Vantage Point: Lessons from doing coordinated space imaging[1]

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ABSTRACT

Modern cinema has shown time and again that looking at a scene or story from multiple perspectives can produce unique and important insights. We explore in this paper our lessons from seeking to answer the question:
"Can coordinated space imaging provide unique and important insights?"

Our coordinated space imaging uses three different sensor modalities including:

- **On-Orbit Space to Space Imaging Network:** A network of on-orbit space to space imaging assets supported by analytics provided by HEO Robotics ('HEO').
- **On-Orbit Neuromorphic Camera:** An on-orbit event-based neuromorphic camera hosted on the International Space Station (ISS) and provided by Western Sydney University (WSU) International Centre for Neuromorphic Systems (ICNS) in collaboration with the United States Air Force Academy (USAFA) Space Atmospheric Research Center (SPARC).
- **Ground Based Neuromorphic Camera:** A ground based neuromorphic camera observatory called Astrosite provided by WSU-ICNS.

Given today's contested, congested, and cluttered space environment, having different views and data sources can help provide space operators the most accurate insights about what is happening around their assets. This paper discusses the advantages of using multiple phenomenologies from multiple angles to help operators decide between different courses of action including decisions about whether to expend precious fuel or take other actions. The evolution of commercial and civil Space Domain Awareness (SDA) architectures, combining both ground-based and space-based assets along with the broader availability of commercial SDA networks is increasing the opportunities for coordinated space imaging. The goal of this activity is to optimise the use of resources to reduce cost while creating the best possible SDA.

1. INTRODUCTION

Space Domain Awareness (SDA) has developed to focus on: not just, what is going on up there, but also, what can satellite operators do about it? This requires having the right set of data to understand the behaviour of others' space assets. Understanding the intent of the behaviour is key. Is the satellite just passing by to take a picture for your insurance claim? Or is there an un-manoeuvrable piece of debris headed your way? Different types of data may help inform the SDA including launch manifests, regulatory filings, news or social media, and sensors using different types of phenomenology. Each piece of data can enhance the overall understanding of what is on orbit, what it can do, what it is trying to do, and what options are available to the satellite operators.

Understanding each type of data available helps create recommendations for courses of action (COA). Perhaps an additional observation can reduce the error covariance of an object to the point where a conjunction is no longer of concern. Or perhaps no ground-based optical observations are possible because of an incoming hurricane/cyclone. Understanding the probability of success for each COA as well as the value of each COA can enhance resource usage as well as increase SDA. Additionally, the possibility of coordinated space imaging of resident space objects (RSOs) from multiple vantage points brings a further dimension to decision makers. This newer multiple vantage point possibility is aided by several factors including:

- **SDA Architectures:** More complex, more capable architectures that combine ground-based and space-based assets are becoming the norm [1][2][3].
- **Commercial Sensing Networks:** The increasing availability of commercial space sensing networks is opening the possibility of more complex SDA architectures. These architectures are now available to more than the best resourced countries. These commercial sensing networks include, for example:

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[1] Approved for Public Release

    - *Exoanalytic Solutions:* A commercial SDA sensor network with currently 300+ sensors and 30+ observatories [4]
    - *Slingshot Aerospace:* A commercial SDA sensor network with currently 150+ sensors and 20+ observatories [5]
    - *LeoLabs:* A commercial radar network currently with six sites [6]
    - *HEO Robotics:* An on-orbit space to space imaging and analytics network with currently 38 sensing satellites [12]
- **International Collaboration:** International participation in events like Sprint Advanced Concept Training (SACT) and conferences like AMOS are on the rise. Additionally, papers specifically discussing the tools to be enable this collaboration are also appearing [7]. This paper was an international collaboration, the team working this experiment spanned Australia, USA, and South Africa. Additionally, the HEO network used in the experiment spans other international boundaries through its supplier network.

Within this context, this paper takes initial steps in the exploration of coordinated space imaging - its value and its challenges. In this experiment, we seek to highlight the value of using neuromorphic sensors along with more traditional CCD-based sensor types to better inform future coordinated use of these sensor types. We use the HEO Robotics on-orbit space to space imaging network ('HEO Network') and two neuromorphic (event-based) imaging systems - the Western Sydney University (WSU) Astrosite ('Astrosite') located in South Australia and the WSU/ United States Air Force Academy (USAFA) nadir; ram camera combination ('Falcon Neuro') installed on the ISS. Fig 1 shows the simplified concept architecture for our experiments.

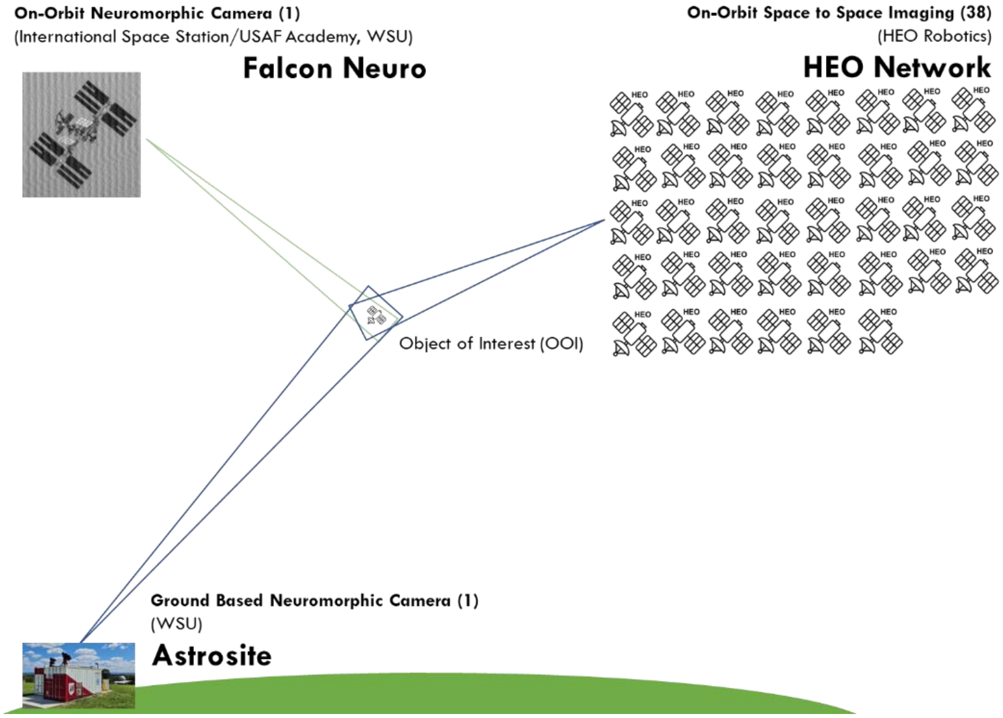


Fig 1. Simplified Experiment Architecture

Defining Terms

It is important that we define several terms within our question "Can coordinated space imaging provide unique and important insights?".

Firstly, what do we mean by *coordinated space imaging*? We define coordinated space imaging as imaging a RSO using:

- Differing sensor geometric vantage points (e.g. Falcon Neuro, Astrosite, HEO Network)
- One or more sensor modalities (e.g. Event-based Optical and CCD-based Optical)

- Over differing timeframes:
    - **Short timeframe ("Scene Based"):** Single coordinated imaging from multiple sensors provided within close time proximity, from <1min up to 5 hours.
    - **Longer timeframe ("Story Based"):** Regular coordinated imaging from multiple sensors provided over a longer time, where there is potential for a developing story about the RSO.

Secondly, what do we mean by *insights*? Defining insights is more involved, OxfordLanguages defines *insight* as "the capacity to gain an accurate and deep understanding of someone or something". This describes our intent. Our approach goes beyond observations to actionable insights that are based on accurate and deep understanding of the RSO. The follow-on question is "what *accurate and deep understanding* of RSOs do we want and need?"

Ackermann [1] uses the United States Air Force (USAF) (pre-United States Space Force (USSF)) five pillars to identify the categories where operational insights are valued including object *detection, tracking, identification*, c*haracterisation*, *tactical warning and attack assessment.* Bloom [2] similarly identifies object *detect* and *track* with a focus of Collision Avoidance (ColA) as well as *characterise* and *assess* with a focus on threat mitigation.

We have adapted their work to create Table 1 which includes insight categories, example insights and examples of where assets in our architecture have been previously used to derive actionable insights. The types of insights we focused on are the "higher level" categories, namely object characterisation, object identification and object activity. The reasoning behind this includes:

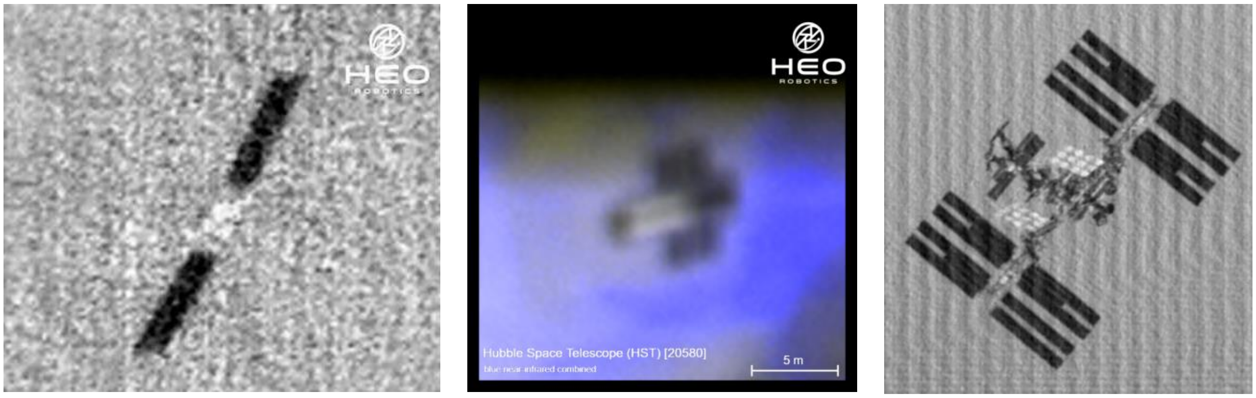
- **Object Detection & Tracking Availability**: The "marketplace" for object detection and tracking is well served. Whilst the WSU Astrosite is well suited to object detection and tracking [15], it was hoped that all our elements (HEO Network, Astrosite, Falcon Neuro) will produce the "higher level" insights. Additionally, our goal in conducting coordinated space imaging is to add insights, not duplicate.
- **HEO Network:** The strengths of the HEO Network include its size (network reach) but also its proximity to the imaged RSOs. The nodes in the HEO network work much more like the Geosynchronous Space Situational Awareness Program (GSSAP) concept [1], where the sensors are located quite "close" to the objects with a narrow, observable volume, than it is to the Space Based Space Surveillance (SBSS), Sapphire and Operationally Responsive Space 5 (ORS-5) concepts [1][2] that are focused on larger volume search and track from a "much further" distance. The "close" flyby operations nature of the nodes in the HEO network is such that it is excels at imaging satellites, providing insights around object characterisation, object identification and object activity.

