CANADIAN PHOTOMETRIC MEASUREMENTS DURING THE MULTINATIONAL PHANTOM ECHOES SPACE SITUATIONAL AWARENESS EXPERIMENT

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ABSTRACT

In February 2020, the Northrop Grumman *Mission Extension Vehicle – 1* (MEV-1) completed a series of complex orbit circularization and proximity operations culminating in the first commercial docking with the Intelsat 901 satellite. Once captivated, MEV-1 the assumed orbital and attitude control of Intelsat 901 extending its mission lifetime. This unique space operation served as a cooperative reference object for a multinational, five-eyes SSA experiment, called *Phantom Echoes*, to track and monitor MEV-1's progress throughout its multi-stage orbital evolution and docking with Intelsat 901. This paper summarizes Canadian SSA research sensor photometric measurement findings from both ground and space-based assets prior to, during and after Intelsat 901's captivation event.

INTRODUCTION

On-Orbit Servicing (OOS) is a specialized space operation where a servicing satellite can interact, repair, maintain and correct issues with other satellites. Technologies supporting this space mission type have shown steady progress with the development and testing of small satellite proximity operations [1] and robotic intervention for repair and upgrade of satellites [2]. OOS offers the possibility of economical satellite life extension, technology refresh, anomaly resolution and the mitigation of space debris. Private space operators have begun to embrace this technology. In 2019, Space Logistics LLC, developed and launched the *Mission Extension Vehicle-1* (MEV-1) to perform the first commercial docking and life extension of the commercial communications satellite Intelsat 901 in geosynchronous orbit. As of this writing, the Mission Extension Vehicle-2 is en-route to service Intelsat 10-02 in late 2020.

Despite the benefits of this technology, OOS raises questions pertaining to space security where these technologies could be used to interfere mechanically, electronically, or damage, disable or upset the operations of satellites on orbit. Recognizing this, a multinational S&T team operating under the Technical Cooperation Program [3] organized a Five-Eyes experimental campaign called *Phantom Echoes* to track and observe the orbital evolution of MEV-1 during various phases of its flight. Technical questions pertaining to ground-based and space-based Space Situational Awareness (SSA) sensors' ability to track and monitor space objects performing OOS space operations at long stand-off ranges, such as geosynchronous orbit were assessed. Participating nation SSA research sensors were used to characterize the two space objects. SSA sensors were provided by the United States, Canadian, United Kingdom, Australian and New Zealand participants and data was centrally administered by a cloud-based system administered by the University of Arizona.

Figure 1. TTCP Phantom Echoes Mission Patch

This paper gives an overview of MEV-1's encounter from a Canadian SSA research sensor perspective during MEV-1's approach, captivation, and life extension of Intelsat 901. A summary of the key photometric characterization lessons-learned during the campaign are also described.

PHANTOM ECHOES SCIENCE AND TECHNOLOGY OBJECTIVES

The Phantom Echoes team consists of Defence Scientific researchers from Five Eyes laboratories located in Canada (DRDC), United States (AFRL), United Kingdom (dstl), Australia (DSTG) and New Zealand (DTA). Under AFRL, the University of Arizona provided cloud-based SSA data processing services using dockerized application hosting on their Cyverse *VERSSA* platform [4]. MEV-1's operator, Space Logistics LLC, also acted as a team participant during the experiment.

The Phantom Echoes experimental objectives focused on the application of collective SSA capabilities to track and observe an unusual SSA operation with distributed data processing using cloud infrastructure. The main science and technology objectives of Phantom Echoes were:

- Use the cooperative satellite servicing mission to characterize this space operations' unique optical tracking phenomenology
- Track and characterize both MEV-1 and Intelsat 901 objects prior to, during and after MEV-1's docking with optical astrometric and photometric measurements
- Utilize the *VERSSA* system as a cloud-services node for data storage and processing

Canadian photometric measurements of both Intelsat 901 and MEV-1 are described in the remainder of this paper. Canadian optical SSA measurements were collected using the DRDC Ottawa Space Surveillance Observatory, the NEOSSat satellite [5] and Sapphire [6]. A general overview of each sensor is shown in Figure 2.

