The Use of Flyby Space-to-Space Non-Earth Imagery to Rapidly Identify and Characterise Unknown Objects

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ABSTRACT

Resident Space Object (RSO) identification and characterisation is essential for various space operations, including attribution, accurate tracking and propagation as well as capability and threat assessment to avoid operational surprise. Traditional satellite characterisation methods have predominantly relied on the use of ground-based observations, both non-resolved optical and radar, to estimate information about the size, shape, attitude, and material properties of unknown objects. However, these methods are often only able to achieve partial characterisation and typically result in large uncertainties with multiple possible solutions, limiting the effectiveness of this analysis for the applications outlined above. Recent advancements in the use of space-based assets to obtain resolved imagery through flyby imaging introduces a significant enhancement in capability for rapid RSO characterisation. This paper provides an overview of a novel approach to rapid RSO characterisation through the utilisation of flyby Non-Earth Imagery (NEI) developed by HEO. Unlike ground-based methods, flyby NEI produces resolved imagery of target objects enabling specific components, such as solar panels, thrusters, antennas and payloads on the target object to be identified and analysed. This information enables RSOs to be quickly identified and characterised as active payloads, rocket bodies and debris, as well as confirmation of satellite class based on comparison with known satellite types. For objects that do not match a known satellite bus type or class, HEO performs further focused imaging on the target in order to produce a 3D model and make an assessment of its capability.

1. INTRODUCTION

The recent rise in accessibility of space through both national and commercial launch providers has led to a considerable increase in on-orbit objects within the last five years. As more organisations attempt to utilise the benefits of space for scientific, commercial, and military purposes it is expected that this trend will continue. In particular, the introduction of ride-share launches, where a single rocket deploys multiple smaller payloads (e.g. the recent Transporter-11 mission operated by SpaceX deployed 116 payloads to low earth orbit (LEO)) has been a major innovation for the space industry enabling rapid development and testing at significantly lower cost. While this innovation creates a great opportunity by reducing barriers to entry for new entrants to the space domain, it also increases the challenge for organisations attempting to provide space domain awareness (SDA), through the tracking, identification and characterisation of these spacecraft.

Ground based observations, predominately radar and non-resolved optical observations, have been traditionally relied upon to provide SDA information. While these methods are effective for tracking RSOs and generating orbital state information to predict the future position of RSOs, they have been less effective at characterisation. Characterisation is the process of determining information about the size, shape, attitude, and material properties of unknown objects. Characterisation techniques from radar observations were drawn from the field of planetary radar astronomy where they were developed to estimate the shape and spin of natural satellites. These radar-based methods included cross sectional estimation and range Doppler interferometry [9]. Light curve based RSO characterisation from a combination of non-resolved optical observations has been found to be a particularly challenging problem due to the limited amount of information that is present in the light curve data and the fact that it is difficult to separate the different characteristics in order to solve for them individually [3]. There has been significant research into light curve based characterisation using both theoretical [10, 7, 5, 3] and data-driven approaches [4, 6, 2]. However, typically these approaches have been applied to constrained versions of the problem using simulated data or have focused on debris objects that are known to be rotating and subsequently have a repeating pattern in the light curve. Currently, RSO characterisation remains both an active and an unsolved problem [8], particularly in the context of active or newly launched RSOs.

Prior to 2016, identification and characterisation of active RSOs was less critical as the average payload to launch ratio was approximately two, making it relatively simple to identify RSOs based on there orbital state data and

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activity status (i.e. maneuvers). Figure 1 depicts the recent significant increase in the payload to launch ratio over the last 5 years with the introduction of ride-share missions, causing the identification and characterisation of newly launched RSOs to become increasingly challenging. This has led to a corresponding rapid rise in the the number of tracked but unidentified and uncharacterised RSOs, which can also be seen in figure 1.

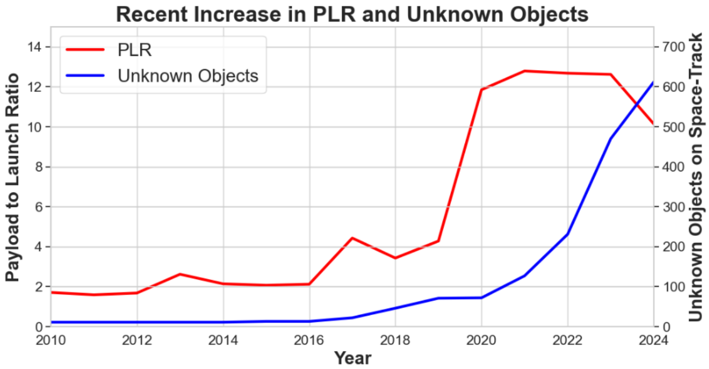


Fig. 1: Recent rapid increase in unidentified objects coinciding with a significant increase in the payload to launch ration (PLR) [1]

As of September 2024, there are more than 600 unidentified RSOs in the Space-Track catalogue[1] maintained by the 18th Space Defense Squadron, a large proportion of which have come from foreign launches. It is expected that this number will continue to increase without a pronounced improvement in identification and characterisation capabilities as international launch providers increase the cadence of ride-share missions.

