CAN WE USE LOW-COST SMALL SATELLITE TO OBSERVE SPACE DEBRIS MISSED BY GROUND SYSTEMS?

Peter Senior[1], Steve Eckersley[1], Victoria Irwin[1], Ben Stern[1], Andrew Haslehurst[1], Andrew Cawthorne[1], Alex da Silva Curiel[1], Sir Martin Sweeting[1]

[1] *Surrey Satellite Technology Limited, Tycho House, 20 Stephenson Road, Surrey Research Park, Guildford GU2 7YE, United Kingdom, Email: info@sstl.co.uk*

ABSTRACT

There is still a range of debris objects that can only be observed from space. An industry perspective on the space debris problem is provided, particularly on the major requirements of a space-surveillance system.

We show that low-cost small satellites have a valuable part to play in the monitoring of this global problem, providing unique viewing opportunities and filling in the blind spots of ground-based systems. The trade-offs between instrument size, instrument agility, and platform size are key to delivering a cost-effective solution.

Two viable small satellite concepts are presented, balancing cost and capability, which illustrate how these requirements can be effectively answered.

1 Introduction

This paper will briefly cover space debris, its detection, and its mitigation from the perspective of Surrey Satellite Technology Limited (SSTL). Based in Guildford, UK, SSTL is a vertically-integrated small satellite manufacturer with over 30 years of experience in space, which has included building spacecraft from 3 to 3000 kg and from low orbit (LEO) to geostationary orbit (GEO) and beyond.

We will discuss common requirements for space situational awareness (SSA), also called space surveillance and tracking (SST), and how these requirements affect a system engineer's understanding of the solution space. Reasons for and against space-based systems are presented, as well as the variety of technologies available for SSA missions.

The paper will then focus on space-based systems, and their key design choices and drivers. Finally, two interesting low-cost concept solutions from SSTL will be presented along with their design rationale.

2 Background

We present here some brief background from SSTL's perspective on space debris.

2.1 Operational Impacts

From SSTL's extensive operational experience of over 500 satellite-years in orbit, on average each satellite has to perform a manoeuvre every year or two, with the number of conjunction warnings increasing over time. The improvement in conjunction analysis tools has decreased the number of manoeuvres required, however there is still a need to sift the ever-increasing number of conjunction warnings which require further investigation. The vast majority of our satellites are in polar sun-synchronous low-Earth orbits, which are some of the most congested regions of space. Fig. 1shows a plot of the density of objects larger than 10 cm and the locations of major ESA missions in LEO. Debris larger than 10 cm can completely destroy a satellite [1]. The most recently available statistics at time of writing were that there are 34,000 objects of this size in orbit [2].

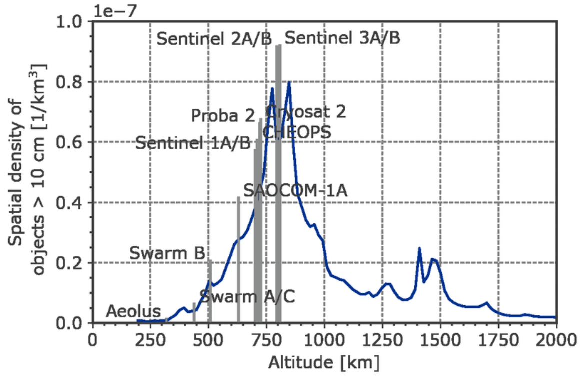

Figure 1: Operational ESA missions in LEO compared with the spatial density of objects > 10 cm from [3]

The impact of very small debris and micrometeorites (<1 mm) results in the degradation of spacecraft surfaces, particularly solar cells. The expected degradation is designed into the satellite with an additional margin for the solar cell area. The need to avoid larger debris adds a slight increase to the propellant required for missions in these regions. A more significant impact resulting from debris avoidance is the outage required to manoeuvre the satellite to avoid debris. Often a debris avoidance manoeuvre is combined with orbit maintenance manoeuvres, which reduces the overall manoeuvre

Proc. 8th European Conference on Space Debris (virtual), Darmstadt, Germany, 20–23 April 2021, published by the ESA Space Debris Office
Ed. T. Flohrer, S. Lemmens & F. Schmitz, (http://conference.sdo.esoc.esa.int, May 2021)

impact. However there still will be some time required for the orbit data of a satellite to settle into the accuracy required for some operations.

While approximately 28,210 objects are catalogued, a far greater number of objects are not. A statistical estimation is for 34,000 objects greater than 10 cm, and for 900,000 objects between 1 and 10 cm [2]. Objects larger than 1 cm are of concern to satellite operators as they can cripple or destroy a spacecraft [1]. Without a catalogue of these objects operators must tolerate the risk they pose without options to mitigate it.

2.2 Cerise

Cerise was a small 50 kg satellite built by SSTL for the French military, launched in 1995 into LEO.

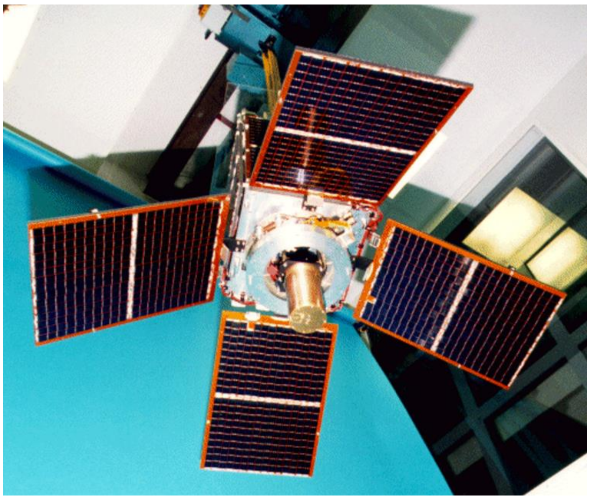

Figure 2: The Cerise Satellite

In July 1996 the satellite experienced a sudden loss of attitude control and telemetry showed a change in the satellite's moments of inertia. This indicated that the spacecraft's 6 m long gravity gradient boom had been severed. Further analysis using the debris catalogue in [4] showed that the most likely cause was an impact by a fragment of an Ariane 1 rocket upper stage which had exploded in November 1986. The satellite survived and was able to continue to operate with some degradation to performance. The severed boom mass became a new object of debris in a very similar orbit.