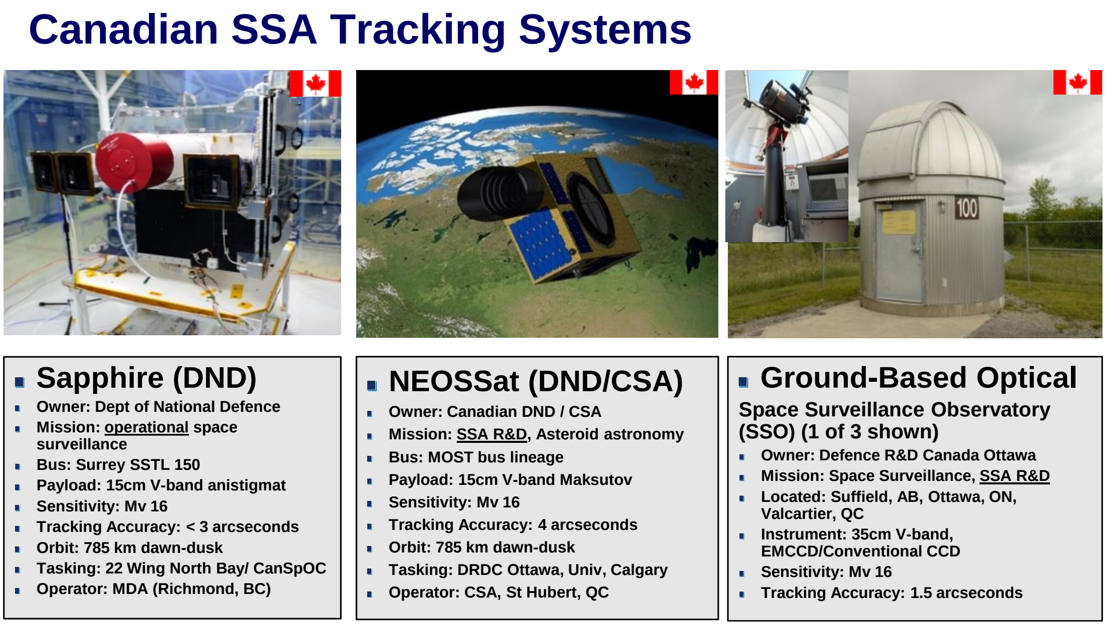

Figure 2. Sapphire, NEOSSat and Ground Based Optical space surveillance systems used by Canada during the Phantom Echoes experimentation

CLIENT AND SERVICING SATELLITE DESCRIPTION

Client: the client satellite was Intelsat 901, which is registered on the US Space Surveillance Catalog as #26824 and as COSPAR: 2001-024A. Launched in 2001, this communications satellite was inserted into geosynchronous orbit and stationed at 24° west longitude. It has two linear solar arrays and two east/ west antenna reflectors. The bus is cubical with approximate dimensions of ~2 meters per side.

Servicer: MEV-1, (SSN 44625, COSPAR 2019-067B) is based on the Orbital Sciences GEOStar small geosynchronous satellite bus (see Figure 3 left). Unlike most geosynchronous satellites MEV-1 is equipped with proximity cameras, a harpoon, docking clamp, and Hall effect thrusters for specialized orbital maneuvering and satellite captivation. MEV-1 is designed to approach a geostationary satellite and insert a harpooned clasp into the client satellite's apogee kick motor (see Figure 3 right). Once the harpoon is retracted a docking clamp ensures positive mechanical capture of the client satellite.

MEV-1 used Hall-effect thrusters for orbit circularization after its launch in October 2019. This electric thrust system provides continuous low thrust providing gentle, but constant orbital adjustment using small amounts of propellant. This efficient system saves on system mass leading to reduced launch costs as heavy hydrazine-based propulsion systems are not required for orbit circularization. Electric thrust systems are a challenge for SSA tracking systems as classical orbit propagators cannot predict the propulsive effect during live system operation. This system's use, prior to the docking, was of interest during Phantom Echoes.

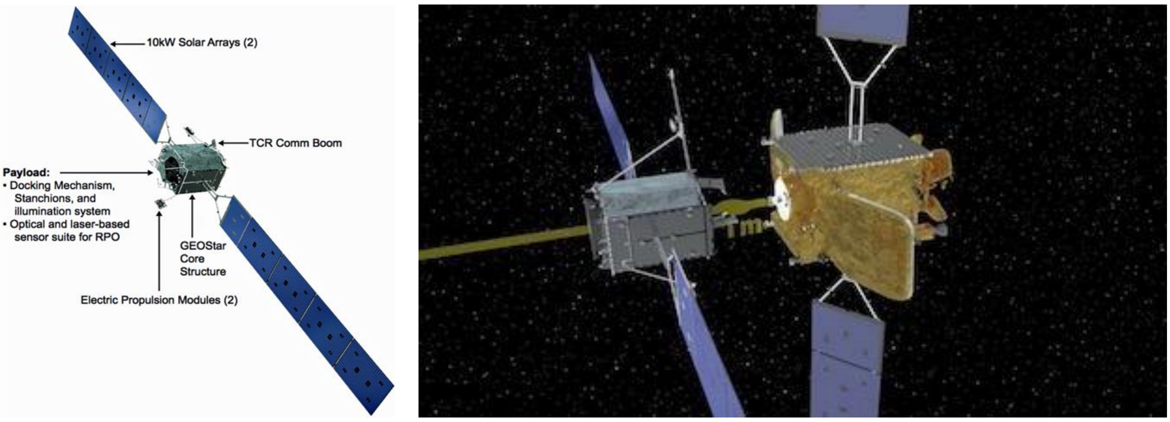

Figure 3. (Left): Artist depiction of MEV-1. (Right): Artist rendering of MEV-1 docking with Intelsat 901. Image credits: Space Logistics LLC.

TIMELINE OF EVENTS

To properly characterize a space operation, a-priori characterization data on space objects is required to establish their baseline characteristics. For this OOS operation, observations on Intelsat 901 and MEV-1 prior to docking was required. Table 1 details key timeline of characterization activity for both space objects and when Canadian sensing activities took place.