Non-Earth Imagery (NEI) is the use of space-based telescopes and sensors to perform resolved imagery of other objects in space. The term flyby refers to the utilisation of passive imaging opportunities (non-intrusive) where the orbit of the imaging sensor is not actively adjusted in order to create a favourable imaging opportunity with the target object. This approach has several challenges: objects in space are far apart from one another, are typically moving with very high relative velocity and imaging opportunities occur with a range of different lighting conditions. To perform flyby NEI successfully and within a sensible time-scale, multiple imaging platforms on different orbital planes are required with high resolution telescopes and a suitable automated infrastructure. HEO achieves this by leveraging existing Earth Observation platforms, supplemented by purpose built NEI telescopes in regions with low coverage, to perform high-cadence, resolved images of RSOs in space.

Flyby NEI provides significantly more information than traditional characterisation techniques and presents a potential solution to both reduce the number of unidentified RSOs currently on orbit as well as to rapidly identify and characterise newly launched RSOs in the future. Unlike ground-based methods, flyby NEI produces resolved imagery of target objects enabling specific components, such as solar panels, thrusters, antennas and payloads on the target object to be identified and analysed. This information enables RSOs to be quickly identified and characterised as active payloads, rocket bodies and debris, as well as confirmation of satellite class based on comparison with known satellite types. For objects that do not match a known satellite bus type or class, HEO performs further focused imaging on the target in order to produce a 3D model and make an assessment of its capability. In this paper, an overview of the flyby NEI methodology implemented by HEO will be provided as well as an analysis on how resolved imagery data can be utilised to identify and characterise unknown RSOs, with reference to specific real-world examples, which have been successfully characterised by HEO. Additionally, a case study on the Chinese space plane launch in 2023 will also be included to demonstrate how flyby NEI can be used to rapidly provide characteristic information on unknown objects from a foreign launch, where threat assessment is required in a timely manner.

2. METHODOLOGY

2.1 HEO Sensor Network Overview

As of September 2024, HEO has access to a network of 46 space-based sensors which are utilised to capture NEI. This sensor network includes a range of EO sensors (both panchromatic and multi-spectral), as well as HEO's own purpose built NEI sensors. Through distribution of these sensors over different altitude bands and inclinations, HEO is able to provide high cadence flyby NEI of a large portion of the LEO regime up to an altitude of approximately 750km. Figure 2, depicts HEO's current sensor coverage, in terms expected image quality as a function of altitude and target RSO size. Areas in the figure that are more blue indicate high quality imagery or good coverage, while white/yellow indicates poor coverage. HEO plans to further increase coverage to both

