operations.

Research work is ongoing to normalise space-based photometric measurements from both SAPPHIRE and NEOSSAT such that it is possible to more readily compare space-based and ground-based light curves. Ground- and space-based sensors play complementary roles during typical SDA operations; normalising space-based photometric measurements will help to further increase the utility of space-based measurements for this application and help to mitigate the operational limitations associated with ground-based sensors (e.g. weather and daylight constraints).

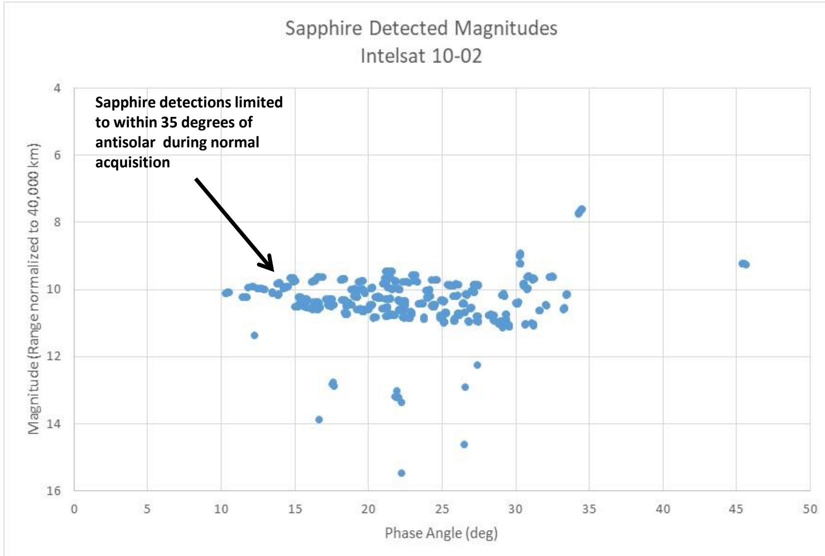

Fig. 14. Photometric measurements of IS10-02, collected by the Canadian space surveillance satellite, SAPPHIRE, between January 2021 and April 2021.
Note the variability in the measurements with phase angle due to the combined effects of changing observer baseline, and the aggregation of tracks collected on different days under different solar phase angle geometry.

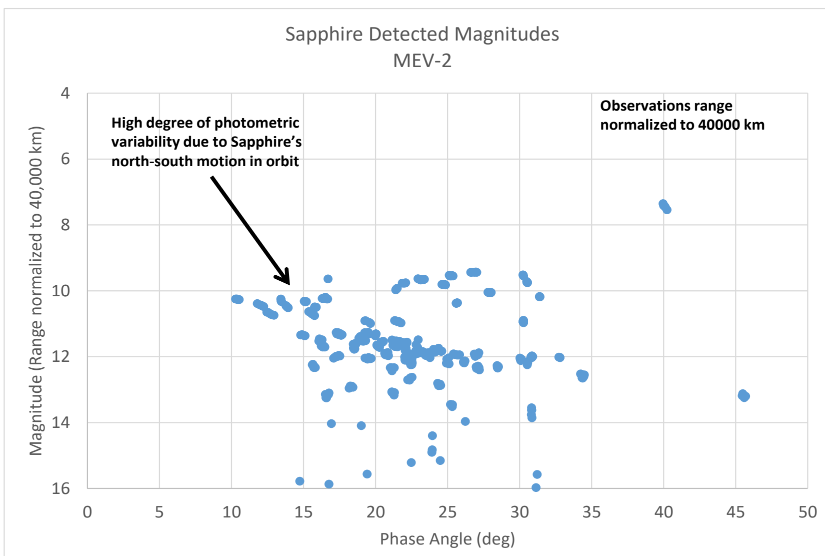

Fig. 15. Photometric measurements of MEV-2, collected by the Canadian space surveillance satellite, SAPPHIRE, between January 2021 and April 2021.
A higher level of photometric variability is observed as compared to IS10-02 (Fig. 14), and is attributed to the frequent attitude variations of the MEV-2 vehicle undertaken during the RPO process.