Table 1: Phantom Echoes Timeline 2019 - 2020

Observing Phase	Activity
Jan 2019	GBO Ottawa – pre-event ground-based photometry of Intelsat 901
9 Oct 2019	MEV-1 Launched. Intelsat 901 at 29.5 °W
Nov 2019 – Jan 2020	MEV-1 begins orbit circularization and inclination changes Multinational observations on MEV-1 and Intelsat 901.
16 Dec 2020	-Intelsat 901 raises orbit altitude +300 km above GEO into graveyard orbit for proximity encounter with MEV-1 -NEOSSat tracking periodically occurs on Intelsat 901
25 Feb 2020 07:15 UT	MEV-1 docks and captivates Intelsat 901
2 Apr 2020	Combined Vehicle Stack (MEV-1 and Intelsat 901) resumes services at 27.5°W longitude
April 2020	GBO Ottawa performs post-docking photometric characterization
May 2020	Phantom Echoes Experiment conclusion

PRE-DOCKING CHARACTERIZATION

In winter 2019 the DRDC Space Surveillance telescope collected photometry of Intelsat 901 at its station keeping location at 29.5°W. These measurements help establish baseline photometric characteristics of the client satellite prior to the docking event a year later. The detected photometry of Intelsat 901 is unfiltered therefore the visual magnitude (M_v) measurements are approximate and are relative to the detector response of a silicon-based CCD. The object brightness is corrected to exo-atmospheric brightness and range normalized to 40,000 km by use of

$$M = M_{apparent} + 5log_{10}(R/R_0) - kX$$

where R is the range at detection, R_0 is the reference range (40,000 km), k is the atmospheric extinction coefficient in magnitudes/airmass (approximately 0.22 magnitudes/airmass for Ottawa, ON), X is the airmass which is approximately $X \sim 1/\sin(El)$ where El is the elevation of the space object above the horizon.

Figure 4 shows five light curves collected on Intelsat 901 where its brightness spans M_v 15 to M_v 9. The specular glint of its main solar arrays is visible at phase angle $\varphi = 0°$ with a near linear magnitude fading for $\varphi > 20°$ at a rate of 0.5 M_v/hour. At $\varphi \sim 40°,52°$, small glint features are visible suggesting evidence of an eastward pointing facet on Intelsat 901. This glint feature is possibly Intelsat 901's eastward pointing antenna reflector. The reason for its apparent shift in phase angle location is believed to be due to the changing illumination position of the Sun with respect to the local time of the ground-based observer. This feature is not always visible suggesting that this feature has a solar declination dependance which may cause it to have seasonal apparitions when viewed from the ground.

Some space-based measurements were acquired by NEOSSat on Intelsat 901, but the light curves did not show sufficient detail to identify features on the vehicle. This will be shown in a later section.

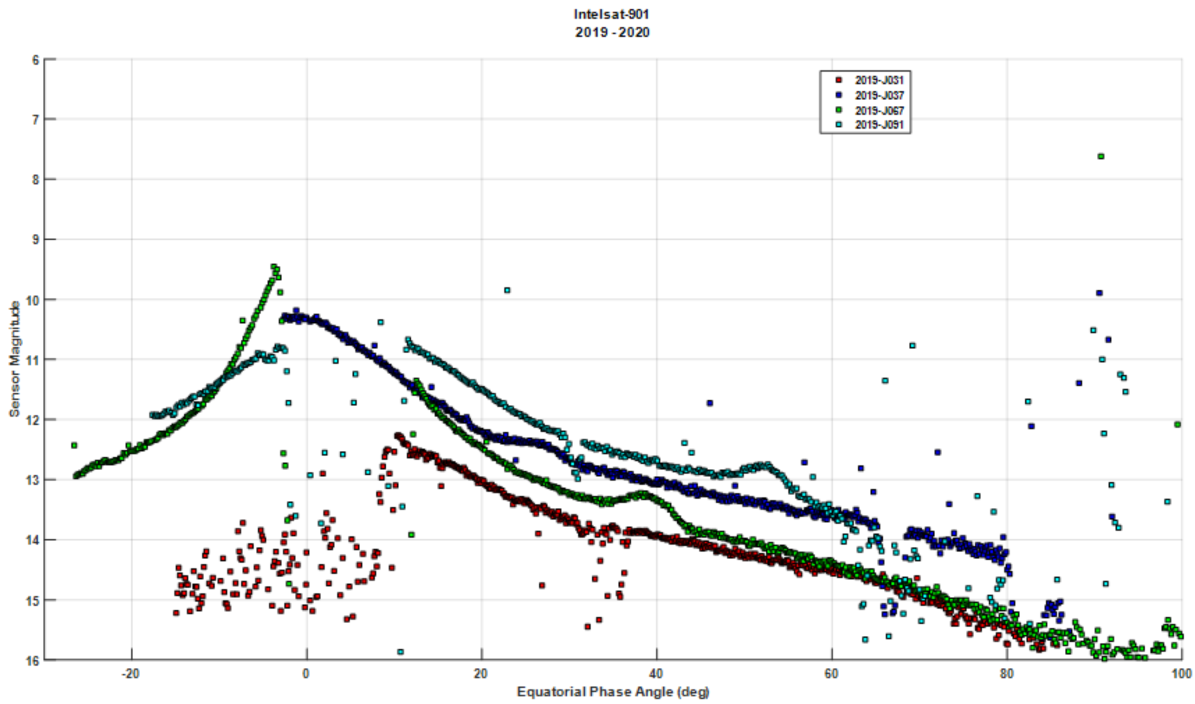

Figure 4. DRDC Ottawa ground-based measurements of Intelsat 901 in winter 2019 approximately 10 months before the launch of MEV-1. Two small glint features appear near phase angles of 40° and 52° phase angle. Scatter on the image is due to cloud fade or star streak overlapping the point source