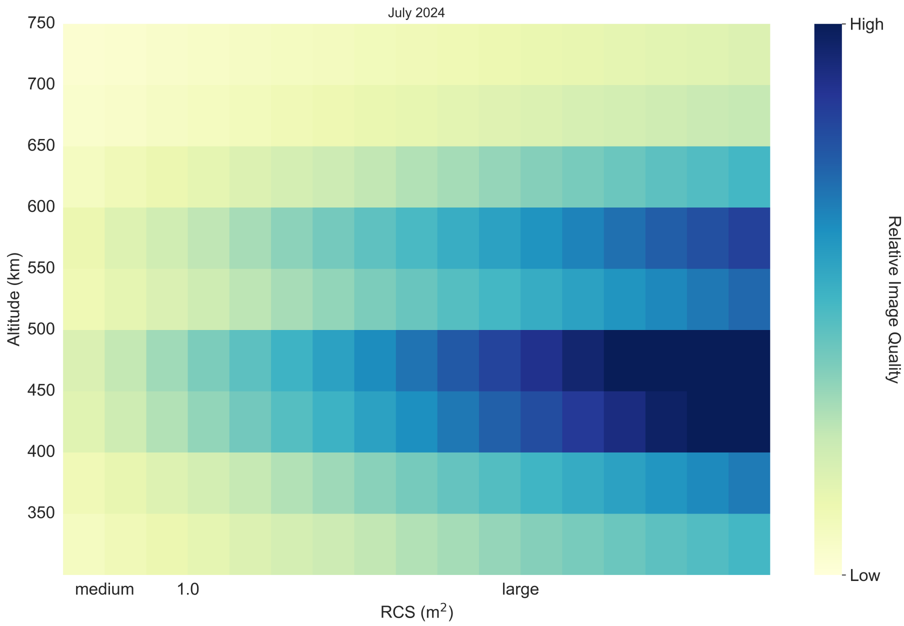


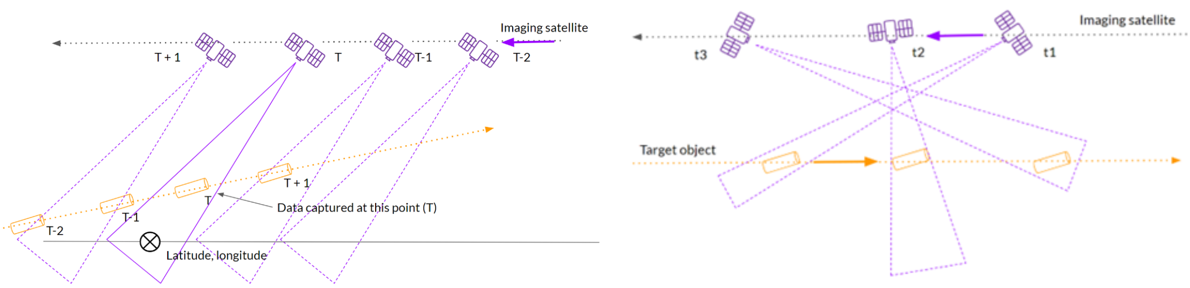
Fig. 2: HEO's current coverage at various orbital bands for RSOs of different sizes, blue indicates increased image image quality and likelihood of characterisation

the high LEO and geostationary orbital regimes as well as increase capability within the LEO regime to improve image quality and reduce image delivery time.

2.2 Opportunity Selection and Image Collection

During regular imaging operations, HEO predominately utilises passive flyby NEI where the orbit of the imaging sensor is not actively adjusted in order to improve the quality of an imaging opportunity (curated flyby) or to enter into relative proximaty operations (RPO) with the target RSO. Instead the imaging sensor is re-orientated during the imaging opportunity in order to most effectively capture the target RSO in frame. HEO's software automatically selects opportunities based on the best opportunities available to the sensor network and tasks them through integrated APIs with the relevant supplier. These automated integrations combined with the passive flyby operation enables HEO to conduct cost effective, high cadence imaging of a large number of target objects, allowing HEO to conduct more than 2000 successful NEI collections over the last two years. It also has the distinct advantage compared to curated flyby NEI or RPO NEI of being non-intrusive and non-detectable from ground based tracking operations.

Figure 3 presents two separate flyby NEI CONOPS the are routinely used by HEO. Figure 3a depicts the fixed pointing CONOPS, where the the imaging sensor is locked at fixed attitude during the imaging window and the target RSO passes through the sensors field of view. In Figure 3b, the imaging sensor is activey slewed during the imaging window to enable the target to be locked in the field of view.



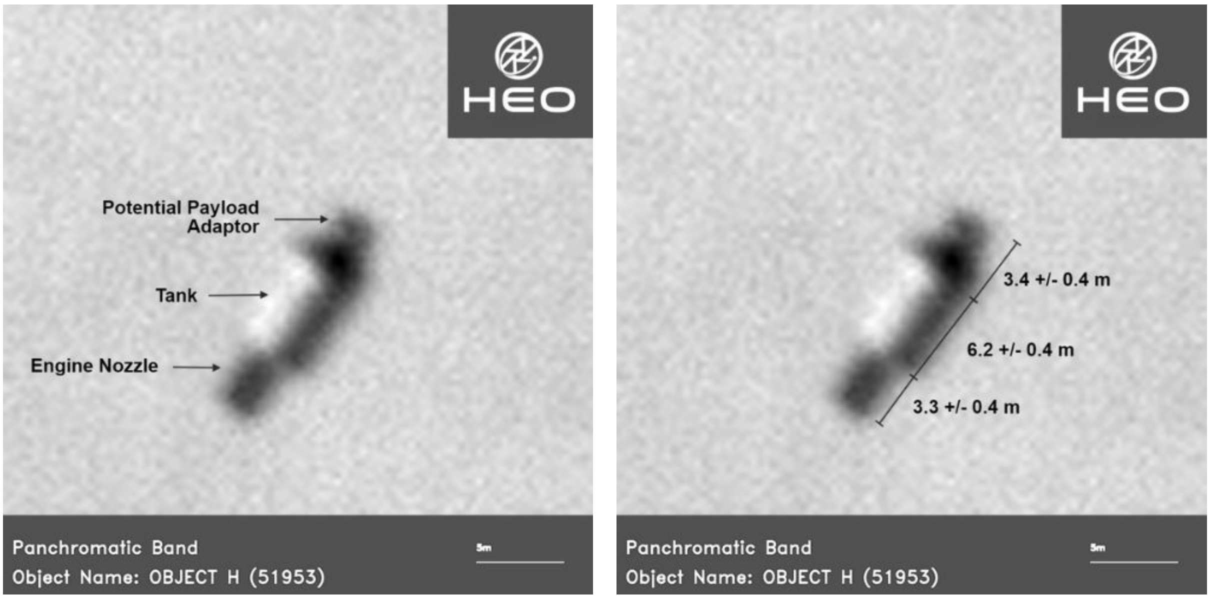
(a) Fixed Pointing CONOPS

(b) Active Pointing CONOPS (slewed NEI)