3 Detection Technologies

For any SSA system, a trade-off must be performed between which detection technology is best suited to fulfilling the mission’s goals within the required cost.

Passive optical systems are most common as they are very simple and do not require much power to operate. They can perform discovery, tracking, and photometry or spectrography. However they are dependent on range, target composition, and heavily dependent upon the solar illumination angle. A further issue with passive optical sensors is due to their structure. As a grid of pixels with very slight gaps between pixels, there may be times when an image spot straddles several pixels. This will substantially reduce the light collected by a single pixel in many cases, necessitating more or longer exposures.

Active radio-frequency (RF) systems such as radar are not affected by the ambient illumination as they can control their own illumination and can image freely towards the Earth. They also can give range and velocity from a single measurement. Some systems can return a resolved image at longer ranges than optical system [5]. However this comes at the cost of a very significant power requirement. This is less of an issue (but still significant) in ground-based systems, but can be a major system capacity and size driver in satellite systems. The returned radar signal also diminishes with the fourth power of the range rather than the square as in passive optical systems. This will considerably increase the power requirement as the operational range increases.

Passive RF systems are less demanding but harder to gain value from. Passive systems require an emitter, which can either be the target or some other form of illumination. In combination with other sensing methods a target can be identified as dead, alive, or a "zombie" where some failure has prevented the operation of a satellite but has left it transmitting some form of RF radiation. This knowledge can inform the situation management, for example an alive but previously uncatalogued target indicates a national security asset, which in the case of a close conjunction can inform avoidance manoeuvres.

4 A Discussion of Common SSA Requirements

There are two types of space surveillance and tracking, which generally fall under "civil" and "defence" banners. SSA for defence tends to require the ability to watch for malicious activity in space, for example satellites manoeuvring suspiciously or missile detection. Civil SSA requirements are more passive and focus on protecting financial investment in space through the prevention of impacts. Space traffic monitoring and space traffic control are other descriptions for this type of activity. These two types can, and often are, mixed.

There are a number of broad requirement areas which are common. This section of the paper will be dedicated to discussion of these requirements and how they relate to both the goals of the system and the design of the eventual components of the system.

4.1 Object Physical Properties

The fundamental aim of a SSA system is to detect objects in space. This can be with a variety of methods, though traditionally active RF systems (Radar) and passive optical systems have been used. The ability of the method used to detect objects will depend on the properties of the possible targets and those of the detector. For the target this will depend upon the size and shape of the target, the materials it is made from, the distance between the target and the observer; and in the case of passive optical systems the angles between the target, the observer, and the sun.

Most satellites are made up of highly specular components, particularly multi-layer insulation (MLI) and bare metal faces. Other parts of a satellite can have a matt surface, for example thruster nozzles after firings. Launcher upper stages often lie somewhere in between, depending on the original colour and the length of time the parts have been in space [6]. Generally for requirements purposes a diffuse sphere at a set distance is used as a target, as the diameter of the sphere relates to the size of real targets detectable. In other cases a requirement visual magnitude is specified. Given, as discussed, a satellite is highly specular, the diffuse sphere requirement will not relate to the reality of what can be detected by the system. However it is a simple and clear requirement. A set signal-to-noise ratio at a specified visual magnitude is easier to design for and to verify but does not give any indication of the size of the target which could be detected by the system. The object size is important as it relates to the damaged which can be caused on impact. Objects larger than 1 cm, for example, are capable of crippling a satellite [1].

Eq. 1 is an equation relating the physical properties of an object to its apparent visual magnitude, from [7].

$$m_v = -26.75 - 2.5\ \log\frac{\rho A F(\Phi)}{R^2} \qquad (1)$$

-26.75 is the visual magnitude of the sun. ρ denotes the reflectivity and A the projected area of the object. $F(\Phi)$ is some function of the phase angle which depends upon the type of object. For example, the phase function for a diffuse sphere is shown in Eq. 2.

$$F(\Phi) = \frac{2}{3\pi^2}\big((\pi - \Phi)\cos\Phi + \sin\Phi\big) \qquad (2)$$

These equations can be used to relate the physical size of an object to its apparent brightness. However an awareness of the limitations of these equations must be maintained. The reflectivity and phase function of a notional object may not reflect reality, particularly in the case of a diffuse sphere.

Fig. 3 and Fig. 4 show a qualitative comparison between a diffuse sphere and an approximately representative satellite, with Fig. 5 serving as a real-world reference. Note how different parts of the satellite reflect light in very different ways. Metal components have an almost mirror finish. Multi-layer-insulation foil is highly reflective but the wrinkled skin is not as predictable as bare metal. Solar cells have unusual reflection characteristics as discussed in [8], given they absorb a fraction of the incident light normal to the face, but this fraction reduces as the incident angle increases. It is also notable that the solar cells used on spacecraft have a brown tint, rather than the blue typically used in illustrations.