MEV-1 ORBIT CIRCULARIZATION PHASE

MEV-1 was launched on 9 October 2019 into an elliptical, super synchronous orbit. Upon system checkout, MEV-1 began a series of long duration electric thrust intervals to circularize its orbit and reduce its orbital inclination. Constant thrust systems are difficult to maintain orbit custody by SSA sensors as their continuous operation, while exceedingly small in thrust magnitude, is not well handled by classical orbit estimation techniques. Two Line Elements were often found to be insufficient to keep orbit custody of MEV-1 and only tended to be useful when its electric thrust system was inactive.

The Phantom Echoes observation team did manage periodic observation of MEV-1 during the orbit circularization phase but relied on wide field (> 1°) field of view instruments. DRDC Ottawa acquired one track on MEV-1 for approximately 38 minutes on 30 January 2020. The relative position of the object inside the GBO field of view is shown in Figure 5 where the object noticeably drifts relative to the sensor field of view. At its apparent rate of motion during these frames, MEV-1 would have been drifted outside GBO's field of view in 117 minutes.

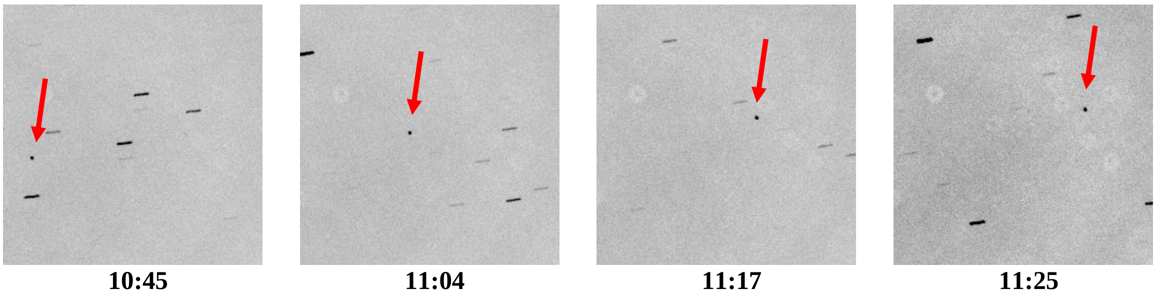

Figure 5. Time evolution of MEV-1 (marked) during the short track by DRDC Ottawa on 30 Jan 2020. MEV-1 drifted ~0.14 degrees off-elset in the 38 minutes it was tracked.

The light curve for MEV-1 is shown in Figure 6. The light curve is brief in duration but shows some fade/glint features on a relatively monotonic M_v ~12.8 trend in the short interval in it was observed.

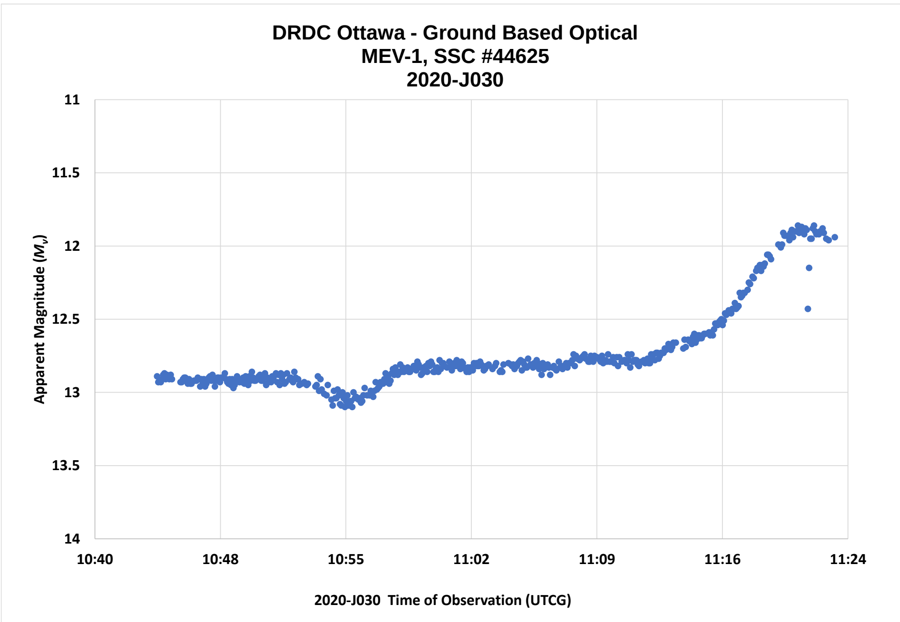

Figure 6. Ground-based measurements of MEV-1 during the 30 January 2020 short arc track

NEOSSat attempted tracks on MEV-1 and struggled to maintain orbit custody during MEV-1's constantly changing orbit. Some sporadic measurements were obtained but were not sufficient to photometrically characterize the vehicle in comparison to the ground-based measurements.