Fig. 3: Flyby NEI CONOPS

2.3 Identification and Characterisation from NEI Datasets

Once NEI imagery and data has been successfully collected, the datasets are processed and analysed by HEO. Image processing techniques are implemented to improve contrast and clarity within the imagery as well as to reduce motion blur caused by high relative velocity between the imaging satellite and target RSO. In house analysis tools are then utilised to collect characteristic information and insights on the observed target. Figures 4 and 5 display two examples of NEI datasets of unidentified RSOs that were collected by HEO in November 2023 for the purposes of identification and characterisation.



(a) Object H (51953): Component Labels

(b) Object H (51953): Measurements

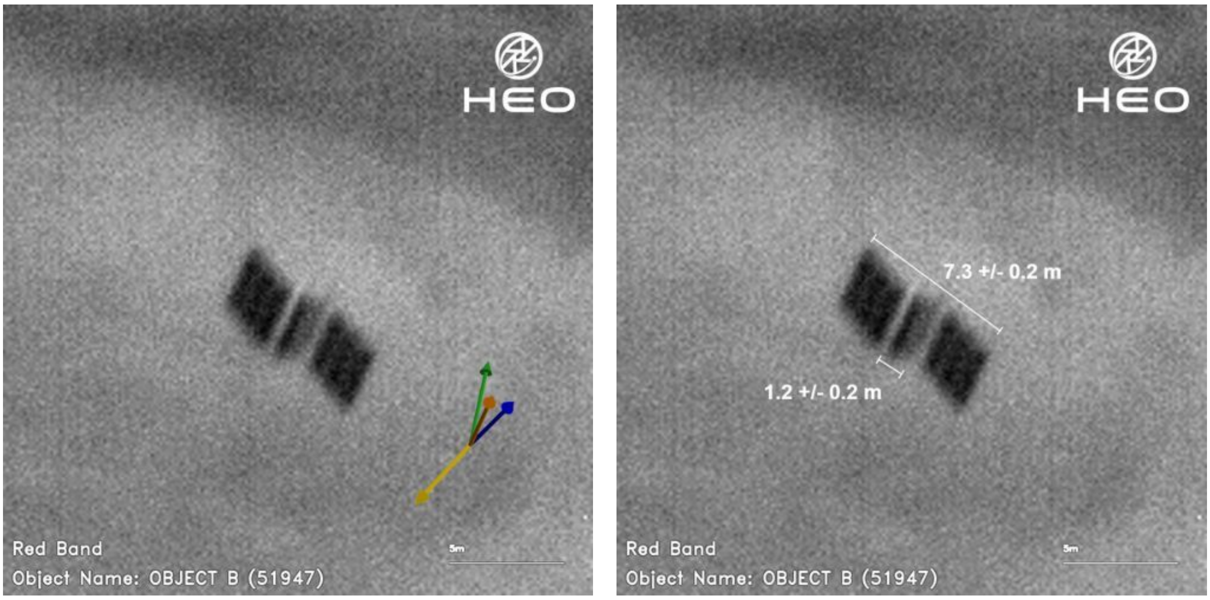
Fig. 4: Example Identification and Characterisation of Object H (51953): Long-March 2C

Figure 4 depicts Object H (NORAD: 51953) that was imaged by HEO in November 2023. Object H was launched by China on the 5th March 2023, with the launch resulting in 8 tracked objects published to Space-Track (7 listed as large Radar Cross Section (RCS) objects and 1 medium RCS object). As of August 2024 all 8 of the objects from this launch remain unidentified on Space-Track, listed as Objects $A -> H$. As can be seen in Figure 4a, a distinct advantage of resolved NEI compared to non-resolved observations from ground based optical or radar is that key characteristic features are directly observable in the processed imagery, enabling rapid assessment and identification of the object. The tank, engine nozzle and payload adapter are clearly visible in the imagery allowing the object to be easily identified as a rocket body. Even this level of characterisation is important for effective utilisation of resources, as the classification of the object as a rocket body as opposed to an active object, significantly reduces the potential threat level of the object.

Measurement analysis was then conducted on each of the identified individual components with the data depicted in Figure 4b. Cross-referencing these measurements with known data about Chinese launch vehicles as well as publicly available information and tracking data from the launch enabled Object H to be positively identified as a Long-March 2C rocket body.