Table 1: Insights

Insight Category	Example Insights	Examples from Our Assets
Object Detection	• Find	**Astrosite** [15]
Object Tracking	• Localise • Orbit Update • Orbit Verification	**Astrosite** [15]
Object Characterisation	• Size • Materials • Power Generation Capabilities • Structure and Appearance • Antenna Size	**HEO Network**: Starlink Mini [9] and Fig 2 (a)
Object Identification	• Function (including lack of) • Threat (including unintended) • Attribution	**HEO Network**: HST [10] and Fig 2 (b)
Object Activity	• Spin Rate and Axis • Behaviours and changes over time • Relationship with satellite's orbit • Antenna Direction	**HEO Network:** HST [10] and Fig 2 (b) ISS [11] and Fig 2 (c)

It is important to note that operators will also use combinations of insight category, for example:

- **Radio Frequency Interference (RFI) Assessment**: RFI assessment uses both object characterisation and object activity. Coordinated space imaging from both space and ground can glean important RFI insights on a particular RSO, including assessment of antenna type, power, frequency etc. For example, observing a parabolic antenna size reveals elements of its link budget in terms of power and gain. It's not perfect because we don't know the antenna efficiency, but it provides insights. Add in analysis of solar panel size to infer power generation capabilities and the picture is refined further. This may be the difference between knowing a transmitter can inadvertently overpower you, or not. Direction of the antenna is important as well, providing both additional insight into the link budget and determining if the direction is of interest to the operator. This all helps with RFI investigation, mitigation, and prediction. Additionally, using regular coordinated space imaging over time gives a more complete picture including for example, how the pointing changes over time.
- **Orbit Update/Verification**: Object Update/Verification will be assisted by all the insight categories. Coordinated space imaging from both space and ground can be used to identify RSOs that are currently untracked, as well as give better orbital dynamics to existing RSOs. Generally, more data equals more precise numbers. Timing, inclination, relative estimated speed, azimuth/elevation, can all be gleaned from optical observations, which translates into an orbit state.



(a) **Starlink Mini** [9]: this is the first reported space to space image of the Starlink Mini showing their new solar panel configuration

(b) **HST** [10]: this is part of a series of HST images which observe changes in the telescope's orientation and aperture door state.

(c) **ISS** [11]: this is part of a series of ISS images that help understand its activities including the recent addition of power generation capabilities

Fig 2. HEO Robotics Example Images

2. ASSETS

The following sections provide a brief overview of each of the imaging assets in our experiment setup.

HEO Network: On-Orbit Space to Space Imaging Network

HEO assists defence, governments, and commercial operators [8][9] to visually monitor their spacecraft and other space objects through proprietary satellite-to-satellite imagery and analytics. Operations are currently conducted with a network of Earth Observation (EO) satellites leveraged to conduct satellite to satellite imagery through HEO's software and dedicated Non-Earth Imaging (NEI) cameras developed by HEO. HEO receives imaging requests through HEO Inspect, an on-orbit satellite inspection program which integrates APIs with third-party satellite providers to task the most appropriate satellite in the network to capture imagery of various RSOs. Once tasked, the platform communicates autonomously via API with third party providers up until the time of imaging to carry out the mission.

Currently, HEO's sensor network consists of 38 sensors in LEO [12], at altitudes ranging from approximately 350-600km. CONOPS with third party satellite operators allow for rotating sensors to high off-nadir angles giving HEO Robotics effective coverage up to 700km altitude. 'Flyby' inspections are performed where conjunction type passes are leveraged to image the RSO passing by a sensor in the HEO Network. When selecting an imaging opportunity, several variables are considered, including:

- **Distance**: ideally between 20-100km,
- **Relative Velocity**: ideally lower than 10km/s,
- **Solar Illumination**: the RSO must be illuminated.

In most cases, an RSO will have multiple imaging opportunities across the HEO Network over the 7-day forecast period. The ‘best’ opportunities that will likely result in the highest quality image are manually or algorithmically selected. Fig 2 shows example images from the HEO Network.

Falcon Neuro: On-Orbit Neuromorphic (Event-based) Sensing

Space is an extreme environment and one that poses a unique set of challenges. Hardware deployed to space cannot easily be retrieved, fixed, or upgraded. The systems deployed need to meet a challenging set of requirements. They need to be highly reliable, robust, power efficient, and weigh as little as possible. They also need to carefully consider the costs of data transmission in a manner fundamentally different from terrestrial systems. Whilst it may not be evident on the surface, drawing inspiration from biology in designing such systems can lead to some significant advantages. Biological systems exist in extreme environments and show aptitude for adapting to them. They are also inherently power efficient, given the cost of acquiring energy. The field of neuromorphic engineering is a discipline focused on developing biology-inspired solutions to real-world problems, drawing upon how biological sensing and computation is performed and applying these concepts to silicon and computation hardware.

The field of neuromorphic engineering has led to the development of a type of imaging sensor that functions more like a biological eye than a conventional camera. These sensors, known as event-based sensors or neuromorphic vision sensors, differ from conventional cameras at the pixel level. They include specialised circuitry in each pixel to allow each pixel to detect contrast and only emit data in response to a change when a user-specified contrast change is detected. Each pixel also operates independently and asynchronously, providing the sensor with an extremely high temporal resolution, a very high dynamic range, and most importantly, dramatically lower data rates when observing sparse scenes.

Neuromorphic vision sensors are ideally suited to the space environment. They provide all the benefits of a high-speed and high dynamic range camera without the size, weight, power, and data requirements of conventional high-speed cameras.

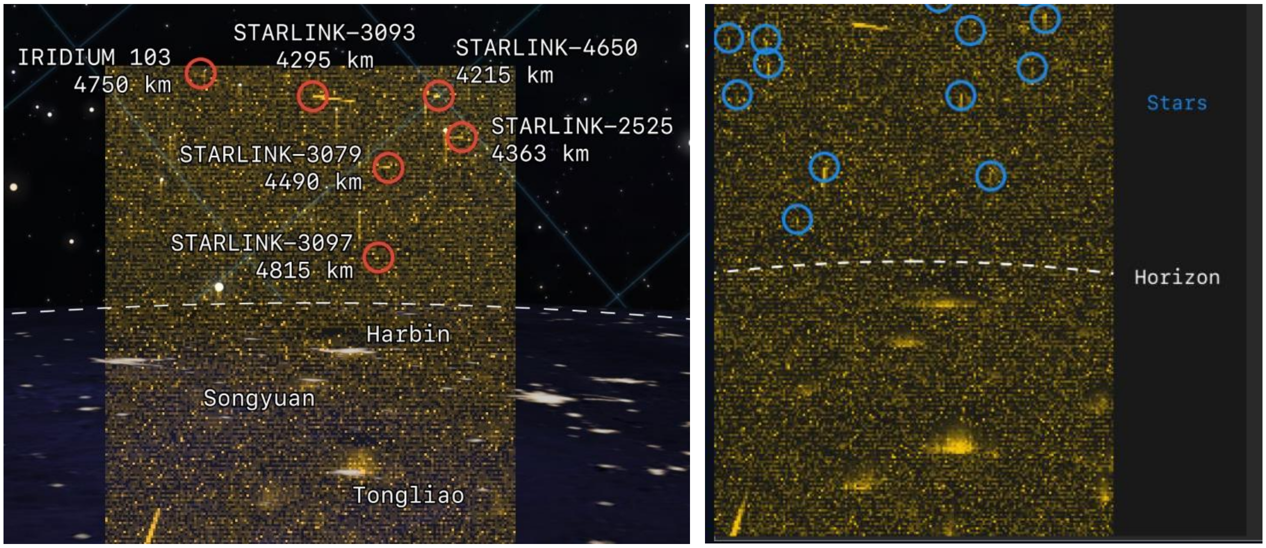
Space Situational Awareness (SSA) and Space Domain Awareness (SDA) are perfect applications for the use of neuromorphic sensors as they are sparse scenes where the objects of interest are either moving or photometrically changing. Simply put, neuromorphic sensors only provide data on the objects of interest in the scene, rather than having to continuously capture images of all the empty pixels in the scene. This drastically reduces the data generated.

Western Sydney University pioneered the use of these sensors for terrestrial applications through their Astrosite system, which consists of a network of fully autonomous neuromorphic telescope observatories built into standard shipping containers. These units make use of neuromorphic sensors to track RSOs, to perform continuous astrometric fits on the stars whilst the telescope is in motion, and to leverage the high-temporal resolution of the sensor to characterise the objects.

Deploying this technology to an orbital platform brings even more significant benefits. Western Sydney University has also deployed the first neuromorphic sensors to space and collected real-world space-based data to validate the use of neuromorphic sensors for on-orbit SSA and SDA operations.