MEV-1 PROXIMITY OPERATIONS AND CAPTIVATION OF INTELSAT 901

NEOSSat tracked MEV-1 once it entered proximity (< 100 km) of Intelsat 901 on an interval beginning on 4 Feb 2020. This interval corresponds with times where MEV-1's constant thrust system performed much smaller orbital changes compared to the orbit circularization in the prior months. A sample image from NEOSSat showing both MEV-1 and Intelsat 901 is shown in Figure 7 where the objects were separated by approximately 31 km. As both objects were in the graveyard orbit, they drifted westward such that they were not visible from the North American landmass. NEOSSat's space-based measurements were able to maintain orbit custody - one of the advantages of space-based sensors.

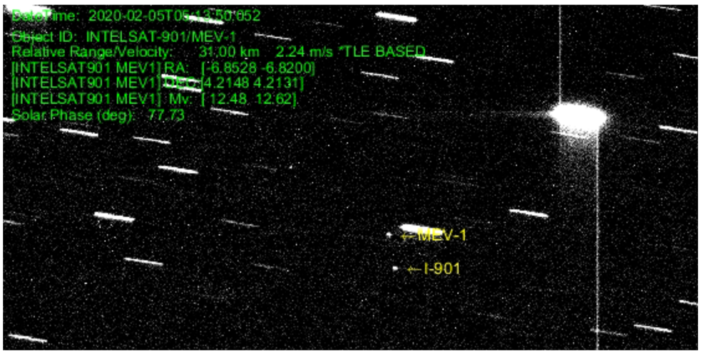

Figure 7. NEOSSat measurements of MEV-1 and Intelsat 901.

NEOSSat began an increased rate of measurement acquisition on 4 Feb 2020 in anticipation of the docking of the two vehicles. Figure 8 shows the increased acquisition rate of Intelsat 901 when the objects entered proximity to one another. NEOSSat first detected MEV-1 on 9 Jan 2020 (see Figure 9), but the observation success rate increased in early February 2020 when the objects entered proximity of one another.

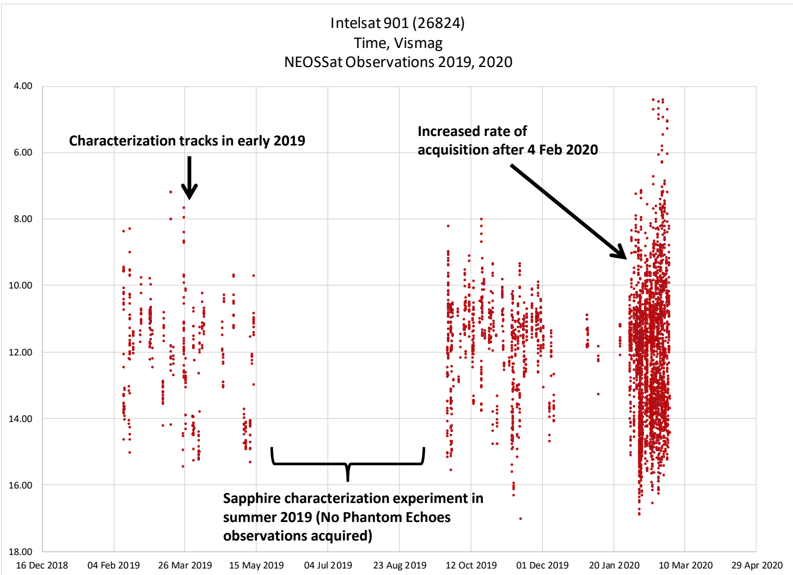

Figure 8. NEOSSat photometry of Intelsat 901 during all stages of Phantom Echoes. The increased rate of acquisition by NEOSSat occured on 4 Feb 2020 when MEV-1 entered proximity to Intelsat 901.

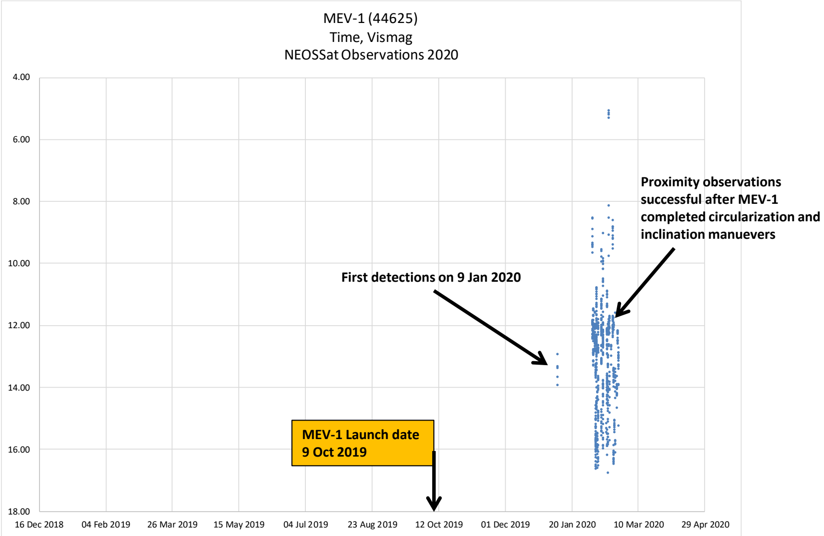

Figure 9. NEOSSat photometric observations of MEV-1. Note the first detections occured on 9 Oct 2019

