The Use and Calibration of Opportunistic Sensors for In-Space Situational Awareness

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ABSTRACT

Spaceborne sensors onboard operational satellites present an opportunity to be repurposed for Space Situational Awareness (SSA) observations, for example, Astroscale's ELSA-d satellite which has completed its main mission phase and is fitted with an off-the-shelf camera. Depending on the functionality of a given satellite and sensor, different observation planning methods and calibrations are required. Opportunistic sensors on satellites are potentially degraded due to radiation, may be onboard a satellite with little to no attitude control and in the utilisation of these sensors for SSA these factors must be considered to create useful data. We present objectives for the operation of repurposed spaceborne sensors to perform SSA activities with a view towards expanding the number of sensors in orbit observing and monitoring the space environment. These methods can also inform the potential outputs from the addition of simple sensors to future missions to increase the SSA/SDA capabilities from orbit.

1. INTRODUCTION

Year on year, the space environment is becoming more crowded than ever before with no signs of this congestion slowing down. With this increase in the population of satellites, monitoring the space environment is highly important to minimise the risk of collision with active satellites, debris and meteoroids. To this end, Space Situational Awareness (SSA) is required to characterise the objects present, identify changes and assess collision risks. The data required to assess the orbital environment is predominately obtained through ground-based observations using radar, optical telescopes and laser ranging. Using these observations, it is possible to track Resident Space Objects (RSOs) accurately and predict their future positions, allowing for collision risk assessments to take place.

SSA observations can be augmented with further observations from space-based sensors to perform In-Space Situational Awareness (ISSA). Repurposing sensors requires the definition of new objectives or requirements of the system. The Cross Government Space Domain Awareness (SDA) Requirements Publication, released in 2023, defines the UK SSA requirements for Space Surveillance and Tracking (SST) [1]. The requirements underpin the civil and military dual-use SDA systems. The inclusion across various sectors in this publication indicates the importance of making full use of opportunities to generate and integrate SSA data across many partners.

Spaceborne sensors can be repurposed to perform ISSA observations, for example, the End of Life by Astroscale – demonstrator (ELSA-d). This spacecraft, launched in 2021, performed a demonstration of Astroscale's Rendezvous Proximity Operation (RPO) capability. This satellite consisted of two spacecraft, a servicer and client, connected using a ferromagnetic docking plate. Following the main mission phase and separation of the client from the servicer spacecraft, the servicer has been used as a test platform for basic ISSA observations [2]. This is making use of the visible camera (VISCAM) from the RPO sensor suite.

The Active Debris Removal Astroscale – Japan (ADRAS-J) satellite is a spacecraft selected by the Japanese Aerospace Exploration Agency (JAXA) to perform inspection of large debris, with the end objective to remove that debris from orbit. Scheduled for launch in 2023, this satellite is an ISSA mission to inspect a Japanese upper stage rocket body. This inspection is to demonstrate RPO capabilities and to obtain images to assess the suitability of the rocket body for Active Debris Removal (ADR). The close-in inspection of a debris object is not possible to achieve from ground-based observations alone, hence an in-situ mission to examine the satellite is required, especially for an object that has been exposed to the space environment for an extended period.

The Astroscale Cleaning Outer Space Mission through Innovative Capture (COSMIC) is a mission to remove two defunct British satellites, launching in 2026. This mission will host an ISSA payload to investigate using space-based observations as a secondary payload to observe RSOs. As a secondary payload, the ISSA payload will have minimal impact on the overall mission design and operations. Thus, the payload will be to investigate the use of opportunistic imaging and explore the outputs of such imaging in addition to the impact the payload will have on the overall mission.

Through these missions, Astroscale is expanding its capability in ISSA to aid in the accumulation of accurate information on the state of a client object before performing ADR or In Orbit Servicing (IOS). A sensor suite required for RPO can be utilised for ISSA observations and become dual-purpose sensors. Additionally, satellites possess numerous sensors onboard, with optical cameras and star trackers being commonplace, presenting a prime opportunity to use these spaceborne sensors to perform ISSA observations.