Through a collaboration with the USAFA, Western Sydney University built and deployed two neuromorphic sensors to the International Space Station in December 2021. The payload, known as Falcon Neuro [13][14], became operational in January 2022 and continues to provide highly impactful space-based data.

Fig 3 shows an example of data from the ISS rendered using 30 seconds worth of captured data. The sensors used in the Falcon Neuro payload have a resolution of 240 x 180 pixels as opposed to the 1280 x 720 resolution of the current generation of neuromorphic sensor. In the figure, the horizon is located approximately in the middle of the field of view, resulting in approximately 120 pixels looking above the limb of the earth. Note that the sensor can see ground features, satellites, and stars all simultaneously, and records this data with microsecond resolution. The 30-second recording is approximately 1 Mb in size and contains five RSOs and enough stars to perform an astrometric fit. This validates the use of neuromorphic sensors for a wide range of on-orbit space-based applications, including SSA and star tracking.

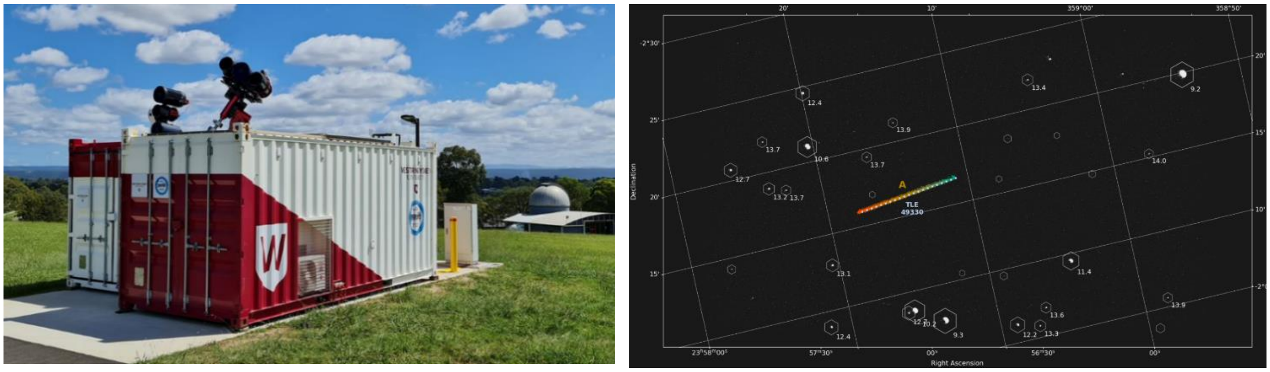


(a) RSOs (b) Stars

Fig 3: Falcon Neuro On-Orbit Neuromorphic Sensor Recordings

Astrosite: Ground-Based Neuromorphic (Event-based) Sensing

The Astrosite is a mobile neuromorphic telescope observatory built into a standard 20ft shipping container (Fig 4a) [15]. Astrosite 1 (front) remains on the Werrington campus of Western Sydney University. Astrosite 2 (back) is currently located in South Australia. Built around the neuromorphic sensors attached to the telescopes, the Astrosite makes use of motion to detect and capture observations of RSO across all orbital regimes. The Astrosite observatories are designed to be moved and redeployed rapidly, leveraging the existing infrastructure for shipping, and moving shipping containers by land, sea, and even air. The Astrosite container has a sliding roof and a lifting mechanism to raise the telescope out of the container for observations and has the form factor of a standard shipping container when not in use. It is capable of fully autonomous operation and fully remote manual operation.



(a) Astrosite 1 and Astrosite 2 side-by-side at WSU. (b) Astrosite produced Star Map

Fig 4: Astrosite – Ground-based Neuromorphic (Event-based) Imaging

The Astrosite system provides a good example of a neuromorphic solution that changes the observation method to allow the neuromorphic sensor to operate in a highly effective manner. The Astrosite moves the telescope mount whilst observing satellites to allow for the simultaneous recording of resident space objects and the stars in the field of view. The algorithms developed then extract the star data and satellite data from these recordings, identify the satellites, and solve the star field to convert the sensor measurements from camera coordinates to sky coordinates. The output data is then used to build a plot that integrates all the information into a single figure. An example of such a figure is provided in Fig 4b. This star map produced by the Astrosite demonstrates the output of a highly optimised event-based algorithm. The image shows the culmination of numerous event-based algorithms used in the Astrosite to produce a highly informative output. In the figure, the event-based data is shown in the background of the figure, with the events generated by the satellite shown in colour (A). The colour indicates time, showing the direction and speed of the object. The events from the stars have been converted into world coordinates, collapsing them into points representing stars. These are then used to perform an astrometric fit and find the exact location of the field of view in the sky.

Similar algorithms have been developed for motion compensation, tracking, characterisation, and classification of neuromorphic event-based data. By leveraging the benefits provided by neuromorphic sensors directly, these algorithms can produce high-speed, power efficient, and reactive systems that produce data which cannot be produced with conventional sensing approaches.

3. SETUP

HEO led the selection of imaging opportunities in this experiment. A list of potential imaging candidates was selected, which included the International Space Station (ISS), Hubble Space Telescope (HST), and communications satellites including BlueWalker 3 and several Starlink V2 Mini satellites. These objects were selected mostly because they are large in size, meaning that they would be easy to identify in ground-based imagery as well as space-to-space imagery.

The process of finding potential imaging opportunities started with fetching the latest TLE from Space-Track for each object on the candidate list using the python spacetrack module. Then, for each object, passes were found using the python module Skyfield’s ‘find events’ function. An altitude threshold of 10 degrees was passed to this function, meaning that only events where the satellite rose higher than 10 degrees above the horizon would be considered. For each pass, the timestamps corresponding to the satellite rising above 10 degrees, culminating (reaching the highest point in the sky), and setting below 10 degrees were saved, along with a flag indicating whether or not the satellite would be illuminated at each of these three points.

Next, these passes were compared against a list of flyby events with sensors in the HEO Network. HEO regularly runs a service that calculates all potential flyby opportunities with all objects in LEO. The process of pulling this data and looking for opportunities within some margin of a pass over the Astrosite was automated. Initially, this margin was set to 90 minutes, however it was later relaxed to 6 hours to increase the number of candidate opportunities. HEO’s flyby opportunity service accounts for sensor off-nadir limitations and lighting conditions, so no additional filtering was performed on these opportunities.

This process produced two lists - one with passes over the Astrosite, and another with space-to-space imaging opportunities that occurred within the set time margin of a pass over the ground-based sensor. At this point, the opportunities were manually analysed to determine which ones should be attempted. The criteria for selecting which opportunities to attempt included minimising the time between the ground-based and space-based imaging, favouring higher resolution space-based opportunities, and preferencing either early morning or late evening attempts depending on the weather forecast.

Once opportunities were selected and communicated to the Astrosite team, HEO added the corresponding space-to-space opportunities to the automated task management system. After the opportunities were tasked, HEO’s software platform communicated with the appropriate sensor provider to provide pointing information. Currently, HEO can update pointing information based on the availability of the last groundpass for the satellite that will be taking the image. Occasionally, requests to use a particular time slot on a sensor are rejected if the sensor is unavailable at that time.

Once data is downlinked from the satellite and received by HEO, the captured images become available on the platform for internal analysts to assess whether the object was successfully captured in frame or not. This process is assisted by automated machine learning algorithms and metadata provided by the sensor providers.

Astrosite operates in a semi-autonomous manner, with user input or supervision required in two distinct places. First, a user must update the list of satellites priorities through the Astrosite cloud web application. The cloud application then generates a schedule that specifies which satellite to record at any given moment. Once the schedule is deployed at the Astrosite physical shipping container, the later can operate autonomously without interacting with the cloud application. User input is only required at the beginning of the night to start the deployment sequence. This is typically done after checking that the Astrosite's subsystems are in a normal state.

Falcon Neuro may only be operated from the US Air Force Academy by personnel with clearance to interact with NASA. Recordings are acquired manually during availability windows updated weekly by the ISS operation center. This process's complexity partly comes from the fact that Falcon Neuro is a path finder rather than an industrial solution, but it illustrates well the added cost and time of operating on-orbit systems.

4. IMAGING RESULTS

HEO Network Imaging

HEO captured seven imaging datasets for the target objects over the period from the 28th of July to the 1st of August. Three of these image sets were of the HST (Fig 5, Fig 6, Fig 7, Fig 8), three were of two different Starlink Mini V2 satellites, and one image set captured BlueWalker 3.

Fig 5: Wide image of HST taken at approximately 93 km range

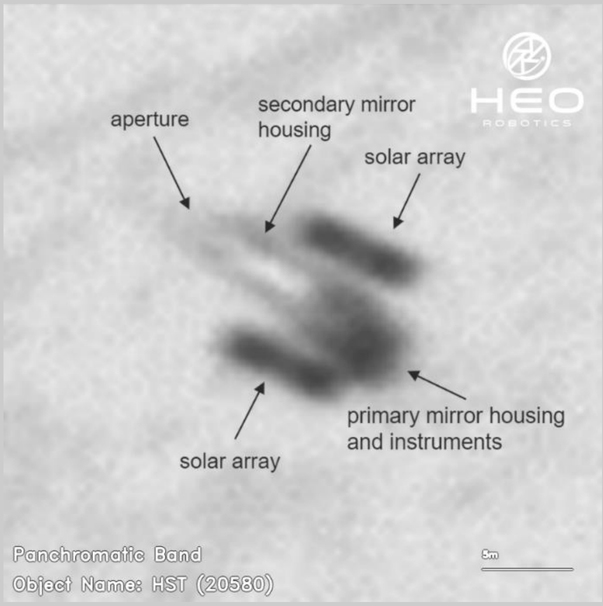


Image capture time: 2023-07-31 10:55:23 UTC

Imaging distance: 93 km

Image plane relative velocity: 12.92 km/s

Image captured in panchromatic band.