NEOSsat collected enough space-based photometry of Intelsat 901 to create a light curve characterized against phase angle (see Figure 10). It is apparent that the broader dispersion of magnitude measurements reflects NEOSSat's north-south orbital motion where NEOSSat has a varying observer aspect angle on the object. A ground-based sensor has reduced degrees of freedom, and moves largely with the geosynchronous satellite, producing smoother monotonic light curves where glint features such as solar panel offset angles can be infered. A space-based sensor flies through different reflection phenomenology causing a larger variation in brightness.

A space-based sensor has the advantage observing a target on the dayside sector of Earth. Such measurements are reflected in the phase angle measurements near 140 degrees phase angle in Figure 10. This capability helps maintain track custody where positional (astrometric) measurements can be maintained. Figure 10 shows some evidence of a dayside brightening feature near $\varphi \sim 140°$ The glint feature in Intelsat 901's light curve near φ =40°, 52° are not detectable due to NEOSSat's rapidly changing observer position causing the increased scatter in photometric measurements. This is a shortcoming of space-based photometry but represents an area where ground-based sensors can provide value to identify unique features of space objects.

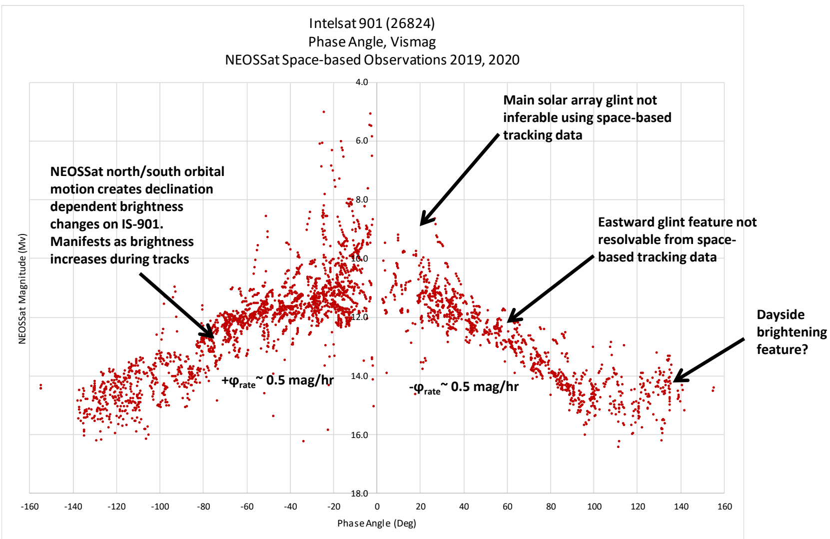

Figure 10. Space-based photometry of Intelsat 901 showing photometric variation due to NEOSSat's orbital motion

While less data was collected, MEV-1 shows a similar space-based light curve (see Figure 11). A possible dayside brightening feature, likely due to Earthshine backreflected from the satellite appears near 140° phase angle.

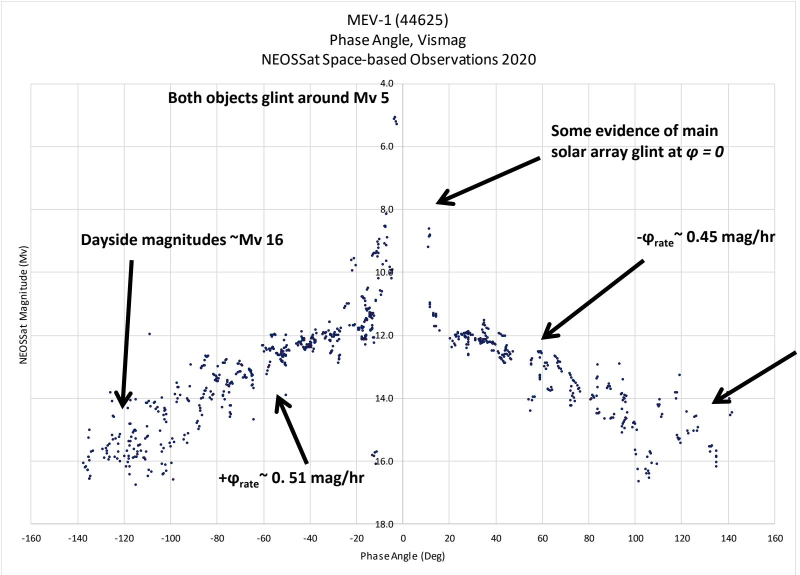

Figure 11. Space-based photometry of MEV-1 acquired from NEOSSat

Object Differentiation by Photometry: One of the characterization objectives was to determine if space-based photometric data could be used to differentiate and identify the client and servicing satellite based simply on their relative brightness prior to their docking. This is of value as simultaneous relative photometry on both objects can be obtained with a single image when the objects are in proximity to one another. The relative magnitude is expressed as

$$dM = M_{secondary} - M_{primary}$$

where $M_{primary}$ is the magnitude of the brighter, larger, client object (Intelsat 901) and $M_{secondary}$ is the brightness of the smaller servicing satellite. The relative brightness of the two objects collected during MEV-1's proximity to Intelsat 901 is shown in Figure 12. A histogram of this same photometric data is shown in Figure 13.