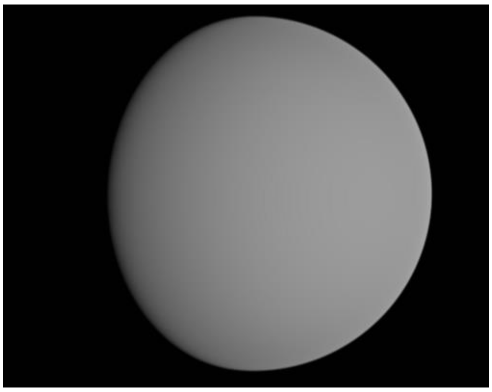

Figure 3: A diffuse sphere

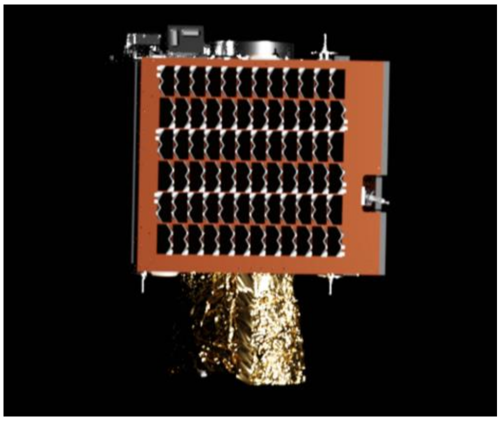

Figure 4: A representative small satellite, in identical lighting as the diffuse sphere

Figure 5: Telesat LEO 1 as a real-world example of a satellite's appearance

For certain phase angles it is almost impossible to detect an object visually, as shown in Fig. 6. This is based upon the assumption of a diffuse sphere. However a strong specular reflection, for example from a metal panel, could still reveal a target. There is also the issue of lunar and solar exclusion zones where the brightness of the moon and sun are enough to overwhelm the faint target signal.

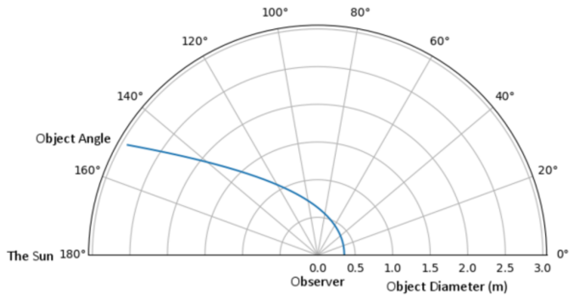

Figure 6: For a fixed visual magnitude, how does the minimum detectable size vary with phase angle?

The object size detectable for a set magnitude increases linearly with distance for a diffuse sphere. Fig. 7 shows the increase in minimum object size detectable by a system as the range increases from LEO to GEO distances.

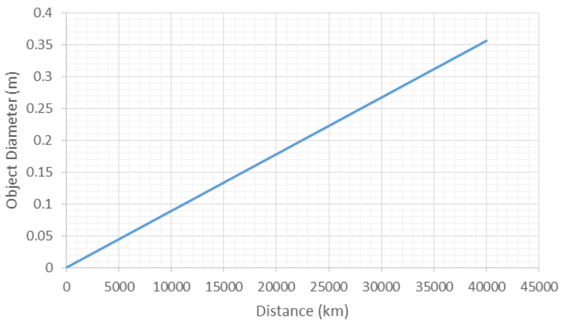

Figure 7: A graph of object diameter over distance

A real-world target with predicable reflective behaviour would be the sodium-potassium (NaK) droplets in LEO. These are spheres up to around 5 cm in size and are highly reflective to radio waves allowing their positions to be well known [9]. Thus these could make a reasonable in-orbit validation test for both optical and radar systems.

Capturing either a set of images over time or a long streak can reveal whether an object is stabilised or tumbling, this is a valuable indication of whether the object is controlled or not. An example is shown in Fig. 8. These light curves can also give some indication of the shape of the object. By capturing these curves in different wavelengths, either using broadband filters or ideally a spectrograph, a much greater awareness of the composition of the object can be gained [6]. This spectral response can be used as a fingerprint for an object [10]. Similarly, the radar polarisation [11] response can be used to identify an object, or in some cases large radar systems can create an image of a target [5].

Figure 8: An example of a tumbling target in a staring mode

For an optical system, a panchromatic detector is very simple and gives the highest sensitivity. Including broadband filters requires a filter wheel or wavelength dependent splitting, and increases the exposure time required for an adequate detection. Spectrographs are considerably more expensive and complex, and require an even greater exposure duration for an acceptable signal-to-noise ratio.

A radar system's ability to detect objects scales with the fourth power of the distance from the observer to the object, while for objects in Earth orbit the variation in solar illumination intensity is negligible thus the apparent visual brightness of an object scales with the square. This means for longer distances such as GEO, the required power from observation radar systems becomes increasingly prohibitive, while the increase in capability for an optical mission is more modest.

Using data from [12] a very approximate assessment of the types and locations of major debris types has been performed in Tab. 1. Data have been roughly grouped into LEO, MEO (Medium Earth orbit), and GEO regimes. Note that some object orbits move between bands, for example Geostationary Transfer Orbits (GTO) move between MEO and GEO regions. These orbits have been assigned to the region which contains their apoapsis as this is where they spend most of their time. As can be seen from Tab. 1, LEO has by far the most objects. However it must be noted that the minimum detectable size in LEO is much smaller than for GEO so there may be many small objects in GEO which have gone undetected. Reference [13] shows that the risk posed by small objects in the GEO region should not be underestimated, particularly from objects in highly elliptical orbits such as GTO as this has an increased relative velocity. Additionally, [13] notes the sizes of objects of risk as being >20 cm for destruction and >1 cm

Table 1: A rough study of the number of objects in LEO, MEO, and GEO

	Payloads	Payload Fragments	Payload Unknown	Payload Deliberate	Launcher Bodies	Launcher Fragments	Launcher Unknown	Launcher Deliberate	Unknown	Total
LEO	4494	6563	130	198	1120	3428	155	906	1127	18121
MEO	337	4	5	53	112	58	1	5	272	847
GEO	1358	82	3	68	680	2611	12	67	3125	8006

Table 2: An approximation of the average surface area per object (m^2) in LEO, MEO, and GEO

	Payloads	Payload Fragments	Payload Unknown	Payload Deliberate	Launcher Bodies	Launcher Fragments	Launcher Unknown	Launcher Deliberate	Unknown
LEO	4.594	0.003	0.036	0.376	13.312	0.000	0.000	1.918	0.002
MEO	8.283	0.000	0.000	0.119	18.829	0.000	0.000	3.040	0.000
GEO	25.952	0.000	0.000	1.012	19.476	0.000	0.000	13.716	0.000

for damage. The numbers of debris objects in the LEO region has been significantly inflated by a small number of catastrophic events.