The solar arrays are clearly visible. The housing around the primary mirror and instruments appears darker in the image as it is smooth and highly reflective. The aperture door cannot be clearly observed to be opened or closed.

Fig 6: First capture during the experiment period of the HST from a HEO on-orbit sensor

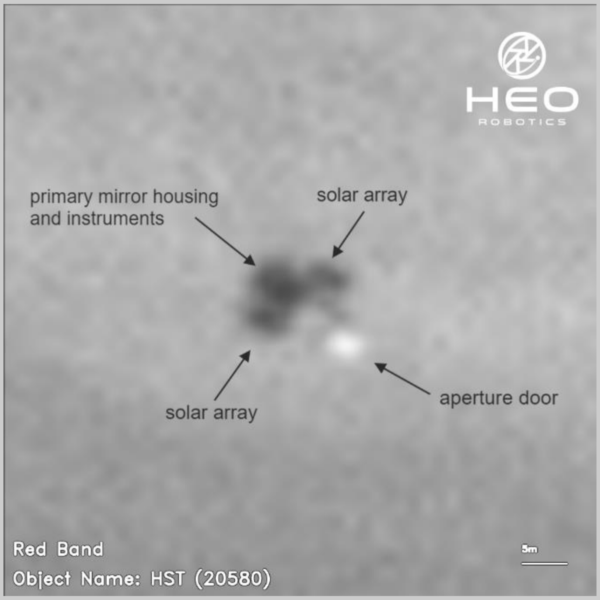


Image capture time: 2023-08-01 12:16:37 UTC

Imaging distance: 165 km

Image plane relative velocity: 13.1 km/s

Image captured in red multispectral band.

The solar arrays are clearly visible. The housing around the primary mirror and instruments appears darker in the image as it is smooth and highly reflective. The aperture door is reflecting sunlight in this image.

Fig 7: Second capture during the experiment period of the HST from a HEO on-orbit sensor

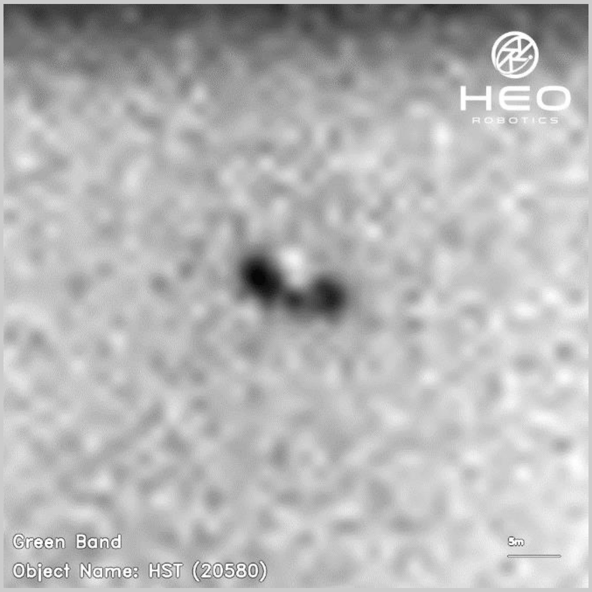


Image capture time: 2023-08-01 13:52:19

Imaging distance: 156 km

Image plane relative velocity: 13.1 km/s

Image captured in green multispectral band.

The HST appears at lower resolution in this image. The solar arrays are likely visible on either side of the telescope.

Fig 8: Third capture during the experiment period of the HST from a HEO on-orbit sensor

Data collected from additional captures is included Table 2.

Table 2: Additional HEO Network Image Captures

Object name	Object ID	Capture time (UTC)	Capture range	Comment
Starlink-30177	57305	2023-07-28 23:34:32	244 km	Both solar panels confirmed to be deployed. Satellite span approx 20m.
BlueWalker 3	53807	2023-07-29 04:22:26	148 km	Deployed antenna observed.
Starlink-30037	55712	2023-08-01 20:03:13	166 km	Both solar panels deployed.
Starlink-30037	55712	2023-08-01 20:03:53	303 km	Image taken 40 seconds after previous image. No change in state observed.

Falcon Neuro & Astrosite Imaging

Fig 9 shows imaging results from Falcon Neuro and the Astrosite. As in Fig 4(b), pixels that detect a change are given a colour that represents the timestamp of the change. The first three RSOs (4882, 15308, and 2431) are tumbling objects recorded with the Astrosite. RSOs 49141 and 49433 were recorded from the ISS by Falcon Neuro. The camera on Falcon Neuro is a DAVIS240C, which has fewer pixels and higher noise levels than the more recent Prophesee Gen4 used on the Astrosite. The two last objects are non-tumbling satellites recorded by the Astrosite. The different colour scheme highlights the different time scale, which is much shorter because these two objects are fast LEOs.

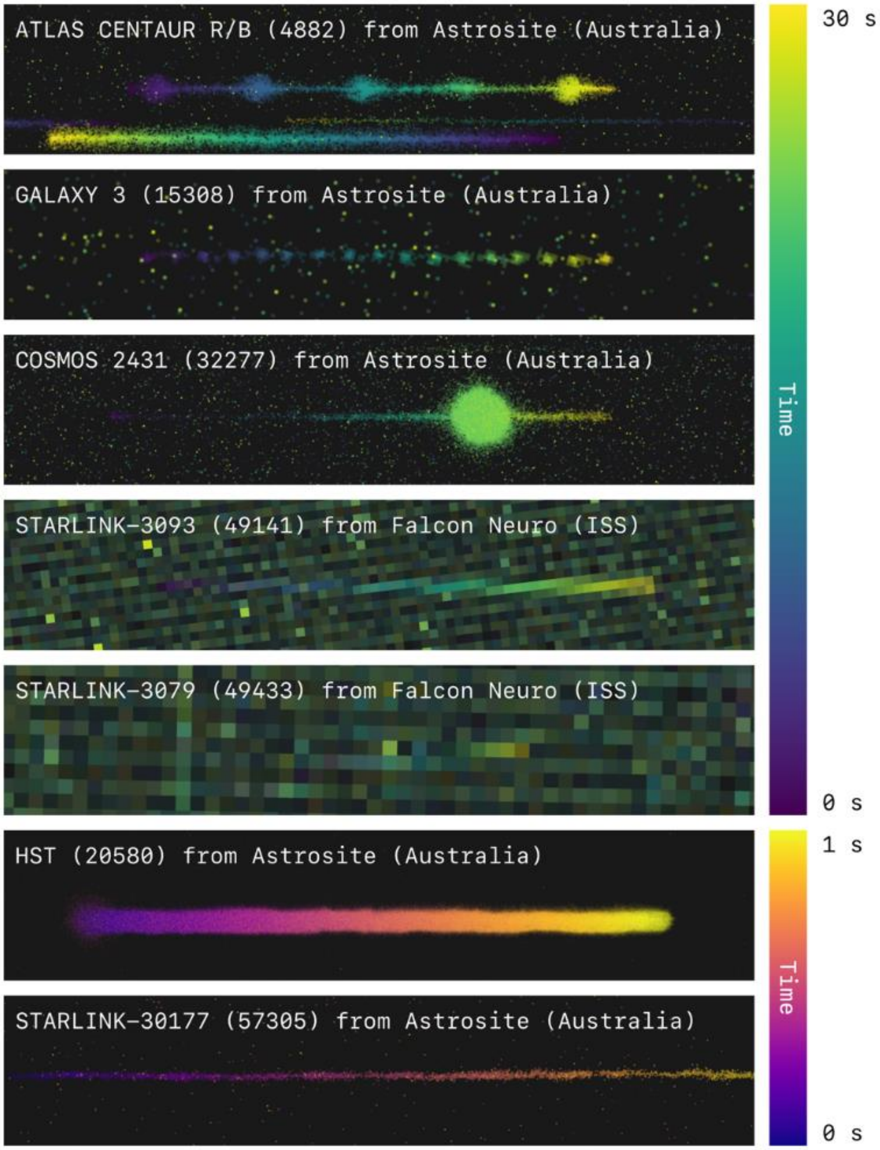


Fig 9: RSOs recorded using Falcon Neuro and Astrosite

Coordinated Space Imaging

During our experiment, our team explored four configurations for coordinated space imaging shown in Fig 10. Our team achieved coordinated imaging in three of the four configurations. The fourth configuration involving three-way imaging was not achieved due to operational limitations on the ISS which significantly limited the Falcon Neuro field of view and reduced the number of opportunities to an impractical level.

Fig 10 shows some additional details on the RSOs imaged as well as the time gap between imaging for that configuration. Analysis is ongoing but we can say that our coordinated space imaging produced important insights, their uniqueness will be the subject of ongoing analysis.