ISSA observations can ameliorate the SSA data obtained through ground-based observations by overcoming some limitations. Effects due to the atmosphere are not present in orbit and the range to an observation target is reduced. Expansion of the temporal and spatial diversity of observations is a benefit of having no reliance on the regular day/night cycle on Earth, although satellites experience eclipses. A space-based observer gains a different observation geometry and timing than ground-based observations, creating opportunities for different surfaces or illumination conditions of RSOs to be observed. Approximately 68% of the Earth's landmass is located in the Northern hemisphere, thus limiting the geographical diversity of SSA sensor locations [3]. Utilising in-orbit observations can mitigate this bias on observation location.

In assessing the tumble rate of objects, this is primarily done through optical observations of the object of interest and creating a time series of the brightness observed termed a 'light curve.' Depending on shape of the RSO, the observations can be limited to estimating the tumble rate of the object along the in-track and cross-track directions leaving rotation about the radial axis (Fig.1) uncertain, especially if the object is stabilised and symmetrical. There can also be uncertainty in estimating the shape of the object [4]. Different viewing angles made available by space-based sensors can create opportunities to determine rotation about the radial axis for such objects. This change in viewing angle may present opportunities to better identify the characteristics of a given object by expanding the range of solar phase angles and spacecraft faces that could be observed [5].

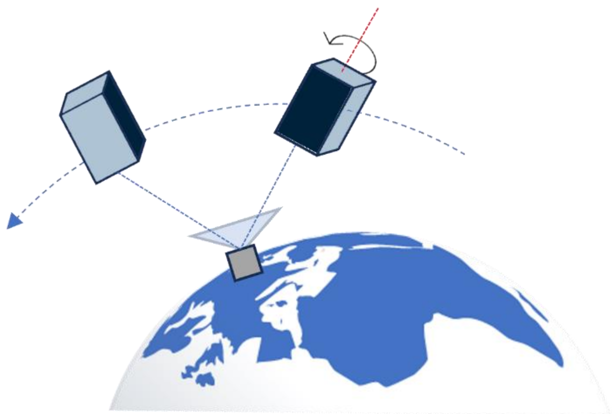

Fig. 1. Example illustration of the difficulty to use ground-based observations to determine the rotation about the radial axis on a symmetrical or cuboid satellite.

Sensors of opportunity, such as VISCAM on ELSA-d, are valuable to investigate their potential to gather ISSA data. This study investigates the definition of "useful" ISSA data and defines them as objectives. Subsequently, two cameras are chosen for comparison of their opportunistic use against these objectives; a basic, repurposed camera (VISCAM) and a purpose designed SSA camera. Scenarios in which a satellite has full attitude control, and no attitude control are used to examine the potential utility of repurposing a camera in either scenario. In this study, only optical sensors of visible wavelengths were considered.

2. METHOD

Several assessment criteria were gathered to determine the likelihood of a successful observation with a given configuration of camera and satellite parameters. The criteria were taken from Brydon et al. 2022 as Astroscale's previously identified ISSA objectives [2]. These were re-examined to ascertain if they are appropriate for only optical sensors. Additionally, they have been updated with requirements from the Cross Government SDA Requirements Publication.

These assessment criteria are then used to investigate various scenarios for their capability to produce useful ISSA data. The scenarios are based upon a basic, off-the-shelf engineering camera, using the VISCAM onboard ELSA-d as an example, and a purpose built SSA camera. Following this, the satellite capabilities are defined with varying limitations that would affect SSA observations, such as limited slewing capability or low pointing accuracy. Both cameras applied in the various satellite configurations are assessed against the different criteria defining useful ISSA observations.