5. CONCLUSIONS AND NEXT STEPS

Through successful execution of observation campaigns aligned with key phases of the MEV-2 mission, the FVEY SDA S&T community have made continued progress towards development (and demonstration) of a collaborative sensor and processing architecture for coalition research in SDA. As part of Phase II of the PHANTOM ECHOES experiment, the UK, US, Canadian, Australian and New Zealand defence S&T laboratories have collaborated to explore future SDA challenges surrounding protection of allied spacecraft in GEO and identify possible solutions.

Between August 2020 and April 2021, a multi-national sensor architecture of ground- and space-based assets was operated on a "best effort" principle to gather tracking and characterisation data on GEO targets relevant to an allied safety-of-flight mission in Deep Space. This effort brought together SDA experts and capabilities from across government, industry, academia and the amateur community to demonstrate novel capabilities which may provide valuable insights towards these types of events within a future allied SDA system. These campaigns were delivered wholly virtually, due to the impact of the COVID-19 crisis. The resulting data collection and planned analysis activities are targeting improvements in allied capability within S&T for tracking and custody of constantly-manoeuvring objects, and have resulted in a large quantity of real-world observations which can support future development of command and control (C2) capabilities for handling GEO RPO events.

At present, there remains a significant quantity of data and results which are yet to be fully analysed: this will be capitalised upon within future work. Other planned research steps include:

- Further analysis of collected datasets; particularly, full archive of data acquired from the PE2 RPO Campaign
    - Cross-comparison of obtained operator "truth" data with collected astrometric, RF and tracking data
    - Full examination of broadband optical light curves for extraction of object geometry and attitude
    - Analysis of angular resolution capabilities from different classes of optical instrument
    - Fusion and comparison of colour and polarimetric signatures to distinguish between objects
- Exploration of further software/processing capability within VerSSA:
    - Expansion of software processing tools for exploitation and analysis
    - Routes for "livestreaming" of metric observation data into VerSSA for real-time processing
    - Testing of the current (and future) toolset with real-world event data collected during Phase II
- Sharing of real-world tracking data with the wider TTCP and science community via the open-source tracking and state estimation framework, Stone Soup [19]; particularly, researchers in tracking and data fusion

Through ongoing analysis of the comprehensive archive of data captured within Phases I and II of the PHANTOM ECHOES experiment, the FVEY SDA S&T community anticipate making further progress towards potential sensor, processing and C2 solutions which may be of future relevance to the Combined Space Operations community regarding RPO events in GEO. If possible, these results will be presented in a future publication.

ACKNOWLEDGEMENTS

Content includes material subject to © Crown copyright (2021), 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

The authors are indebted to the hard work of a number of other individuals and organisations who have contributed to the PHANTOM ECHOES 2 experiment, which stretches far beyond the names listed at the head of this paper. The authors would therefore would like to extend thanks the following personnel for their contribution: Joe Anderson, Roberto Armellin, Donald Bedard, Travis Bessell, Tanner Campbell, Clinton Clark, Garry Copper, Josh Davis, Lee Devlin, Kris Drozd, Dirk Froebrich, Roberto Furfaro, Trevor Gainey, Peter Genovese, Joe Gerber, Nick Harwood, Tim Jennings-Bramly, Martyn Hole, Moriba Jah, Jim Johnston, Emma Kerr, Richard Mathers, Calum Meredith, Nick Pallecaros, Andy Partridge, Yann Picard, Laura Pirovano, Vishnu Reddy, Jared Rieckewald, Chris Saunders, Paul Seidman, Rob Sherwood, Duncan Smith, James Symons, Stefan Thorsteinson, Bob Trevan, Leigh Tschirpig, Fay Waltho, Klaas Wiersema, and Dave Wright.