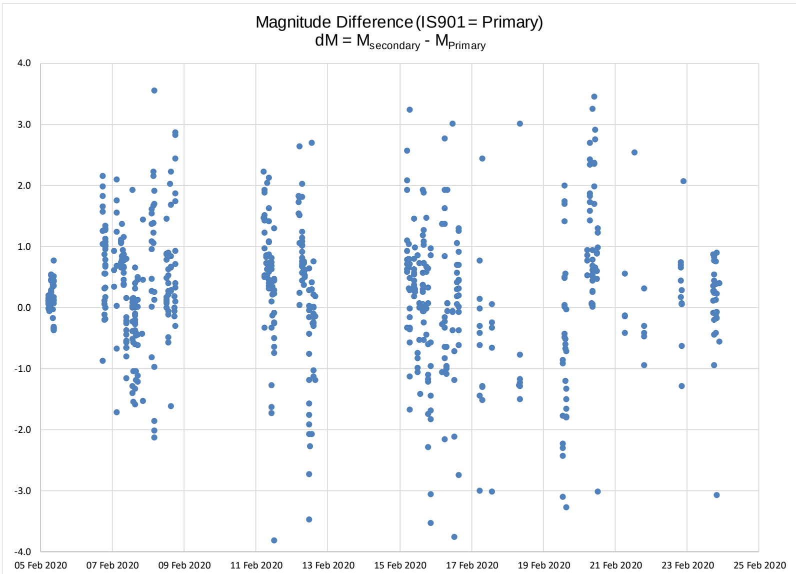

Figure 12. Relative photometry of the client with respect to Intelsat 901

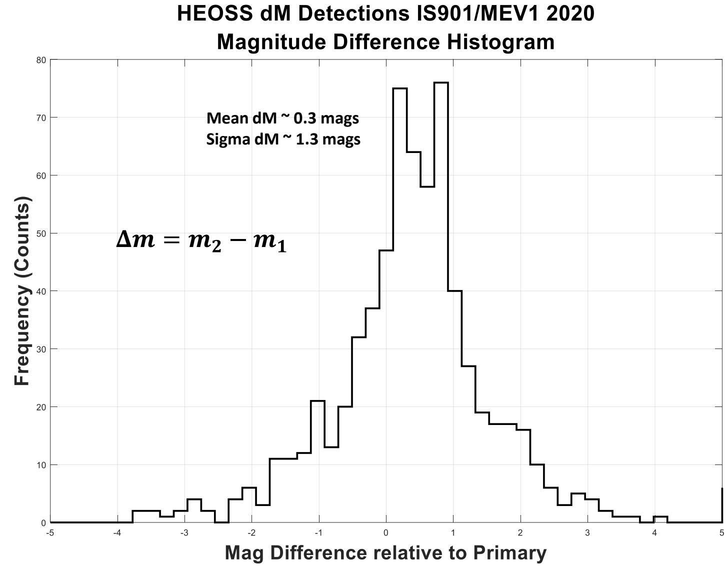

Figure 13. Relative photometry of the two objects – histogram plot

Figure 13's relative brightness measurements show a slight bias of +0.3 magnitudes suggesting that Intelsat 901 is somewhat brighter than the MEV-1. Unfortunately, the dispersion in the measurements is significantly larger than the relative brightness, making space-based measurements somewhat limited in their ability to differentiate the objects based on brightness alone. While space-based sensors can certainly report the position of both objects, the additional information contained in the objects' photometry is of the limited use to quickly, and unambiguously, identify each object. More work is recommended to be performed in this area as relative photometry would be a useful, fast indicator of object identificaiton. Ground-based sensors tend to have less photometric measurement variability and are better suited to differentiate the objects due to relative brightness. This is due the fewer degrees of freedom that the observer vector moves relative to the target producing smoother relative light curves.

MEV-1 captivated and docked with Intelsat 901 on 25 Feb 2020. At this time, the objects appeared merged on NEOSSat's field of view and differentiation based on astrometric position was no longer possible.

POST CAPTIVATION RELOCATION OF THE COMBINED VEHICLE STACK (CVS)

Once captivation, docking and initial checkouts were completed, the Combined Vehicle Stack (CVS) of the merged MEV-1 and Intelsat 901 continued its westward drift toward its final station keeping location at 27.5°W longitude and co-located with Intelsat 907. Once positioned, Intelsat 901 took over Intelsat 907's communications services. MEV-1 remains fixed to its client and will provide orbital station keeping and attitude control for the CVS.

Once located at 27.5°W, the CVS re-entered detection range of the DRDC ground based optical facility. Light curves on the CVS were the acquired and compared to the baseline photometry collected in winter 2019. Figure 14 shows Intelsat 901's baseline photometry superimposed with the CVS photometry collected in April 2020.