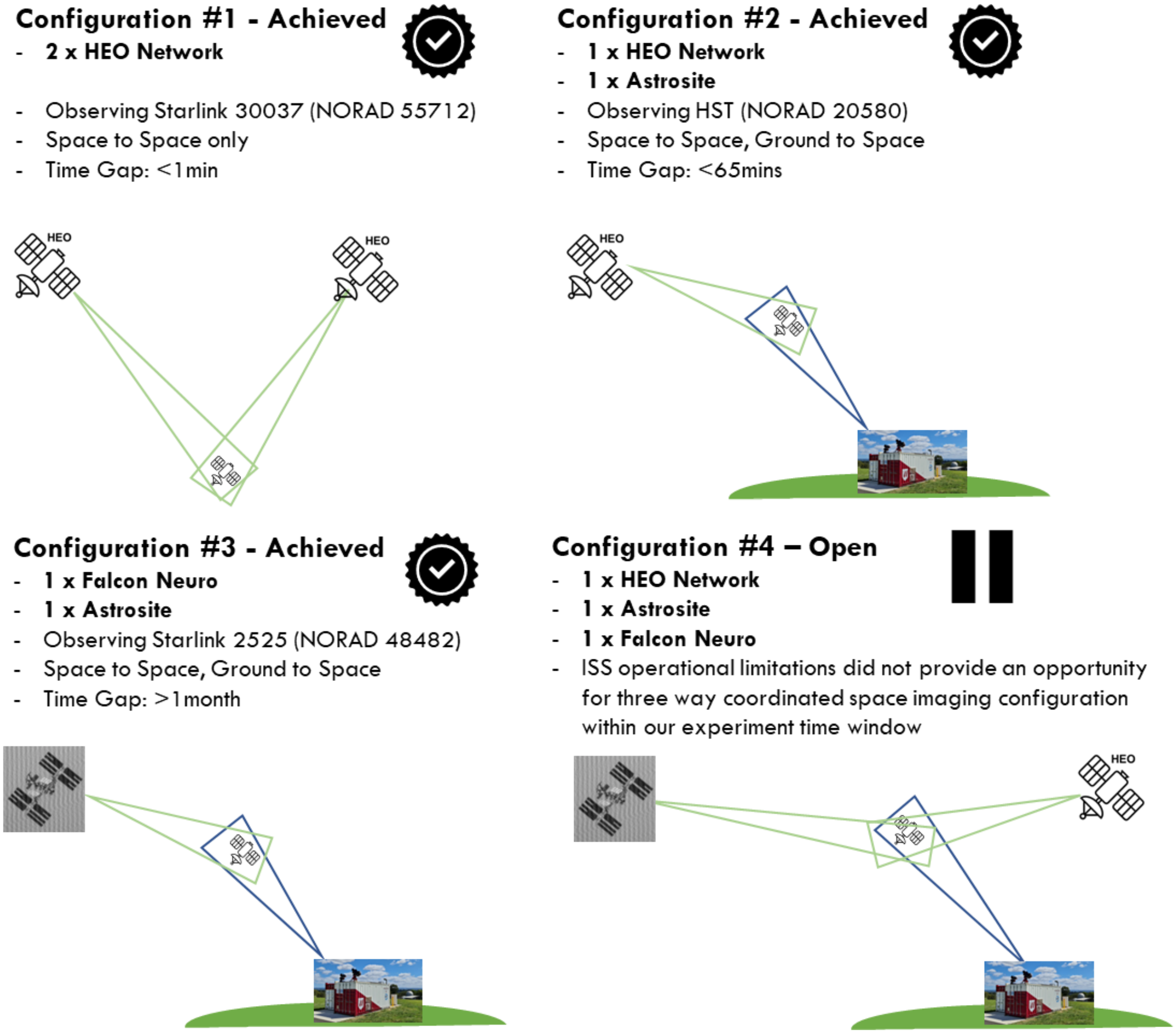


Fig 10: Four Coordinated Space Imaging Experiment Configurations

5. LESSONS

This section discusses the valuable lessons the group gathered whilst conducting this collaborative, coordinated space imaging over the period of a few months.

Architecture

Ackermann [1] and Bloom [2] both discuss the advantages and disadvantages of particular types of assets within an SDA architecture. They also discuss the advantages of architectures that combine ground-based and space-based assets. Whilst both papers focused on the GEO belt and our experiment is focused below 700km, the criteria they use for assessing advantages and disadvantages can easily be adapted to our experiment.

Table 3 summarises our non-empirical evaluation and experiences against our adapted set of criteria.

Table 3: Evaluation of our Experiment Architecture

Criteria	Evaluation
Network Density (Capacity) [2]**:** The extent that network size impacts on number of opportunities. The resilience to impacting events (e.g. weather, down-time etc.). The network architecture characteristic that seeks to increase the number of opportunities through optimised scheduling	• **HEO Network:** The HEO Network size increased the number of overlapping opportunities and increased the resiliency of the architecture. The HEO Network includes 38 sensing satellites with orbital diversity increasing capacity. As the HEO Network grows this will improve. • **Astrosite:** The singular Astrosite limits the number of overlapping opportunities and decreases the resiliency of the architecture due to weather, solar exclusion etc. Additionally, without redundancy there was a small outage on the Astrosite that also limited opportunities. The singular Astrosite limits capacity. This can be improved by increasing the number of Astrosites. • **Falcon Neuro:** The singular Falcon Neuro limited the number of overlapping opportunities and decreased the resiliency of the architecture. Additionally, the operational requirements of the ISS impacted our imaging opportunities. The singular Falcon Neuro limits capacity. This can be improved by having an independent event-based space to space imaging asset(s).
Network Reach (Observability)[3]**:** A network architecture characteristic that defines the extent of the volume that can be observed over a defined period of time, considering factors like solar exclusion	• **HEO Network:** The HEO Network includes 38 sensing satellites with orbital diversity increases observability. As the HEO Network grows this will improve. • **Astrosite:** The singular Astrosite limits observability. This can be improved by increasing the number of Astrosites. • **Falcon Neuro:** The singular Falcon Neuro limits observability. This can be improved by having and independent event-based space to space imaging asset(s).
Timeliness (Initial): The time between deciding a coordinated space imaging request is needed and when it can be fulfilled by the network	• **HEO Network:** The HEO Network includes 38 sensing satellites with orbital diversity lowering the time to initial image for most objects of interest (OOI). As the HEO Network grows this will improve. • **Astrosite:** The singular Astrosite increases the time to initial image for many OOIs. This can be improved by adding Astrosites. • **Falcon Neuro:** The singular Falcon Neuro increases the time to initial image for many OOIs. This can be improved by having an independent event-based space to space imaging asset(s).
Timeliness (Revisit): The time between opportunities for coordinated space imaging	• **HEO Network:** The HEO Network includes 38 sensing satellites with orbital diversity decreasing the revisit time for most OOIs. As the HEO Network grows this will improve. • **Astrosite:** The singular Astrosite increases revisit time. This can be improved by increasing the number of Astrosites. • **Falcon Neuro:** The singular Falcon Neuro increases revisit time. This can be improved by having an independent event-based space to space imaging asset(s).
Weather: The impact of weather of imaging capability	• **HEO Network**: The HEO Network is space-based and immune to weather effects. • **Falcon Neuro:** The Falcon Neuro is space-based and immune to weather effects.

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[2] See Fahrner [3] for further discussion of the capacity concept. Fahrner states "To optimise capacity, we will optimise sensor schedules. To create an intentional schedule of sensors, these sensors must coordinate to determine the best-looking position and dwell time to reach the overall goal. Capacity analysis considers sensor sensitivity, field of view, agility, and quantity to fulfill an objective in a set amount of time.". Again, we apply the concept subjectively. Fahrner also includes a good table describing the differences between Observability Analysis and Capacity Analysis.

[3] Bloom [2] uses Observability, Ackermann [1] uses Sky Coverage Efficiency though it is not clear they are equivalent. Neither provides calculation methods. We apply the concept subjectively.

Criteria	Evaluation
	• **Astrosite:** The Astrosite was limited by weather on several occasions over the period of experimentation. The site was impacted by rain, cloud, and mist. The early morning mist impacted imaging on several occasions. Whilst the Astrosite is portable, the team did not have the opportunity or resources to move it to a more favourable location during the period of the experiment.
Solar Exclusion: The periods when imaging can't be conducted due to the sun	• **HEO Network:** The size of the network and the fact that it is space based helps with solar exclusion. As the HEO Network grows this will improve. • **Astrosite**: The singular Astrosite experiences the expected solar exclusion. This can be improved by increasing the number of Astrosites and providing greater geographic diversity. • **Falcon Neuro:** The space-based location of Falcon Neuro provides some benefit for solar exclusion when compared with the Astrosite. This can be improved by having an independent event-based space to space imaging asset(s).
Illumination: The requirement for the target RSO to be illuminated for successful imaging	• **HEO Network:** The HEO Network includes 38 sensing satellites with orbital diversity which helps provide greater opportunities for correct illumination. As the HEO Network grows this will improve. • **Astrosite**: The singular Astrosite experiences the expected illumination constraints. This can be improved by increasing the number of Astrosites and providing greater geographic diversity. • **Falcon Neuro**: The singular Falcon Neuro experiences the expected illumination constraints. This can be improved by having an independent event-based space to space imaging asset(s).
Background: The backgrounds that support or preclude imaging	• **HEO Network:** The HEO Network can image against a variety of backgrounds including dark space, earth (ocean), earth (land) though for its repurposed Earth Observation satellites the earth (ocean) background provides the best results. • **Astrosite**: The Astrosite images with the night sky as background. • **Falcon Neuro**: Currently Falcon Neuro images satellites best when they are above the earth's horizon. Additional processing needs to be developed to capture images with the earth as background.
Supplier Dependence: The dependence on a 3rd party for conducting imaging	• **Astrosite**: The Astrosite is under the full control of WSU. • **HEO Network:** The HEO Network uses a heterogenous set of suppliers that have lead times for imaging requests. Additionally, there is a risk of task rejection. This occurred on a small number of occasions during the experiment due mostly to lead times being too short. This can be improved by augmenting the existing network with directly controlled assets. • **Falcon Neuro:** Falcon Neuro has two supplier dependencies, USAFA - the operators and the ISS itself. During the experiment, the ISS was realigned for operational purposes which meant the forward-looking "ram camera" was not appropriately aligned for our purposes. This can be improved by having an independent event-based space to space imaging asset(s).
Remote Operations: The ability of the imaging system to be operated remotely without the need for human support at the site	• **Astrosite:** The Astrosite is heavily automated, and most operations are done remotely. The team did not visit the site during the period of the experiment but operated the Astrosite remotely within Australia and from South Africa. The inclusion of South Africa allowed for "follow the sun" operations that improves people's quality of life. • **HEO Network:** The HEO team operates their network remotely and uses automation (APIs) to task satellites within its network. • **Falcon Neuro:** The team did not have the ability to do remote

Criteria	Evaluation
	operations as a 3rd party is required. This can be improved by having an independent event-based space to space imaging asset(s).