A useful metric to approximate the relative sizes of objects in the different regions is averaging the total surface area over the number of objects in that region as seen in Tab. 2. This shows that spacecraft and rockets increase in size as altitude increases (larger GEO satellites require larger launchers). It is important also to note the number of unknown objects compared to the total. In GEO this is significantly larger than for LEO, reflecting the comparatively less capable surveillance of the region due to its significant distance. There will also be a much larger population of uncatalogued debris as a fraction of catalogued debris in GEO than in LEO. Thus, while Tab. 2 is useful as a description of the known object situation, it should not be extrapolated to approximate the unknown object population.

4.2 Observation Strategies

There are three primary strategies for the detection of objects in space. Staring at a likely location, tracking a predicted position, and statistically sampling objects in a certain region.

In a staring mode (Fig. 9), the sensor pointing is static compared to the celestial background. This celestial background can then be used as a very exact pointing reference. Detected objects appear as streaks in the image. The start and end points of the streaks allow an approximate orbit to be derived from a single image. Successive observations allow this estimate to be refined. The signal-to-noise ratio of detected objects is necessarily lower than for tracking modes as the light from the object is spread across several pixels. However staring modes can more easily detect new objects, and the detector pointing requirements are simpler, needing only to track the celestial background.

Figure 9: An image of a space object in a staring mode, which is not noticeably tumbling

Tracking modes (Fig. 10) follow the expected path of an object with the aim of minimising the number of pixels the target light spot will be spread over. This gives the greatest sensitivity but requires some foreknowledge of the target orbit. Tracking also causes the background stars to become streaks which can make using them to refine pointing measurements more difficult. Additional complexity is added to operations planning and the mechanics of the observing system. This method simplifies the capturing of light curves and spectral responses as the target will be maintained in its location on the image sensor. Tracking systems require time to slew to the target and settle to the target tracking rate, which can take some time.

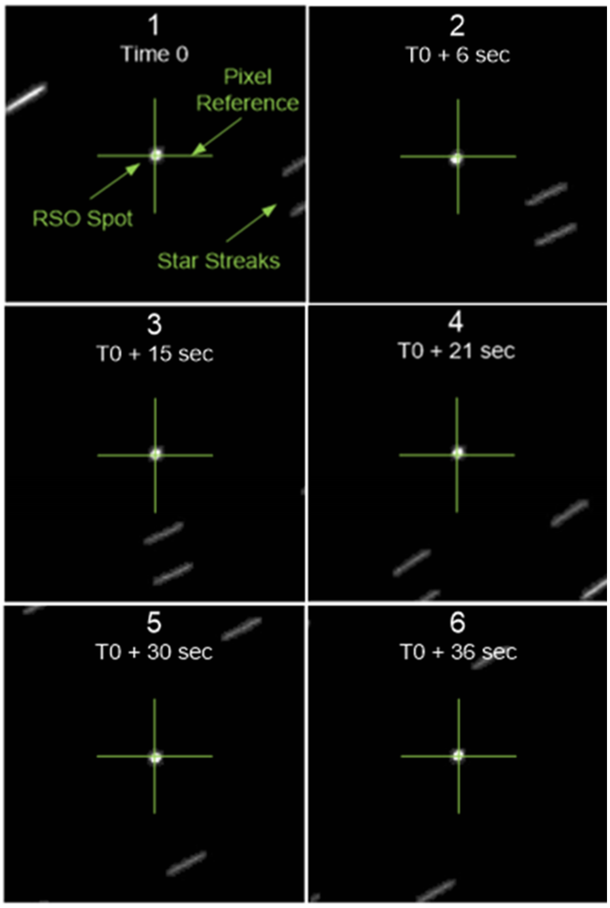

Figure 10: An example set of observations in tracking mode from the Sapphire satellite

A simpler method of assessing the debris environment is statistical sampling of a region. This can be as simple as a panel on a spacecraft passing through the region and detecting impacts or the panel is returned to Earth. The Space Shuttle was extremely useful in this regard for assessing the small debris environment in LEO, and for publicising the dangers of debris. A remote sensing method would be to count the streaks or radar returns corresponding to a certain orbit bracket. This is useful for the smallest debris where tracking each object would be prohibitive but having awareness of how the population as a whole operates is essential. The radar technique for performing this type of sampling is a “beam-park”, where the natural motion of the Earth sweeps the beam out by 360 degrees over a day. Cooperation between radio telescopes can enable confirmation of detections and the detection of smaller objects [5].

4.3 Latency

The total system latency is a very important metric for SSA systems, which is broken down into three sections. This relates to a system's ability to quickly receive an observation request (command), its ability to quickly observe the target (observation), and its ability to return the data back to the requester (reporting).

Ground-based systems tend to have an excellent command latency. A functioning internet connection can deliver a request to the required observing telescope quickly. However the observation latency can be exceedingly long. It could be many hours before the satellite object passes over a telescope when observing conditions are favourable (i.e. night). This is why many ground-based systems use a diverse spread of telescope locations to protect against weather effects and ensure there is a telescope somewhere with an opportunity to observe a target. The reporting latency of a system depends on the speed with which the observations can be turned into actionable information. This will comprise the latency with which a system can return its data to a location for processing, and for the time it takes to process the observations into orbits. For ground systems this will generally be performed quickly.