ISSA Objectives

The previous seven objectives identified by Brydon et al. 2022 were as follows:

I. Object Detection
II. Catalogue Large Objects
III. Targeted Tracking
IV. Unresolved Target Characterisation
V. Flyby Resolved Imaging
VI. Stand-off Resolved Imaging
VII. Short-Range Resolved Imaging

Objectives VI and VII are both objectives at short ranges, at most, tens of kilometres. The range at which an objective is achievable influences the potential number of objectives a single camera can achieve as performing short range observations requires a shorter focal length. This necessitates different focal lengths for the distance at which observations will take place. This is an update on the previous objectives as clarity is required in the list to have long-range and short-range objectives as they cannot be achieved with a single camera.

Since the inception of these objectives, the UK Cross Government SDA Requirements Publication has been released identifying the current desirable capabilities by the UK which can be used to assess the interest in various products [1]. Within this publication, there are requirements that can be added to the current objectives to augment the current estimation of useful SSA data. The requirements selected for addition to the SSA objectives were chosen based on their relevance to optical space-based observations.

The requirement UKSDA-SR-1300 addresses the revisit rate of given objects [1]. This requirement states that the UK SST data shall have sufficient minimum revisit rates for Routine Priority RSOs. Through revisiting RSOs, better estimations of their orbits can be determined and hence this is of interest when assessing the utility of an ISSA sensor.

An additional data type is identified in requirement UKSDA-SR-4900 in which the SST data shall comprise time series photometry data to enable satellite characterisation [1]. This type of photometry data can be used to ascertain the tumble rate of an object. As the object tumbles, the reflected light varies in intensity given the change in the satellite face with respect to the observer. Previously, this sort of assessment was included within object characterisation (objective IV), but with the updated requirements these are explicitly separate. Obtaining photometry data is a different observation strategy than that of object characterisation and hence, objective IV is changed to ‘Unresolved Target Photometric Observation.’

A clarification of characterisation is obtained through requirement UKSDA-SR-7300 of object characterisation [1]. Although mentioned in Table 1, the characterisation of the rotation rate and axis of an object can be obtained through many means, such as through photometric observations and through live videos. Therefore, the characterisation of the rotation rate and axis can remain under a new objective of ‘Object Characterisation’ which comprises the characterisation requirements as defined in the UK SDA Requirements Publication.

Table 1: Various properties that can be considered characteristics of an RSO [1].

Requirement	Characterisation Property
UKSDA-SR-7301	Object Active/Inactive
UKSDA-SR-7302	Status Change Detection
UKSDA-SR-7303	Rotation Rate & Axis
UKSDA-SR-7304	Identification of Satellites (NORAD/COSPAR ID)
UKSDA-SR-7305	Attitude Determination
UKSDA-SR-7306	Mass
UKSDA-SR-7307	Physical Dimensions
UKSDA-SR-7308	Material Properties (e.g. Albedo)
UKSDA-SR-7309	Conjunction Avoidance Capability Assessment
UKSDA-SR-7310	Identification of Satellite Type/Class e.g. bus type
UKSDA-SR-7311	Satellite Payload Identification
UKSDA-SR-7312	Capability Assessment
UKSDA-SR-7313	Orbital Changes and Manoeuvres
UKSDA-SR-7314	Fault/Anomaly Detection
UKSDA-SR-7315	Payload Activity
UKSDA-SR-7316	Associated Signals (i.e., RF etc.)

Following the updates and clarifications to the objectives made using the UK SDA Requirements Publication, leads to the updated the ISSA objectives:

I. Object Detection
II. Catalogue Large Objects
III. Targeted Tracking
IV. Unresolved Target Photometric Observation
V. Flyby Resolved Imaging
VI. Stand-off Resolved Imaging[1]
VII. Short-Range Resolved Imaging[1]
VIII. Object Characterisation[2]
IX. Revisit Rate

[1]Requires a shorter focal length

[2]Characterisation property dependant focal length

Cameras

For this study two cameras were chosen as examples against which the suitability of the scenario to the observation objectives could be assessed: the ELSA-d VISCAM and a purpose-built SSA camera. Throughout this report the cameras are assumed to have the appropriate focal length for the purpose for which they are being assessed. For application, the focal length of the camera must be known prior to choosing which objectives to target as this will limit the camera to either long or short-range observations.