Figure 5 displays NEI of Object B (NORAD: 51947), which originated from the same launch as Object H above. In contrast to Object H, Object B can be clearly identified as a payload with two solar panels deployed and a central bus. Initial measurements depicted in 5b indicate that the hard body radius of the object (inclusive of the solar panels) is approximately 7.3m while the satellite bus is measured to have an approximate width of 1.2m. The vectors depicted in Figure 5a are used to make an assessment of target orientation without performing a full attitude analysis. The yellow vector indicates the direction of the sun, the green vector is nadir pointing, while the blue vector shows the velocity vector of the target and the orange vector depicts the image plane relative velocity vector within the image indicating the direction of motion blur.

Based on this initial dataset for OBJECT B, it was clear that the unidentified RSO was a payload that was most likely active based on the orientation of the solar panels relative to the sun vector. Subsequently, this object was scheduled for a follow up imaging campaign to perform a more detailed analysis. The ensuing NEI datasets, enabled HEO to confirm that the payload was indeed active and most likely a Yinhe-2 satellite (Chinese pathfinder 5G satellite) as well as allowing for an initial 3D model of the RSO to be generated based on characteristic information collected from NEI.



(a) Object B (51947): Image Vectors

(b) Object B (51953): Measurements

Fig. 5: Characterisation of Object B (51953)

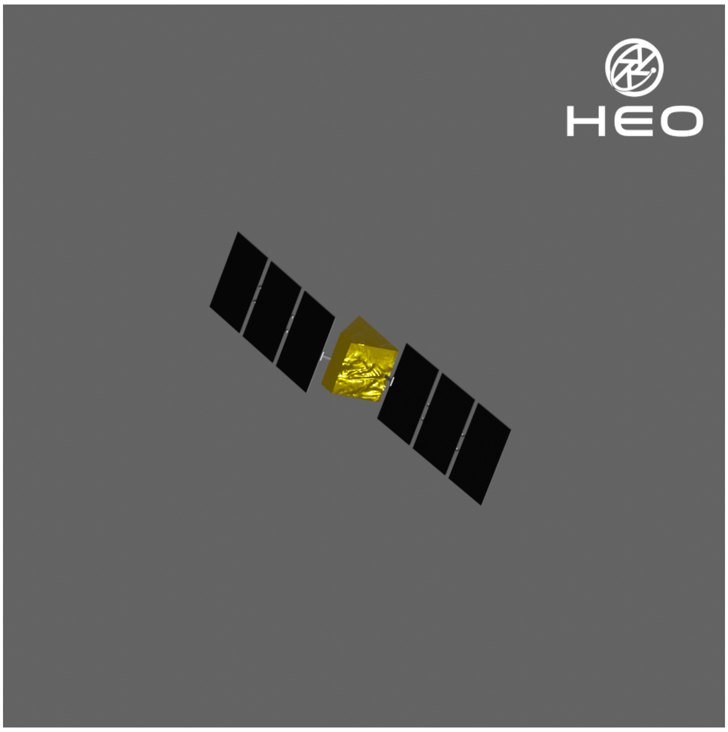


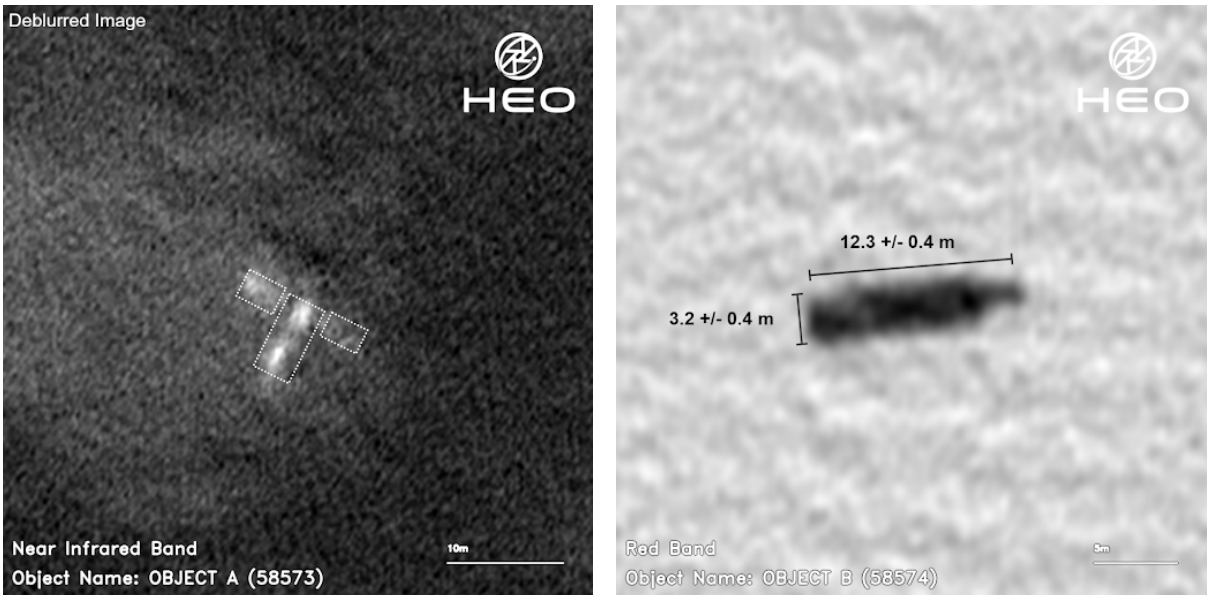
Fig. 6: Initial 3D Model of Object B generated based on NEI