Space-based systems are the reverse. The need to wait for a downlink opportunity significantly limits a satellite's responsiveness to both command and reporting. However this can be mitigated with inter-satellite links (using a low rate radio link to GEO to command the spacecraft for example). Due to the satellite also being in orbit and moving means that the observation latency is also generally better than for ground observatories, especially due to the lack of atmospheric effects. The observation latency for a satellite is a more complex problem than for ground observatories as both the observer and target are moving quickly.

Overall, the latency required depends on the overall goal of the mission. Missions with the goal of improving and refining catalogues do not require rapid response times. However a system which wants to provide actionable intelligence to avoid collisions (for example by providing more accurate orbit predictions for a conjunction), monitor breakups, or detect malicious behaviour, may require extremely rapid reactions to prevent a major incident.

4.4 Track Capacity

The track capacity relates to the number of sets of observations which can be captured in a certain time frame. For most SSA systems a number of observations will be required in order to generate a useful orbit. Each set of observations is termed a track, and it is the number of these tracks it is possible to capture in a specified time period which determines the capacity of the system. Generally a day is used as a generic requirement which covers both space and ground systems (tracks per hour would be highly variable for ground based systems as they are impacted by daylight hours).

The track capacity is influenced by a wide variety of factors. The time each track requires depends on the payload, how sensitive it is and how many separate observations are required for the track to be useful. Between tracks the system must slew between targets (unless it is a wide-angle staring system), and it must settle to its required tracking slew rate (which can be sidereal/inertial). The number of observation opportunities which will be available will also impact the track capacity. Two extreme examples are the Lagrange points. A hypothetical SSA system at the L1 Lagrange point between the Earth and the Sun will enable a great number of observations, whilst an SSA system based at the L2 Sun-Earth Lagrange point the opposite side of the Earth will have almost none due to the poor target illumination. Finally, there are the times needed for transferring data and other housekeeping tasks.

Often a trade-off will need to be performed between track capacity and accuracy while also bearing in mind the cost of the system.

4.5 Accuracy

Fundamentally, what a user of an SSA system cares about with regard to accuracy is the uncertainty of position and velocity of an observed orbit. This will be broken down into position and velocity uncertainties along and across track (the across track uncertainty is generally lower). However the generation of these numbers is a complex stack-up of sources:

- The detector pointing uncertainty
- The detecting asset's position
- The detection time

The pointing of the detector depends on the detecting asset's ability to both point the detector in a certain direction and maintain that direction. This is especially pertinent to tracking systems where using the celestial background to calculate pointing is much more complex, and the tracking will be oscillating slightly as the control system manages the motion. For systems on the ground this will also be affected by atmospheric refraction, especially that due to mass movement of air.

For fixed, ground-based systems, the detector location should be relatively easy to determine to a high degree of accuracy. For systems in space this will be a more complex issue as the spacecraft will be moving at great speed, and will be subject to perturbations. For observations from LEO, GNSS (Global Navigation Satellite System) logs captured concurrently with spacecraft data is an excellent and simple solution to the issue. Propagation of Two-Line Ephemeris (TLE) files of the observer is considerably less accurate.

For both ground and space systems the detection time is a critical datum point. Generally GPS time is an ideal source of time for the system.

4.6 Ownership of data/operations

Depending on the customer, their needs, and any security requirements, there exists a wide range of options for how an SSA system is operated and who owns the data. Traditional institutional missions own and operate the system and maintain custody over the data, however there are other options:

- Contractor operated system, customer operated payload. This is where a contractor performs the day-to-day operation of the system, for example maintaining telescopes or operating a satellite, while the customer controls the observation schedule. It is possible to obfuscate the observations to preserve a level of security over the output data, and operate the customer segment as a "black box" with encryption of the observation data and commanding.
- Contractor operated system and payload. This is where a contractor maintains and operates the whole system, with the customer requesting observations (or final data). In this case the customer pays for the mission and pays the contractor to operate it.
- Contractor operated system and payload as a service. This is an increasingly common business model in the space industry where a customer (or customers) request data from a commercial operator. The operator owns and operates the system.

The choice of system architecture has significant impacts, particularly for a spacecraft where the choice will affect the ground segment. A wholly customer owned system will require at least one customer ground station. The additional ground station cost will affect the system latency, for example, if less ground stations are available the system latency will increase. A contractor service on the other hand will be able to leverage the pre-existing ground station networks for a far wider spread of command and downlink opportunities but will have to answer questions on data security and integrity.

4.7 Interoperability

A companion question to that of data ownership is that of interoperability. Part of the reason for the success of the Sapphire mission is because it can interface with CSpOC and share data. This adds an extra layer of complexity (and hence cost). This complexity lies at the interfaces between the system and the wider ecosystem. For a commercial operator who collects their own data, performs analysis, and then provides intelligence as a service to customers, it may not need to be interoperable and instead operate as a "one stop shop".

4.8 Availability

The capacity for a system to be available when its customer wants it is a key requirement. This availability requirement could be >90% in a set period. There are several factors which affect the system availability, both in space and on the ground. For ground-based observatories the weather can be the largest unpredictable factor in the system design. This can comprise cloud cover, but can also include high winds or precipitation, dust, or sand. While terrestrial weather is not an issue in space, the space environment has its own issues. Spacecraft outages tend to last longer than on the ground as debugging and recovery depend on ground station contacts, and satellites are vulnerable to upsets caused by space weather. High availability spacecraft operate in a fail-operational way rather than a fail-safe way to reduce these impacts, however this adds complexity to the spacecraft design process and thus cost. Ground SSA systems use a diverse spread of observatory locations to mitigate weather effects and increase the overall system availability. The user will not care which observatory was used so long as they get their accurate data in a timely fashion.

5 Space as a Solution

In this section the discussion is narrowed to specifically satellite solutions to the SSA problem, beginning with a discussion of the advantages and disadvantages of spacecraft in SSA.