The first camera, herein referred to as the "simple camera," is based on the ELSA-d VISCAM. This is a visible wavelength camera that was designed for observing the client object to be released by ELSA-d to perform an RPO demonstration (Fig. 2). It is a simple engineering camera with the intended lifetime of the camera being short. This camera has a 51° field of view and 480 x 640 pixels. It has been in orbit for over two years with no radiation hardening, which was not required for the mission, leading to numerous hot pixels present on the sensor. The camera does not have a baffle as it was to operate close to the imaging target. Such a camera is an example of an off-the-shelf camera, designed for an alternative purpose or can be indicative of a repurposed star tracker, depending on the capability of the particular star tracker.

Fig. 2. Left: ELSA-d servicer and client spacecraft with the long-range and short-range cameras circled in red. Right: The Malin Space Science Systems ECAM-C50/M50 which is used as an example in this study [6].

The second camera, herein referred to as "high resolution camera," is based on the Malin Space Science Systems ECAM-C50/M50, shown in Fig. 2, as an example of a camera that is purpose-built for ISSA observations [6]. This is also a visible camera with a higher resolution of 2592 x 1944 pixels. This camera is designed for a radiation environment of five years in Geostationary Orbit (GEO). A baffle is available on this camera to reduce the impact that stray light from the Sun, Earth and Moon has on the observations and the observing time. As the ECAM camera is designed with ISSA as an application, this camera has a higher resolution and longer lifetime than the ELSA-d VISCAM, thus will be used as an example of a high-resolution ISSA camera in this study.

Another design by Flohrer et al. (2005) was considered as a potential example camera designed for ISSA, but this camera is optimised for small debris and hence would not be applicable to our assessment criteria [7]. There was potential to consider repurposed Earth Observation (EO) sensors as these are typically high-resolution and abundant. This was not investigated in this study as the comparison to the simple camera would not be directly applicable as many EO sensors can be multispectral and only possess long focal length options.

Satellite Capabilities

As this paper is deals with ISSA sensors of opportunity, an evaluation of the capabilities of a given satellite is required as the satellites may have various capabilities depending on the point in the satellite lifetime that the sensor is to be repurposed or made dual use. In this study, the satellite capability is defined by the property that has the largest impact on the ISSA objectives - the slewing capacity of the satellite. We also use an idealised satellite with full attitude control/slewing capability as a control.

A satellite with little to no slewing capability may occur for a number of reasons. Tracking data on satellite anomalies from SpaceTrak showed that out of 7,060 spacecraft 120 experienced failures that could lead to a loss of attitude control. Another circumstance causing a lack of slewing capability for an ISSA payload could be due to a primary mission requiring no additional manoeuvres for ISSA purposes, such as the COSMIC mission. As the ISSA payload is a secondary payload, the slewing capabilities during the main mission phase is limited and at times unavailable.

The various combinations of camera and satellite specifications are assessed for their capability to address the ISSA objectives. Considerations for specific hardware constraints are discussed and the various potential observation strategies for the objectives are examined.

3. RESULTS & DISCUSSION

Investigating the scenarios required an evaluation of a given camera and satellite configuration with respect to the nine ISSA objectives. The following discussion is laid out based on the camera type first and the subsequent achievable ISSA observations based on the satellite. Table 2 shows the objectives that each configuration can address with the full attitude control high resolution camera performing the best and the basic camera with no slewing capability only capable of object detection.

Table 2. Capabilities of satellites with and without slewing capabilities with a basic camera (ELSA-d) and a high-resolution camera.