3. CASE STUDY: PRC TEST SPACECRAFT IDENTIFICATION

This section presents a brief case study on the third launch of the PRC Test Spacecraft (NORAD ID: 58573, also referred to as Shenlong Spaceplane), which occurred on 14th December 2023. The spaceplane is the first reusable spacecraft produced by China, representing a significant step forward in the capability of the Chinese space program. As a result of the lack of official descriptions or published photographs there is significant interest in the tracking and characterisation of the spaceplane, in order to gain a better understanding of its utility and capability.

Six separate objects were determined to have originated from the spaceplane launch and were tracked using ground-based observation sites. These objects were initially labelled as Objects A $->$ F and a TLE for each object was published to SpaceTrack allowing additional tracking from commercial providers and HEO to commence NEI operations. HEO subsequently tasked opportunities for each of the objects to help provide insights into the size and characteristics of each object.

Figure 7 displays two images that were collected by HEO on the 17th December, 3 days post launch. While neither image is high resolution, once deblurring was conducted there were determined to be enough characteristics in the images to positively identify the two objects. Based on the measurements conducted on Object B in Figure 7b and it's distinctive shape it was positively identified as a CZ-2F R/B. While it is difficult to make out specific features of Object A in Figure 7a, general shape characteristics can be seen through the overlaid dotted lines in the image. These shape characteristics combined with initial measurement analysis on this dataset and the positive identification of Object B as the CZ-2F R/B enabled HEO to make a high probability assessment that Object A was the spaceplane.



(a) Object A

(b) Object B

Fig. 7: 2023-12-17: Initial NEI Collections of Object A and and Object B (3 days post launch)

The positive identification of CZ-2F R/B and probable identification of the spaceplane as Object A on the 17th December, enabled HEO to focus imaging on Object A over the next 24 hours resulting in the successful collection of additional datasets and subsequently a confirmed positive identification. Measurements were then collated from these datasets to produce a basic 3D model of the spaceplane, providing initial characterisation data.

On the 20th December, 6 days post launch, Space-Track confirmed HEO's identification of Object A as the spaceplane and Object B as the CZ-2F R/B. Publicly released information on this identification indicated that Object A appeared to be emitting modulated signals similar to previous spaceplane launches and the light curve appeared to be very bright and stable. Similarly, the light curve data characteristics for Object B collected over several passes appeared to be consistent with a an upper stage rocket body.

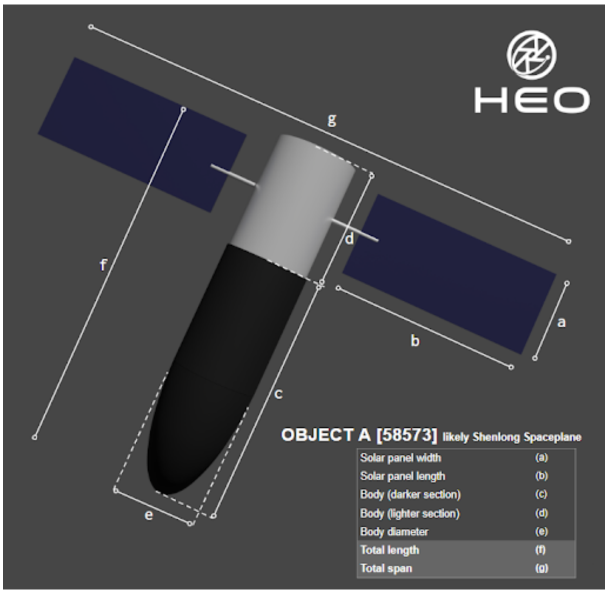
This case study, highlights the effectiveness of flyby NEI for rapid identification and characterisation of unknown objects, particularly in cases where the target objects are non-cooperative. HEO successfully identified both the spaceplane and rocket body from the list of six tracked objects within three days of launch.

Post identification phase, HEO has continued to image the spaceplane, conducting a pattern of life analysis and collecting more than 60 NEI datasets including multi-spectral datasets. The combination of these datasets obtained from a wide variety of viewing and sun phase angles have significantly increased the available characteristic information and enabled refinement of the 3D model.