5.1 Benefits and Disadvantages

Space is not always the best solution for a SSA system, however space-borne sensors do have some significant advantages over ground-based systems. Space-based systems are more expensive and generally use smaller telescopes, as well as requiring the use of one or more ground stations to return their data. This leads to a generally less sensitive system with a poorer overall latency.

However a space-based system also has several benefits. Satellites are significantly less affected by the sun, cloud cover is never an issue, and the range to targets can be considerably reduced. Atmospheric seeing issues are also avoided, as well as absorption of certain frequencies. A key example is the use of optical sensors in GEO to detect objects beyond the reach of any ground-based system. The rapidly varying location can allow the sensor to get a more optimal observing geometry on a greater number of possible targets. It is even in some cases possible to get close enough for direct images although this is seldom needed.

Inter-satellite links are available to improve both the command and reporting latency, allowing satellite systems to react very quickly to emerging situations. Of course, SSA spacecraft must also avoid becoming debris objects themselves.

5.2 Mission Goals and the Space Solution

Placing a sensor in space affects the system requirements which depends upon which regions are of interest. Two broad categories of system are here discussed, LEO-LEO observation and LEO-GEO observation. It is common for both categories to be considered on a single mission.

LEO-LEO observations involve a sensor in low Earth orbit observing targets in similar orbits. The sensor could be looking either up or down from its orbit, with the Earth being a significant obstacle. The instrument itself can be quite small given the reduced ranges involved, however it will need to track at quite high rates. Using staring modes is a valid way of avoiding this tracking requirement. The observation opportunities can be complex with relative movement between the observer and target being significant. Statistical sampling can also be included in this category.

Observing from LEO to GEO requires a more sensitive instrument, given the considerably larger range. However the tracking rates are much slower, and other objects in the GEO belt can be used for closed-loop guidance if the target is compatible with this method. Observation opportunities are simpler to predict. The advantage for a space-based GEO observing mission over ground instruments is that it can observer a larger fraction of the ring, being only limited by a sun exclusion zone and the target phase angle. The solar exclusion zone will depend on the baffle design and can be around 30 degrees for a low-cost design. Given the phase angle limitation discussed above it may not be worth spending the extra effort to reduce this. Obviously the sun must be kept completely out of the field of view of the imager.

5.3 Choices of Orbit

The choice of orbit or orbits will significantly affect the capabilities of a space-based SSA system and therefore it must be made with care. The orbit height will affect whether the spacecraft needs to look up or down to see its targets. An increasing number of earth observation and communication satellites are being launched to low altitudes for performance reasons. However an SSA satellite may struggle to detect the targets with the Earth as a background. This could limit the number of detections which could be made. Low orbits require additional orbit maintenance to prevent premature reentry. Higher orbits make communicating with the ground more difficult and require an active de-orbit at end of mission. Orbits which lie within the Van Allen belts experience greatly reduced lifetimes or require high reliability components and/or increased shielding due to the radiation environment.

An important decision is whether to use a sun-synchronous orbit or not. Sun-synchronous orbits use the Earth's oblateness to cause the orbit to rotate around the Earth's geometric pole. This allows a sun-earth-orbit geometry to be maintained broadly consistently over the lifetime of a mission, and requires particular combinations of altitude and retrograde (>90 degree) inclination. Sun-synchronicity is very common in Earth-observation missions for consistent illumination on the ground, as well as offering an orbit geometry which simplifies spacecraft design.

The local solar time at the equator about which the orbit is fixed is commonly used as a descriptor of the orbit, corresponding to the Local Time of Ascending/Descending Node (LTAN or LTDN). 10:30 is a common choice for optical Earth observation, therefore locating an SSA mission in this type of orbit would allow to closely observe this type of satellite. This is the easiest orbit to find a ride sharing launch opportunity due to its popularity.

Another choice, albeit slightly less common, is a 06:00/18:00 orbit also known as a Dawn-Dusk orbit. This orbit keeps the satellite above the terminator which hugely reduces the number of eclipses the satellite must pass through. Reducing the number of eclipses increases the power the satellite can generate, which is why this orbit is popular for radar satellites. It is also a useful choice for SSA missions observing the GEO ring as it maximises the power which can be generated while also maximising the visibility of satellites in GEO as they are on the opposite side of the Earth to the Sun.

A satellite passing over the poles can also observe all other polar orbiting satellites at some point as they too regularly pass over the poles. A non-synchronous orbit will drift around the Earth allowing the mission's observation geometry to vary more freely and give wider surveillance. However this requires a more complex power system design (e.g. tracking solar arrays) which is able to provide sufficient power despite changing sun-orbit geometry.

Mid-inclination and equatorial orbits use lower inclinations to maximise a satellite's coverage over mid-latitude regions of the globe. It should be noted many of the major LEO communications constellations include a significant mid-inclination component. This area of space is becoming increasingly congested. An SSA mission in a similar orbit to a major constellation or asset allows it to provide monitoring of the space around it to best protect the investment.

The use of multiple satellites creates resiliency in a system, and helps to fill in gaps in coverage caused by the Earth, Moon, and Sun. The effect is shown in Fig. 11 and Fig. 12. The instantaneous coverage is described at GEO, with the regions in view of the satellite coloured blue in the image. The red square is the satellite(s), and major gaps in the coverage due to celestial phenomena are described.