The combined ground-based and space-based architecture is an advantage especially regarding the unpredictable nature of weather.

The size, space-based nature and orbital diversity of the HEO network provided significant advantages to our experiment architecture through providing significantly more overlapping opportunities. As the HEO network grows this will only improve. One improvement to the HEO network would be to have some elements that are not reliant on 3rd parties (i.e. under direct control). This would allow later tasking and more degrees of freedom for image capture.

The Astrosite and Falcon Neuro would both benefit from increased numbers in the SDA network architecture to help improve resiliency, redundancy, network reach, network density and timeliness (initial and revisit). Augmenting the Falcon Neuro with directly controlled satellites hosting neuromorphic cameras would also bring strong benefits.

For future experiments, including one of the large commercial SDA networks would be a natural and significant addition to the SDA network architecture. For future architectures, it will be important for designers to balance the key figures of merit including:

- Network Density
- Network Reach
- Timeliness (Initial and Revisit)
- Resiliency

To aid architecture development and balancing capability-cost trade-offs, standard definitions for these figures of merit would help architects. Commercial network providers publishing their figures of merit would go even further to developing balanced, effective architectures for coordinated space imaging.

Imaging & Analytics

As discussed in Section 1 our focus was on “higher level” insights including object identification, object characterisation and object activity. Our experiment included two modes of imaging - CCD-based and Event-based. Both modes of sensing are important for coordinated space imaging insights but equally or more importantly post-imaging analytics are crucial for achieving the required insights.

CCD-Based Imaging and Analytics

SDA generally involves collecting non-resolved data to facilitate orbit determination and determine when two RSOs may be at risk of collision, or when an object will re-enter the Earth’s atmosphere. Typically, these observations are taken from the ground with radar or optical systems.

Space-based resolved imagery adds additional capability through characterisation of an object, including object identification and parameter estimation [16]. Parameters that can be derived from resolved optical images include size, position, attitude, and subsystems present. The amount of information that can be gained from an image, and the certainty associated with the piece of information, depends on the resolution of the camera, the lighting conditions in which the image was taken, the relative position of the target object, the materials that the target object is made from, and the relative velocity of the flyby pass. CCD/CMOS sensors capture high-quality, low-noise images at high frame rates, meaning that even at high relative velocities, resolvable detail can often be distinguished. Though EO cameras have a resolution on the ground on the order of metres per pixel, images taken of RSOs via space-based imaging typically have a more than five-fold improvement in resolution compared to earth imaging due to the closer range from which they are taken. Additionally, the use of CCD/CMOS sensors with wavelength filters allows for materials analysis, as the response in different wavelength bands can be measured. This type of analysis typically requires images with higher spatial and spectral resolution (captured across multiple wavelength bands within a single imaging attempt) than the images obtained during this experiment. The other factors that determine image quality, and the quality of insights from an image, can be addressed through having a constellation of sensors such that ideal lighting conditions and relative positioning can be selected from a large number of opportunities.

This additional information about the physical parameters of an RSO can be combined with post imaging analytics to create more complex SDA data. Resolved images typically require some amount of processing to remove motion blur and noise and increase the image contrast. Within an individual image set, if spectral resolution is achieved, materials analysis can be performed. Measurements of satellite components and the relative orientation of the object can be determined. Over multiple imaging attempts, a pattern of life profile can be established. For example, changes in object configuration and positioning can be recorded over a period of multiple days. This functionality is enhanced by the greater revisit rate of a space-based network compared to a stationary ground-based sensor.

Event-Based Imaging and Analytics

Neuromorphic cameras do not generate frames but a stream of events. Each event contains a timestamp with microsecond precision and the coordinates of the pixel that generated the event. This sparse representation is key to the high temporal resolution and low data rate of neuromorphic cameras, but it poses a challenge in terms of post-processing. The computer vision techniques used to process conventional astrophotography data do not directly apply to events. While events can be converted to frames to use such techniques, the conversion process usually discards part of the temporal information while generating frames that lack important properties for robust source extraction, such as luminance levels.

Better results can be obtained by using dedicated algorithms that directly process the event stream without converting it to frames – although the figures in this paper use frame representation for visualisation purposes. This approach preserves the temporal resolution of the data, which is particularly important to detect short-lived glints (Fig 9) or accurately localise satellites that are moving quickly relative to background stars without relying on telescope mount feedback. The ability to perform simultaneous satellite and star tracking greatly facilitates on-orbit SSA since the same camera can be used for satellite tracking, satellite characterisation (glints), and attitude estimation (star tracking). The low bandwidth and processing requirements of Neuromorphic cameras are particularly interesting for on-orbit SSA since the raw data can easily be streamed to the ground or even directly processed in orbit.

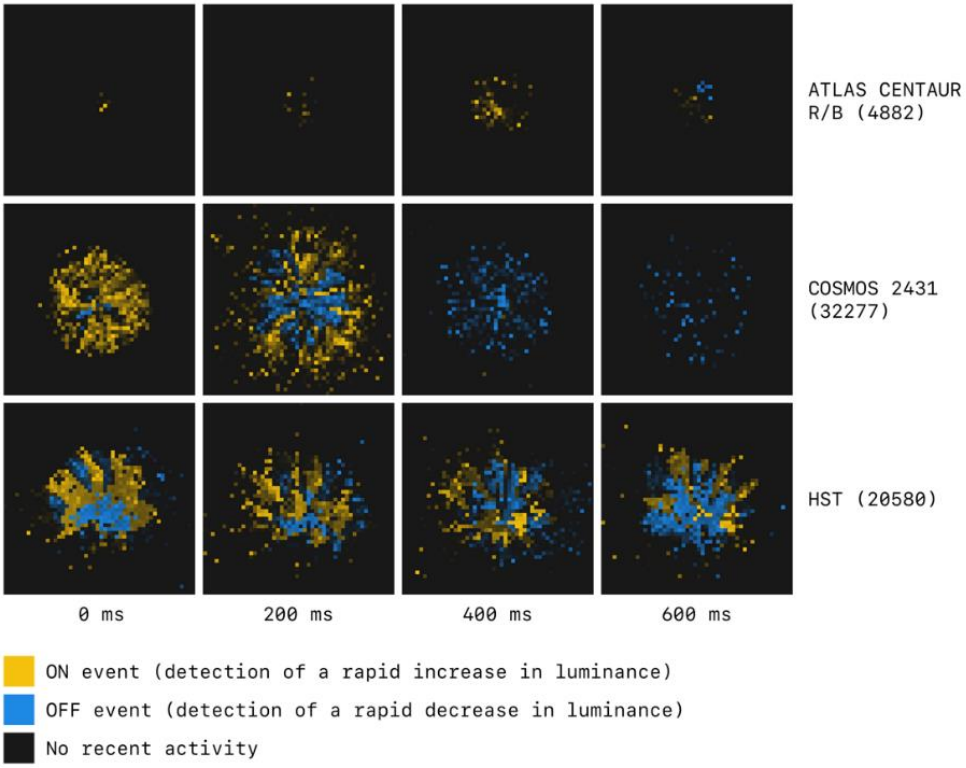


Fig 11: Astrosite Recordings

Besides luminance changes directly caused by the satellite (entire body rotation, solar panels rotations, or hatch movement revealing bright objects), neuromorphic cameras also detect scintillation – that is, luminance changes caused by atmospheric perturbations (Fig 11). This information can be used to implement adaptive optics solutions to improve the image quality of more conventional sensors. It may also contain information that can be used for satellite fingerprinting, assuming that the object is close enough to have a spatial extent that impacts the diffraction pattern. However, scintillation poses a challenge for high-frequency glints detection because the two phenomena can have a very similar appearance. Coordinated observations from other ground locations can be used to minimise the impact of scintillation by searching for correlations in the signals. Likewise, observations from space from other sensor types can provide valuable corroborative evidence.

Fig 11 shows high-luminosity objects recorded from the ground with Astrosite over short time periods, showing diffraction and atmospheric perturbations. Neuromorphic cameras do not measure absolute luminance but detect quick luminance changes. The resulting event stream's temporal resolution is high enough to monitor the evolution of atmospheric perturbations. The two first recordings show glints from tumbling objects whereas the third recording shows the non-tumbling Hubble Space Telescope. In both cases, the Neuromorphic camera recorded complex patterns that quickly evolve over time.

Mission Management

Initially, we planned to use the Raytheon mission management suite from the beginning of this experiment, but several elements precluded this from occurring. The mission management software would have allowed for greater automation of mission planning, opportunity assessment, visibility timelines, developing COA (including for example, mitigations for weather events), scheduling, tasking, status, and reporting. The plan was to interface to a HEO developed REST API that allows for machine-to-machine exchange of the information including opportunities, tasking, status, and imaging reports. Instead, for the current experiment, the activities were manual with humans in the loop exchanging information via email and the HEO API remains ready for future integration and experimentation. Ultimately, we intend to use our full Raytheon mission management suite that includes:

- **Cross Domain Mission Management (XDM)**: XDM will do the *operational coordination* and *enterprise orchestration*. This functionality includes opportunity assessment, visibility times, recommending courses of action (COA) and coordinating (tasking, scheduling) the different sensor modalities. Fig 12 shows the current experiment and the longer-term mission management vision where these commercial sensors would be integrated with sovereign assets and an overarching *enterprise orchestration* capability. This simplistic view ignores the complications of prioritising the experiment's requests against the existing schedules for each sensor. It highlights the C2 aspect, rather than the *data processing*, *event processing* and *analytics* that are needed at the end of the Task, Collect, Process, Exploit, and Disseminate (TCPED) process.
- **Space Threat Assessment Tool (STAT)**: STAT (Fig 13, Fig 14, Fig 15) has a wide feature set but in this paper, we discuss its use in coordinated space imaging:
    - **Imaging Visualisation:** STAT creates visualisations (Fig 13) using the open source Cesium.js. This visualisation supports observation of sun angles in real time, in combination with the ground visibilities. This allows for tightly coordinated observations times and/or to maximise the information value of each collection.
    - **Imaging Visibility Assessment:** STAT computes visibilities from multiple platforms including constraints such as desired sun angles to get the correct lighting. STAT also does detailed visibility analysis between selected RSOs. Fig 14, Fig 15 show screenshots of this analysis for the ISS and Starlink 30037 which was one of the satellites that was imaged by both Astrosite and the HEO Network.
    - **Imaging Angle Assessment:** STAT uses sun angles, time of closest approach (TCA) and relative motion to determine when the best time is to take images. TCA alone might not be the optimal due to the angles. STAT helps determine if more or less altitude will achieve the angle required. The STAT plots shown in Fig 13, Fig 14, Fig 15 help the operator make this assessment.