ISSA Observation Objectives	Full Attitude Control		No Slewing Capability	
	Basic camera (ELSA-d)	High-resolution camera	Basic camera (ELSA-d)	High-resolution camera
Object Detection	✓	✓	✓	✓
Catalogue Large Objects	✓	✓	✗	✓
Targeted Tracking	✗	✓	✗	✗
Unresolved Target Photometric Observation	✗	✓	✗	✓
Flyby Resolved Imaging	✗	✓	✗	✗
Stand-off Resolved Imaging[1]	✗	✓	✗	✗
Short-Range Resolved Imaging[1]	✓	✓	✗	✗
Object Characterisation[2]	✓	✓	✗	✗
Revisit Rate	✓	✓	✗	✗

[1]Requires a shorter focal length

[2]Characterisation property dependant focal length

Basic Camera

The basic camera, based on the VISCAM from ELSA-d, is a simple, off-the-shelf camera that could potentially be onboard any contemporary satellite. This could also include star trackers depending on their exact specifications if they could be adapted for use as an ISSA sensor. The physical specifications of the camera designed for a short lifetime, result in a camera that is not radiation hardened, without a baffle and the camera lens has some artifacts that are apparent in the images. The lack of radiation hardening leads to the accumulation of hot pixels on the sensor of the camera. These are pixels in which the charge stored in each pixel has increased and not returned to a nominal level as the new charge caused by the radiation damage remains in this pixel [8]. These can appear in images as bright pixels and can be misinterpreted as stars.

The absence of a baffle on the camera limits the use of the camera to those windows where the Sun is out of the field of view and at angles where the sunlight cannot be refracted into the lens and the sensor, leading to saturation of the sensor. The camera artifacts present have been noted previously in [8], where the presence of these features in images is consistent and repeated due to defects or dirt on the lens. Typically, corrections are applied in post-processing to remove this by way of flat field correction. This is a method regularly used in astronomy to remove any lens defects before observations by using a uniformly illuminated field to identify lens characteristics for future removal. Although effective, this method relies heavily on the image of a field uniformly illuminated, which is not something present in space.

This basic camera onboard a fully operational satellite with opportunity to operate as an ISSA observation platform can achieve the objectives of object detection, large object cataloguing and short-range resolved imaging (Table 2). As has been shown before with ELSA-d, the camera is capable of imaging objects as they pass through the field of view and can perform targeted observations of objects at given points in time [8]. At short-range, this type of camera can obtain resolved images of a client object, which has also been demonstrated with the ELSA-d satellite.

On a satellite that has no slewing capabilities, the only objective this type of camera would be capable of realising is object detection (Table 2). This would rely on opportunistically imaging objects that enter the camera field of view. This can either be imaging at unspecific intervals or imaging to align the timing with an object traversing the field of view. In this scenario, it would be likely that the object would be captured as a streak in the images.

ISSA Camera

The purpose designed ISSA camera can achieve every objective when paired with a fully functional satellite, although the long and short-range objectives require different focal lengths. Similar to the basic camera, object detection, large object cataloguing, and short-range resolved imagery are all possible (Table 2).

A satellite without the capability to slew, whether arising through mission constraints or a loss of this functionality, limits the targets that a satellite can observe to those that opportunistically cross the field of view. A camera on a satellite with minimal to no slewing capabilities would maintain the same pointing direction throughout its orbit. Depending on the position of the camera on the satellite, this can impact the number of objects and the observation opportunities available. A baffle is included on the purpose-built camera, thus reducing the likelihood of stray light entering the field of view.

With the higher resolution of the purpose-built ISSA camera, in addition to the sole capability of the basic camera to execute object detection, could also perform large object cataloguing and unresolved photometric observations. Collecting photometric observations is possible but is dependent on the orbital geometry of the spacecraft and target object with respect to the field of view of the camera. If the camera is positioned on the velocity/anti-velocity vector, as in Fig. 3, this would be the most advantageous for photometry, especially in GEO due to the potential for observation targets to remain within the field of view for a longer period [9]. This may be a favourable option for a servicer spacecraft on its journey to the client object to take observations opportunistically without impacting the mission objectives. The Earth pointing face of the satellite is the least favourable location for an ISSA camera as the Earth may saturate the sensor.