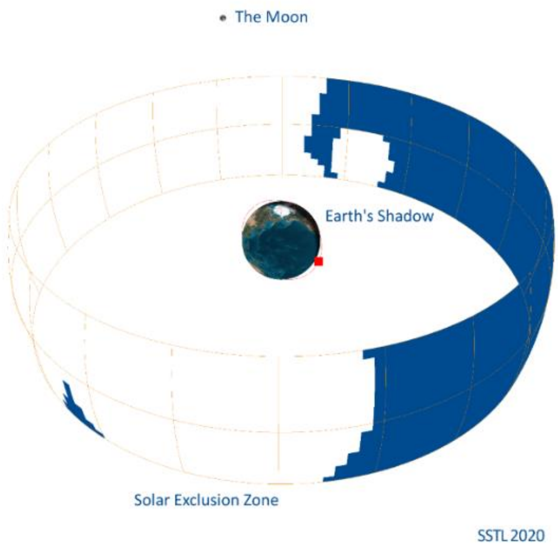

Figure 11: Instantaneous coverage of GEO from a single LEO SSA satellite

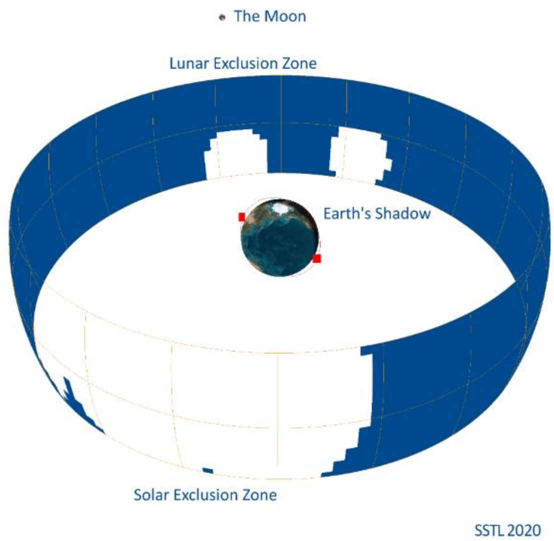

Figure 12: Instantaneous coverage of GEO from two LEO SSA Satellites

Using multiple satellites is not a linear cost increase. Subsequent satellites do not require the system design to be performed again (the non-recurring engineering), and batch or automated build methods can further reduce the recurring cost. Additionally the same level of testing is not needed on all spacecraft, conferring additional savings. However the system capacity increases linearly. This means the cost to benefit ratio increases substantially for multiple-build satellites.

6 Key Design Drivers and Constraints

This first part of the paper has covered many of the most common requirements found when discussing SSA systems. This section will briefly outline the key trade-offs made when designing a system. It is implicit in all these discussions that increasing the system cost will reduce the compromises being made to the design.

The first major trade will be which detection technology and strategy to use, based upon the region of interest and desired minimum detectable object size. Passive optical systems are the cheapest option both in space and on the ground, require very little power, and can detect most objects. However they are limited by daylight. Active RF systems like radar require huge amounts of power which can be expensive and difficult in space. Radar systems can detect cm-sized objects and below in LEO [5], however the returned power substantially diminishes with range leading to GEO-observing systems to be extremely large. Passive RF systems require very few system resources making them an excellent Cubesat payload or secondary payload, however they work best as a supplement to other detection methods. The detection technology and strategy will interact with the choice of spacecraft orbit. A spacecraft closer to its target region will require a less capable instrument but it may lead to other issues.

A second trade-off will be between ground and space systems. For the cost of one satellite a number of ground observatories can be purchased, offsetting some of the disadvantages of ground-based systems compared to spacecraft. However a ground network will still lack the observation flexibility of a spacecraft, and for a sufficient spread of installations agreements will have to be made with other nations. This decision may also be affected by the latency requirements.

A balance will need to be found between the track capacity and accuracy; and the minimum detectable visual magnitude/size. Particularly for satellite missions, the capacity and accuracy are tightly coupled issues. The minimum detectable visual magnitude for an optical system will depend on the telescope aperture and how long an object will spend focussed on one pixel. The telescope aperture will affect the telescope's focal length. Low f-number telescopes, where the ratio between the focal length and the aperture is low, are hard to design and build, and therefore expensive. However a longer focal length makes it harder for a system to keep a target on one pixel with the disturbances it will encounter in operation. This will also depend on the pixel size and sensitivity of the detector used. A satellite will need time to settle to a new pointing direction or slew rate after a change which will result in a significant gap between tracks. The size of this gap will depend on the track accuracy required and the capabilities of the satellite.

7 Past Missions

This chapter briefly discusses previous dedicated SSA missions. There have also been other missions (not discussed here) which have used their payloads to detect space debris. Notably the search for potentially hazardous near-Earth objects has similar problems to solve as SSA missions, although at a different scale.

7.1 Sapphire

Sapphire is a mission by the Canadian Department of National Defence to observe objects in MEO to GEO, and to feed these data into the Combined Space Operations Centre (CSpOC). It is a 148 kg satellite with MDA as the prime contractor, a payload by COM DEV International, and the platform manufactured by SSTL.

Figure 13: The Sapphire satellite

The satellite is primed with a TLE from the debris catalogue, tracks its expected position and performs observations of the target to maintain custody of space objects. These data are then transmitted back to the control centre and then to CSpOC. Up to 360 objects per day can be observed, down to magnitude 15. The mission launched in 2013 and is still in operation.

7.2 STARE

STARE (Space-based Telescopes for the Actionable Refinement of Ephemeris) was a project from the US National Reconnaissance Office built by a group of academic institutions [14].

The project originally consisted of 3 3U Cubesats to demonstrate the observation of space debris with nanosatellites. STARE-A was launched on the 13th of September 2012, and STARE-B on the 20th of November

2013. The payload consisted of a 1.5 U imager and the equipment to process and downlink the data. The satellites would operate in stare mode, detecting objects in LEO. Two missions were launched, however neither were able to become operational. Of note is the expected level of data compression achieved by the mission. It would have been of the order of 100x less than the size of a compressed full frame capture, consisting of GPS logs, the positions of the stars in the frame, and the start and end points of streaks.