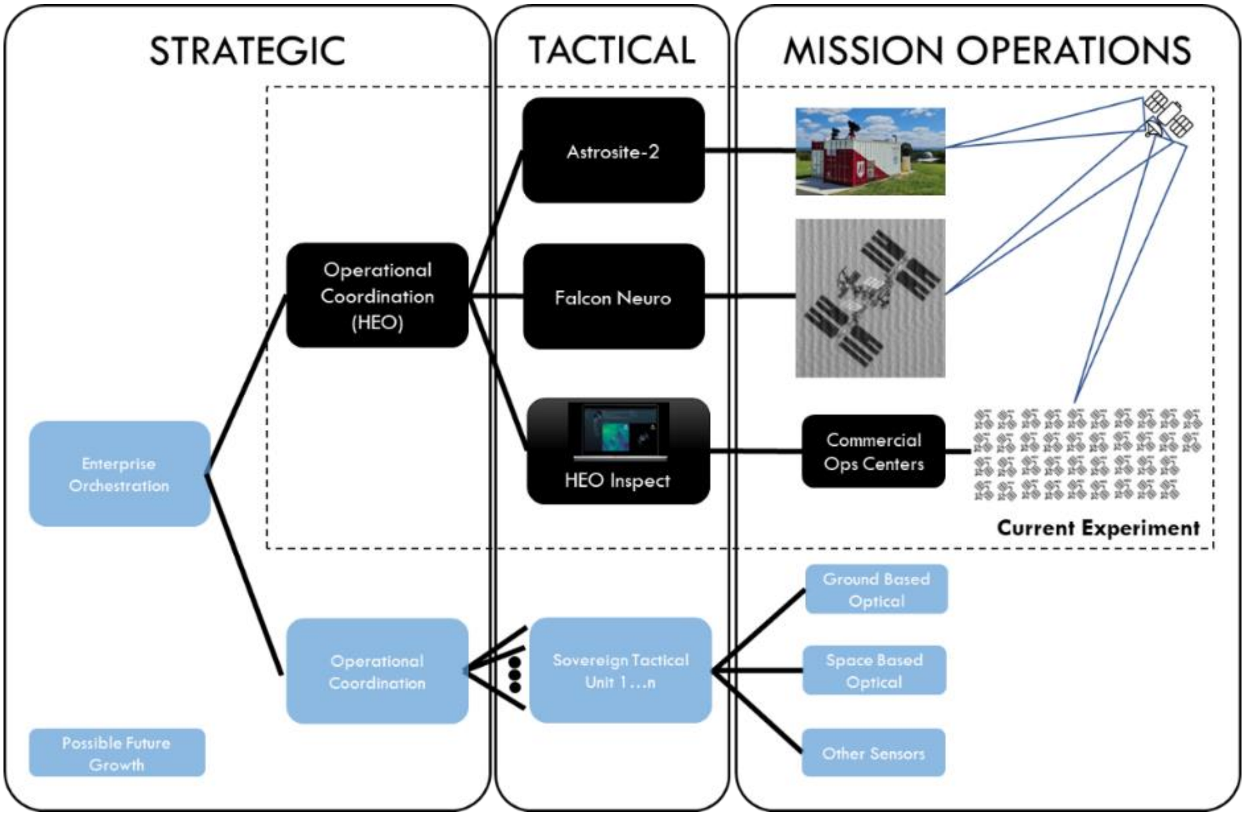


Fig 12: Current experiment along with potential future integration points

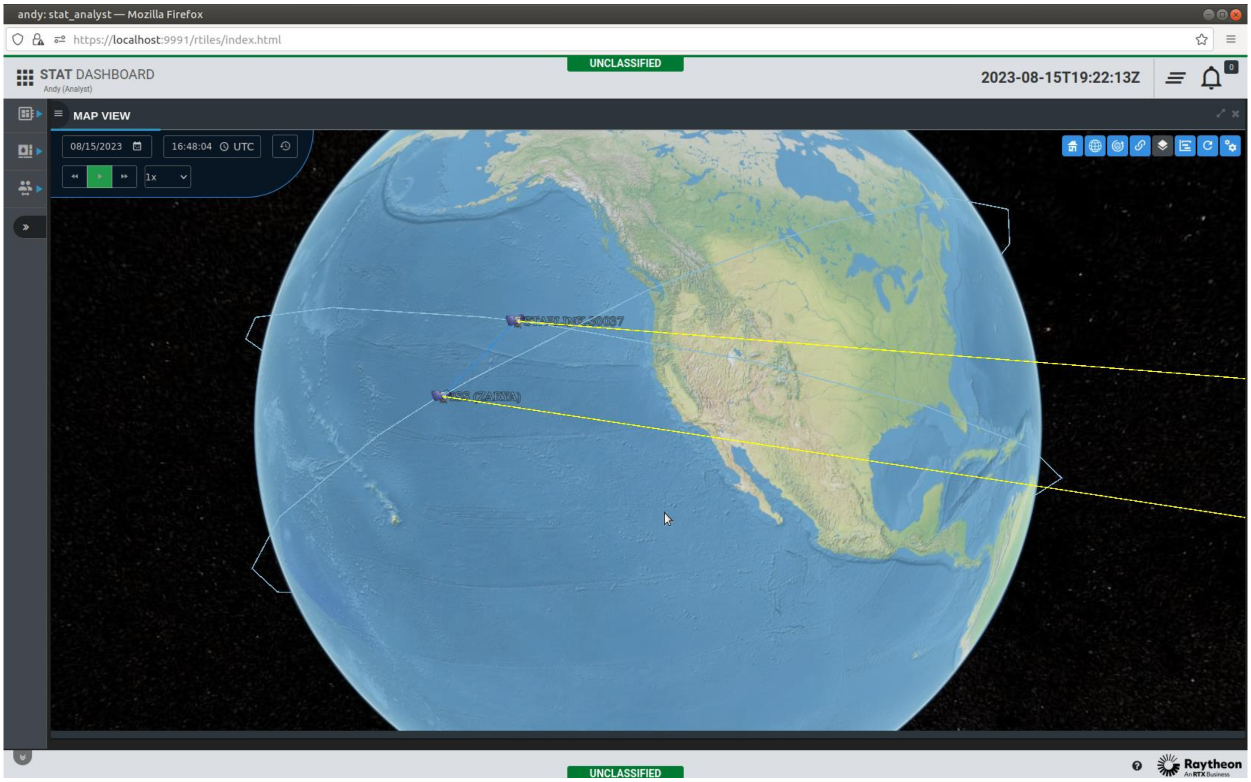
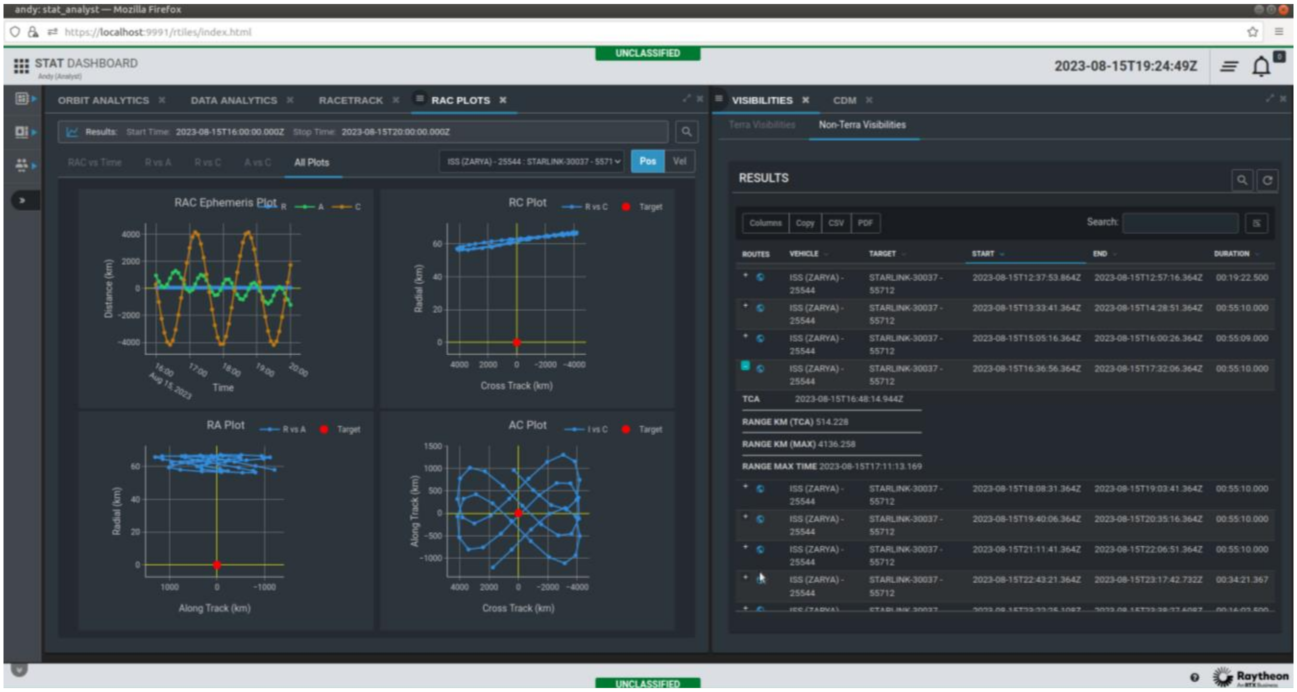