4. CASE STUDY: TRANSPORTER 10 LAUNCH

SpaceX launched its tenth dedicated ride-share mission (Transporter 10) on 4th March 2024, with a total of 53 payloads deployed into SSO over two separate deployment zones at altitudes of 520km and 600km. As outlined in the introduction, these ride-share missions have been a great innovation for commercial space companies, enabling significantly cheaper access to space as well as allowing a much faster iteration and development cycle. However,

(a) Object A: Further Observations



(b) Initial 3D Model and Object Characterisation

Fig. 8: Follow up NEI Collections and Analysis of the Shenlong Spaceplane

they have also created challenges for SDA operators attempting to track, identify and characterise these objects using traditional ground-based methods.

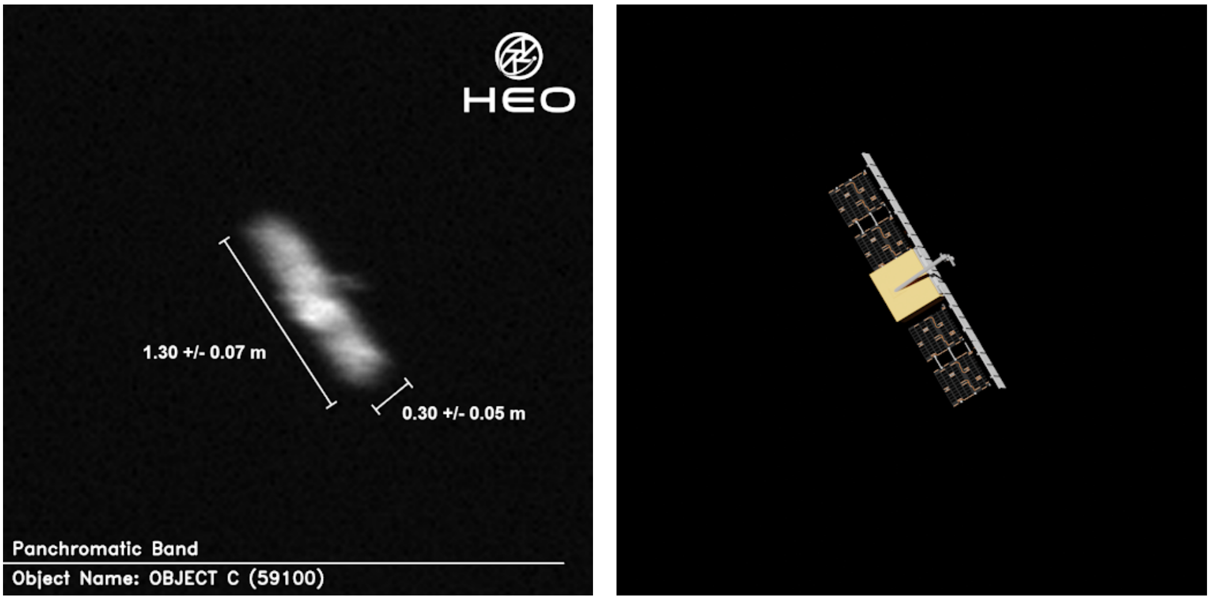
Ride-share launches are particularly challenging for SDA operators as they involve a large number of typically smaller payloads deployed in quick succession in a similar orbit regime. Subsequently, it is very difficult to identify payloads based on orbital state data and due to the similar size of payloads, characterisation based on RCS or light curve data is typically impossible. Instead, operator and transmission information is used for identification when the payload operator makes contact with the spacecraft. This is obviously limited to cooperative spacecraft and operators

At HEO, it was theorised that NEI could provide utility in improving the identification of these payloads, particularly in cases where there is an issue with the satellite. For Transporter 10, it took approximately 2 weeks for TLEs to be first uploaded publicly to Space-Track and when they were the vast majority of tracked objects where listed as 'OBJECT' indicating that their identities had not yet been confirmed. Once TLEs were made publicly available, HEO was able to use this tracking information to cue sensors for NEI collections and collected imagery of OBJECT C (NORAD: 59100) depicted in 9a. HEO then compared the characteristic information of this object extracted from the NEI dataset with publicly available information about objects deployed in a similar orbit regime. Based on this data, OBJECT C was identified as an ICEYE spacecraft that had successfully deployed both solar panels and synthetic aperture radar (SAR) antenna which, can be seen through the rendered image of the object depicted in 9b. This identification was later confirmed by Space-Track on April 10th where the target name was updated to ICEYE X-38, highlighting the benefit of NEI for rapid identificantion and characterisation.

The final example presented in this report is the identification of Optimus, another payload that was launched on Transporter 10. In this case, the spacecraft had failed to make contact with its operator and subsequently after a month on orbit without contact or positive identification from Space-Track and with 17 objects from the Transporter 10 launch remaining unidentified, the space agency of the operator country asked HEO to conduct NEI to assist with Optimus' identification. Identification of the object was a high priority for the space agency as there are liability concerns and implications if Optimus collides with another spacecraft in the future.