The Gravitational-wave Optical Transient Observer (GOTO) project acknowledges the support of the Monash-Warwick Alliance; University of Warwick; Monash University; University of Sheffield; University of Leicester; Armagh Observatory and Planetarium; the National Astronomical Research Institute of Thailand (NARIT); Instituto de Astrofísica de Canarias (IAC); University of Portsmouth; University of Turku; University of Manchester and the UK Science and Technology Facilities Council (STFC, grant numbers ST/T007184/1, ST/T003103/1 and ST/T000406/1).

The Liverpool Telescope is operated on the island of La Palma by Liverpool John Moores University in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias with financial support from the UK Science and Technology Facilities Council.

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

REFERENCES

[1] S. George, A. Ash., T. Bessell, J. Frith, L. Scott, J. Skuljan, R. Furfaro, V. Reddy, PHANTOM ECHOES: A Five-Eyes SDA Experiment to Examine GEO Rendezvous and Proximity Operations, AMOS 2020 Conference (16-18 September 2020, Virtual), 2020.

[2] 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.

[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] Northrop Grumman. https://news.northropgrumman.com/news/releases/northrop-grumman-and-intelsat-make-history-with-docking-of-second-mission-extension-vehicle-to-extend-life-of-satellite (last accessed: 17 June 2021).

[5] JFCC SPACE/J3 [Space-Track.org orbit data]. https://www.space-track.org/ (last accessed: 03 August 2021).

[6] CyVerse [CyVerse Discovery Environment]. https://de.cyverse.org/de/ (last accessed: 22 June 2021).

[7] V. Reddy, R. Furfaro, E. Christensen, R. Seaman, F. Shelly, Synergistic NEO-Debris Activities at University of Arizona, ESA NEO and Debris Detection Conference (22-24 January 2019, Darmstadt, Germany), 2019.

[8] Slack [VerSSA-FVEY PE2 chat channel]. https://slack.com/intl/en-gb/ (last accessed: 22 June 2021).

[9] Numerica [Numerica Telescope Network]. https://www.numerica.us/numerica-telescope-network/ (last accessed: 03 August 2021).

[10] UDL [Unified Data Library]. https://unifieddatalibrary.com/ (last accessed: 22 June 2021).

[11] P. Chote, J. Blake, D. Pollacco, Precision Optical Light Curves of LEO and GEO Objects, AMOS 2019 Conference (17-20 September 2019, Maui HI, USA), 2019.

[12] Northrop Grumman. https://news.northropgrumman.com/news/releases/northrop-grumman-successfully-completes-historic-first-docking-of-mission-extension-vehicle-with-intelsat-901-satellite/ (last accessed: 23 June 2021).

[13] Safran Data Systems [WeTrack]. https://wetrack.safran-group.com/ (last accessed: 03 August 2021).

[14] iTelescope.NET [iTelescope Home Page]. https://www.itelescope.net/ (last accessed: 1 August 2021).

[15] I. Steele, R. Smith, P.Rees et al., The Liverpool Telescope: Performance and First Results, *Ground-Based Telescopes* (edited by J. Oschmann), Proceedings of the SPIE vol. 5489, pp. 679-692, 2004.

[16] Basingstoke Astronomical Society [BAS Home Page]. https://www.basingstokeas.org.uk/ (last accessed: 11 Aug 2021).

[17] Gravitational Wave Optical Transient Observer [GOTO]. http://goto-observatory.org/wp-content/uploads/2021/08/GOTO_prototype_submitted.pdf (last accessed: 11 Aug 2021).

[18] Intelsat [MyIntelsat Public Ephemeris Data]. https://my.intelsat.com/ephemeris/public/ (last accessed: 11 August 2021).

[19] International Society of Information Fusion (ISIF) - Open Source Tracking and Estimation Working Group [Stone Soup] https://isif-ostewg.org/stone-soup/ (last accessed: 09 August 2021).