Fig 13: STAT View ISS and Starlink 30037 – Visualisation of relative position in 3D



Results: Start Time: 2023-08-15T16:00:00.000Z Stop Time: 2023-08-15T20:00:00.000Z

RESULTS

ROUTES	VEHICLE	TARGET	START	END	DURATION
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T12:37:53.864Z	2023-08-15T12:57:16.364Z	00:19:22.500
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T13:33:41.364Z	2023-08-15T14:28:51.364Z	00:55:10.000
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T15:05:16.364Z	2023-08-15T16:00:26.364Z	00:55:09.000
−	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T16:36:56.364Z	2023-08-15T17:32:06.364Z	00:55:10.000

TCA 2023-08-15T16:48:14.944Z

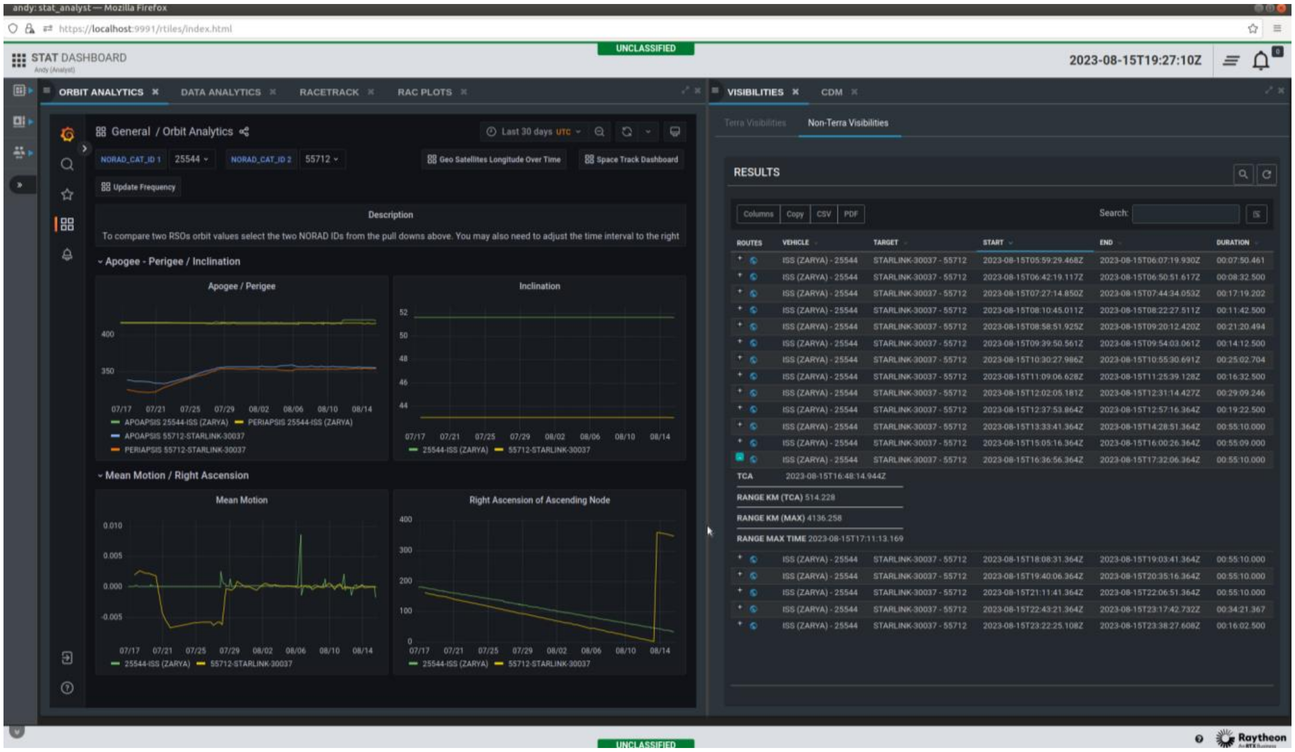
RANGE KM (TCA) 514.228

RANGE KM (MAX) 4136.258

RANGE MAX TIME 2023-08-15T17:11:13.169

ROUTES	VEHICLE	TARGET	START	END	DURATION
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T18:08:31.364Z	2023-08-15T19:03:41.364Z	00:55:10.000
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T19:40:06.364Z	2023-08-15T20:35:16.364Z	00:55:10.000
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T21:11:41.364Z	2023-08-15T22:06:51.364Z	00:55:10.000
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T22:43:21.364Z	2023-08-15T23:17:42.732Z	00:34:21.367

Fig 14: STAT View ISS-Starlink 30037 - Radial, along-track, cross-track (RAC) distance



To compare two RSOs orbit values select the two NORAD IDs from the pull downs above. You may also need to adjust the time interval to the right

RESULTS

ROUTES	VEHICLE	TARGET	START	END	DURATION
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T05:59:29.468Z	2023-08-15T06:07:19.930Z	00:07:50.461
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T06:42:19.117Z	2023-08-15T06:50:51.617Z	00:08:32.500
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T07:27:14.850Z	2023-08-15T07:44:34.053Z	00:17:19.202
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T08:10:45.011Z	2023-08-15T08:22:27.511Z	00:11:42.500
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T08:58:51.925Z	2023-08-15T09:20:12.420Z	00:21:20.494
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T09:39:50.561Z	2023-08-15T09:54:03.061Z	00:14:12.500
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T10:30:27.986Z	2023-08-15T10:55:30.691Z	00:25:02.704
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T11:09:06.628Z	2023-08-15T11:25:39.128Z	00:16:32.500
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T12:02:05.181Z	2023-08-15T12:31:14.427Z	00:29:09.246
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T12:37:53.864Z	2023-08-15T12:57:16.364Z	00:19:22.500
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T13:33:41.364Z	2023-08-15T14:28:51.364Z	00:55:10.000
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T15:05:16.364Z	2023-08-15T16:00:26.364Z	00:55:09.000
−	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T16:36:56.364Z	2023-08-15T17:32:06.364Z	00:55:10.000

TCA 2023-08-15T16:48:14.944Z

RANGE KM (TCA) 514.228

RANGE KM (MAX) 4136.258

RANGE MAX TIME 2023-08-15T17:11:13.169

ROUTES	VEHICLE	TARGET	START	END	DURATION
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T18:08:31.364Z	2023-08-15T19:03:41.364Z	00:55:10.000
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T19:40:06.364Z	2023-08-15T20:35:16.364Z	00:55:10.000
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T21:11:41.364Z	2023-08-15T22:06:51.364Z	00:55:10.000
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T22:43:21.364Z	2023-08-15T23:17:42.732Z	00:34:21.367
+	ISS (ZARYA) - 25544	STARLINK-30037 - 55712	2023-08-15T23:22:25.108Z	2023-08-15T23:38:27.608Z	00:16:02.500

Fig 15: STAT View ISS and Starlink 30037 - Comparison of orbital characteristics

6. FUTURE WORK

There are several avenues of future work for coordinated space imaging including:

- **Mission Management:** Full deployment of the Raytheon mission management suite with machine-to-machine interfaces to the HEO Network, Astrosites, Falcon Neuro and future capabilities will improve efficiency and effectiveness of the overall SDA system.

- **Future Optical Assets:** The number of assets in the SDA architecture is a critical characteristic. Adding ground-based and space-based assets will improve the effectiveness of the overall SDA system. These might include:
    - **Astrosite:** Additional Astrosites with greater geographic diversity, ideally in select sites across the globe.
    - **Falcon ODIN:** The higher resolution Falcon ODIN is in the process of being build, tested, and deployed to the ISS [17]. This capability will bring additional insights for SDA and other applications.
    - **HEO Network:** Future experiments could take advantage of HEO's growing network.
    - **Space to Space Optical SDA Mission:** To overcome the supplier dependency challenges, a small form factor space to space optical SDA mission could be considered. This could combine both the WSU designed neuromorphic (event-based) space to space imager with the HEO designed CCD space to space imager which is undergoing commissioning at this time [18]
    - **Ground-based Commercial Networks:** To increase the network reach and density a commercial ground-based optical provider could be added to the SDA architecture.
- **Longer Timeframe Analytics**: A focus on coordinated space imaging over the longer timeframe "story-based" requires further study and is likely to reap significant SDA insights.
- **Future Interoperability:** As the industry matures, it will be important to define interoperability standards between sensors/sensing networks and mission management systems. Unlike existing interoperability approaches in SDA this should focus on mission planning, opportunity availability reporting, tasking, status, and results reporting. The HEO API provides an example. It uses open standards and could be used to inform such a development. Its REST implementation does have limitations, but it is an excellent foundation. Alternatives should be considered including:
    - **Protocol Buffers**: Protocol buffers (protobuf) with its in-built *optional* interface elements for improved backward compatibility and language/transport agnosticism is a good alternative.
    - **GraphQL**: GraphQL is a newer interface approach that supports concepts, for example, interface queries which lowers the amount of data being exchange between software.

7. CONCLUSION

So "Can coordinated space imaging provide unique and important insights?" Analysis is ongoing but we can say that our coordinated space imaging produced important insights, their uniqueness will be the subject of ongoing analysis.

Coordinated space imaging is certainly difficult. For it to be successful and provide the unique and important insights required in our congested, contested, cluttered space environment it will require:

- Combined ground-based and space-based SDA architectures designed to create the right balance of network density, network reach, timeliness, and resiliency.
- Multi-modal imaging and analytics with a focus on high spatio, temporal and spectral resolution imagery.
- A mission management system that can best coordinate the assets available in the SDA architecture.

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