This turned out to be a challenging case for NEI as relative to HEO's sensor constellation at the time, the orbits of the potential objects where not ideal for high resolution imaging and given the the relatively smaller size of the target object it was difficult to determine defining characteristic information from the collected NEI datasets. Resultantly, HEO used publicly available information about the RCS size of the unidentified objects combined with the launch manifest and TLE data to narrow down the search to four potential candidate objects. These objects were all imaged using NEI over the course of a 3 week period. For two of the four objects, deployed solar panels were observed in the NEI datasets, which immediately allowed them to be removed from consideration as it was known that Optimus has fixed body solar panels.

Of the remaining two unknown objects HEO captured an NEI datasets of OBJECT AG (NORAD: 59128) depicted



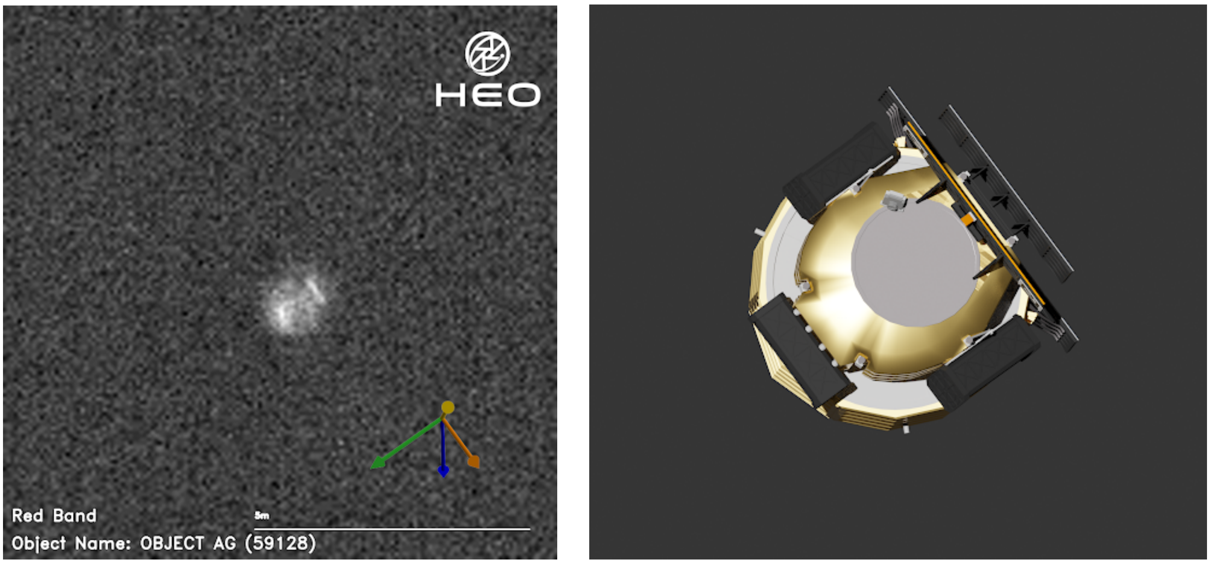
(a) NEI of OBJECT C: Identified as ICEYE X-38

(b) Render of ICEYE X-38

Fig. 9: Identification of Object C and Comparison with a Rendered 3D model Orientated to Align with the NEI Dataset

in figure 10a. While this is not the highest quality dataset due to the challenging orbit and small size of the target, there were some identifiable features in the image that appeared to match up with the expected shape of Optimus. Figure 10b displays a render of the 3D model of Optimus which was generated from publicly available information about Optimus. While this dataset alone was not definitive in enabling a positive identification of Optimus from NEI alone it did enable analysts to indicate that OBJECT AG was most likely Optimus. This also implied that the remaining unidentified object (OBJECT AK) most likely belonged to a different company. HEO was able to reach out to this company and confirm that they were in contact with OBJECT AK, enabling positive identification of OBJECT AG as Optimus.

The identification of Optimus highlights the fact that even for small RSOs or RSOs in challenging orbits where NEI may not be able to definitely identify an unknown object as a specific spacecraft, there will still likely be additional information present in the collected NEI datasets that can be utilised to assist with identification and characterisation.



(a) NEI of Object AG (Optimus)

(b) Render of Optimus: Orientation Aligned

Fig. 10: NEI of Optimus compared with a rendered 3D model of Optimus in a probable orientation. Image quality not high enough for definitive identification solely from NEI

5. CONCLUSION AND FUTURE WORK

Flyby NEI represents a significant advancement in identification and characterisation techniques on traditional ground-based methods using radar and non-resolved optical observations. The ability to determine specific components of an RSO directly from the image enables rapid assessment of object type and function. More in-depth analysis on the component size and orientation can enable identification of the object as well as providing an indication of it's capabilities and subsequently threat level.

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