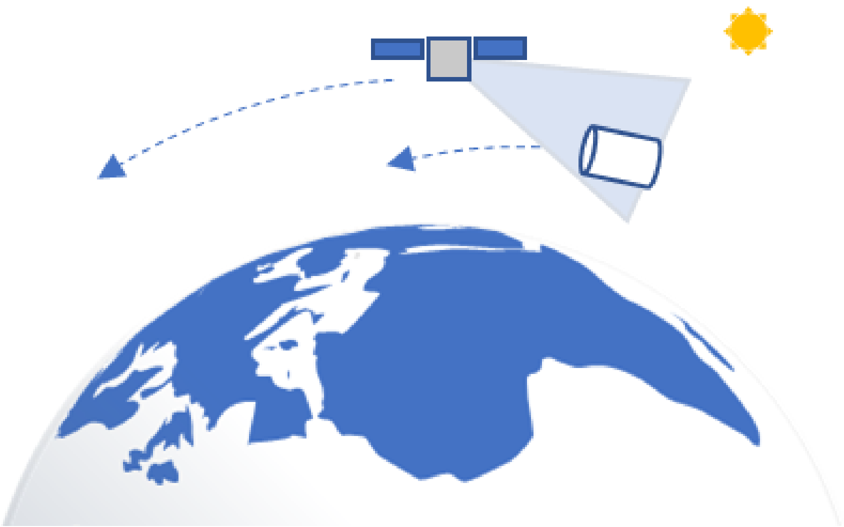

Fig. 3. An example illustration showing the most favourable location on a satellite for an opportunistic sensor to be located to maximise the achievable objectives.

Repurposing Considerations

Dealing with repurposed sensors can show a difference in the requirements for the original purpose versus ISSA requirements. For example, black lines were present in images from VISCAM, in consistent locations although random in their frequency [8]. This did not affect every image and when it did occur a short, black line one pixel in width would be present. This was noted as an issue and could not be addressed before launch, which did not have an impact on the mission as the lines are small and infrequent. A small, randomly occurring black line is not an issue for the short-range imaging of a client object but does become an issue if, for example, the new objective is the observation of light curves to characterise RSOs as this change in brightness of a pixel would introduce uncertainty into the measurements. The specific features of a repurposed sensor need to be addressed to refine the accuracy of ISSA observations.

This study focused solely on optical requirements and sensors. The definition of requirements for all other types of in-orbit sensors is non-expansive, limiting the collation of all requirements or objectives with which to assess the various configurations. In future, these objectives could be expanded to include those achievable by radio frequency, thermal, resistive grid sensors, impact ionisation sensors, etc. These numerous sensors can then be assessed against the different objectives and satellite capabilities to obtain a broader understanding of the possible ISSA observations available to opportunistic sensors.

Different satellite configurations could be considered in future, including different failure modes and limitations. One example is the pointing accuracy of the satellite for performing observations of specific objects of interest and accurately executing orbit determination. Another limitation could be ground resources in operating the spacecraft or processing the data acquired. These restrictions on the implementation of an ISSA observation campaign with an opportunistic sensor need to be further explored to assess the full capability of the potential dual purposing of satellites. Accurate assessments of the configurations against the objectives could be investigated further with modelling of every scenario to estimate the precision that could be obtained within a given situation for a comprehensive assessment of sensor utility for ISSA purposes.

4. CONCLUSION

The cameras currently onboard various satellites have the potential to be repurposed to perform ISSA observations. The objectives of these observations have been identified using previous Astroscale objectives and the recent UK SDA Requirements Publication. This has expanded and clarified the definition of useful ISSA data products. Various opportunistic sensor possibilities have been considered and their utility for use to achieve the ISSA objectives have been defined. Using a basic camera can yield useful ISSA data although without slewing capabilities the only achievable objective is object detection. All objectives can be addressed when using a purpose-built camera, as is expected, although this camera is also limited when there is no slewing available. This study highlights opportunities for using current and near-term Astroscale satellites, such as ELSA-d, ADRAS-J and COSMIC, as ISSA platforms with minimal impact on mission objectives. These objectives can be achieved with many different types of sensors and investigating the various sensors would be a useful expansion of this work. An investigation into the other commonly occurring satellite limitations, while retaining camera functionality, could broaden the utility of this work.

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