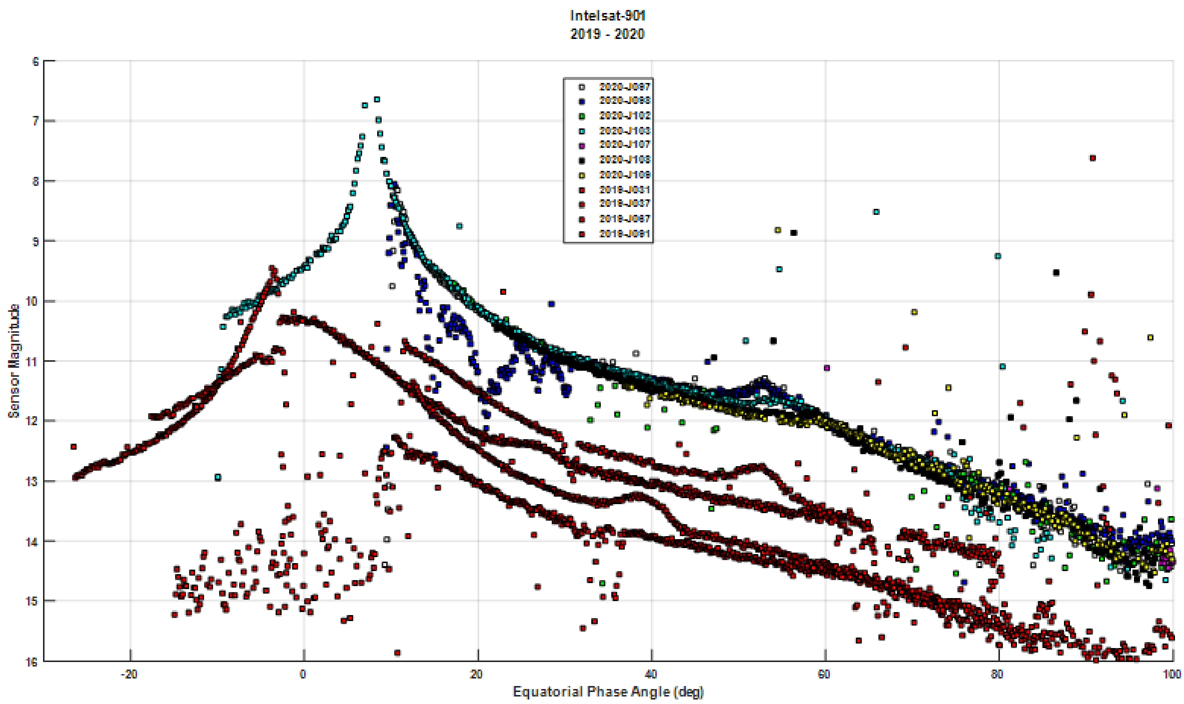

Figure 14. Comparison of pre-docking photometry of Intelsat 901 (red) and the Combined Vehicle Stack (multi-color)

Two main features are noticeable. First, the CVS is nearly 2 magnitudes brighter than Intelsat 901, consistent with expectation that the CVS has a larger reflective surface due to the cruciform arrangement of the two satellites' solar arrays (see Figure 3). Second, the light curve for the CVS is similar to the light curve collected on Intelsat 901 in winter 2019. The glint feature at φ ~ 52° has reappeared but is brighter by 2 magnitudes. A slight change of rate of fade beyond φ ~ 60° also appears. This is possibly due to the motion of the orthogonal solar arrays on MEV-2. Despite the unusual arrangement of MEV-1's solar arrays relative to Intelsat 901's, the CVS' light curve does not show any unusual modulation of the light curve due to the atypical cruciform solar array arrangement, and simply appears brighter by 2 magnitudes.

CONCLUSION

Canada contributed astrometric and photometric observations on the MEV-1 and Intelsat 901 satellites prior to, during and after the servicing of Intelsat 901. Canadian ground and space-based photometric measurements were collected on both space objects during various flight intervals of MEV-1. Ground based sensors provided excellent baseline photometry of the client satellite (Intelsat 901) enabling the identification of unique glint feature unique to Intelsat 901's light curve. Space-based sensors can perform a similar function, unaffected by ground-based weather conditions, and over a larger swatch of the target object's orbital arc, however the photometric variation observed by space-based sensors is considerably larger compared to the ground-based photometry. NEOSSat was able to maintain orbit custody of the two space objects during their proximity events which were unobservable from ground sensors in North America. Relative photometric measurements using space-based sensors to attempt the unambiguous identification of MEV-1 and Intelsat 901 were not successful due to NEOSSat's north-south motion causing significant photometric variances making it difficult to unambiguously identify which object was which based on relative photometry alone. Ground-based measurements of the CVS consisting of the cruciform-patterned MEV-1 and Intelsat 901 showed an expected increase in brightness of ~M_v +2. The glint features observed on Intelsat 901 the prior year were subsequently observed in the CVS' light curve. The cruciform solar array pattern did not appear to modulate the light curve of the object pair despite the usual orientation of their solar arrays in geosynchronous orbit. This experiment shows photometry has a role in SSA observations of On-Orbit Servicing missions, but care must be taken when attempting object discrimination during proximity operations when using photometry.

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