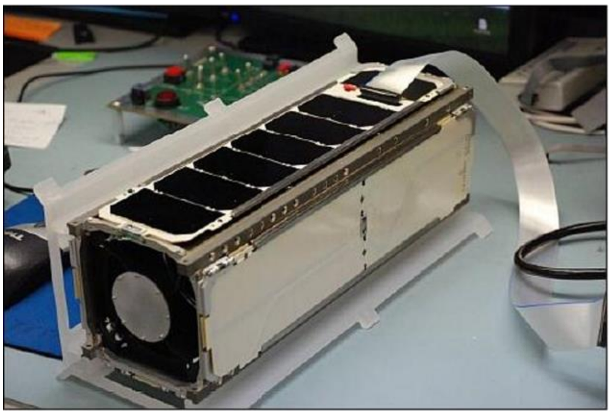

Figure 14: A STARE Cubesat (Image Credit: NPS)

7.3 S5

The Air Force Research Laboratory's Small Satellite Space Surveillance System (S5) was a ~60 kg satellite launched to near-geostationary orbit in 2019 [15]. The spacecraft was manufactured by Blue Canyon Technologies as an experiment in detecting objects in and around the GEO belt.

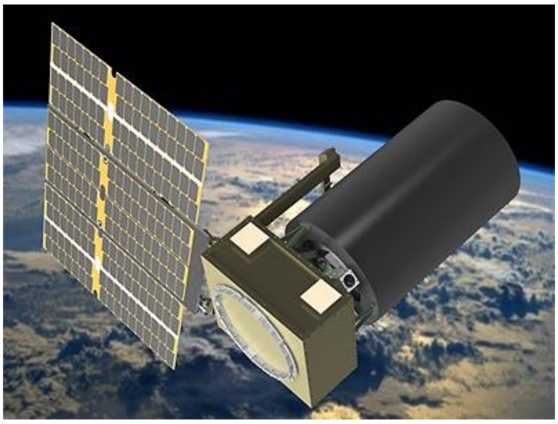

Figure 15: The S5 Satellite (Image courtesy of Blue Canyon Technologies)

Unfortunately the satellite was unresponsive after release.

7.4 Mycroft

The spacecraft Mycroft is a part of the ESPA Augmented Geostationary Laboratory Experiment (EAGLE) mission. Mycroft was designed to demonstrate self-inspection technologies and the assessment of the region around its parent satellite. After its initial mission it was also used to inspect the S5 satellite after it was found to be unresponsive.

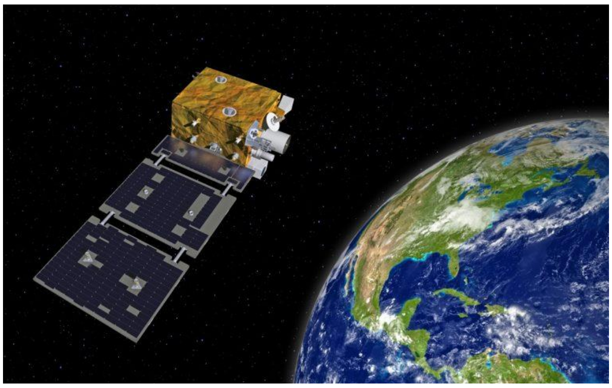

Figure 16: The Mycroft Satellite (Image credit: Orbital ATK)

8 Planned Missions

There are a number of planned SSA missions, both institutional and commercial. Northstar Earth & Space aim to sell space traffic data and predictions as a service to customers using a constellation of microsatellites in service by 2024 [16]. Their initial mission is for three spacecraft in LEO dedicated to the detection of objects from LEO to GEO. ESA also is planning a space-based optical component to their space safety programme, initially as a hosted payload and then as a dedicated mission. The emphasis on these missions is on the statistical sampling of very small (~cm scale) objects in LEO, with the additional capability of observing objects in GEO. This mission is aiming for a launch in the mid-2020s.

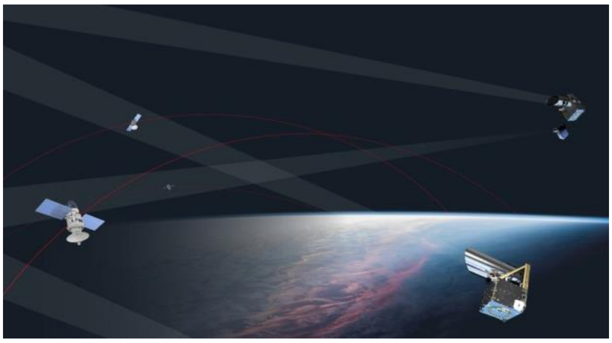

Figure 17: A conceptual image of the Skylark satellites under construction for NorthStar Earth and Space (Image courtesy of NorthStar Earth and Space)

9 Example Solutions

In this section we present two example solutions for SSA systems which leverage SSTL's experience with low cost small satellites with optical payloads. To minimise any additional design effort they are based upon standard SSTL platforms with only the modifications needed for them to perform their mission. This is the approach taken with the highly successful Sapphire mission whose platform was based upon that of the RapidEye constellation. Both of these examples presented work best with more than one spacecraft, allowing access to the benefits discussed previously. They are intentionally low cost and have been designed with repeat builds in mind in order to make it easier to access the benefits to being in more places at once.

In order to fulfil availability requirements both of the solutions presented are single-failure tolerant.

9.1 SSTL-MICRO

This first example, based upon the SSTL-MICRO platform, has a total mass including payload of around 120 kg. It is designed to operate in a dawn-dusk orbit with a focus on the detection of objects in LEO. 10:30 orbits can also be accomodated. It is capable of detecting objects of a magnitude of 16.5 in a tracking mode, and is also capable of statistically sampling objects in the space around it. For such a small system, cooling of the detector is required to achieve this detection level reliably. This is achieved passively with a dedicated platform radiator which is part of the base platform. Tracking is also how satellites with a telescope of this size can achieve detection of very dim objects.

The use of a dawn-dusk orbit allows the use of static deployable panels. With the spacecraft nominally pointing its payload away from the sun there is no need for tracking arrays in order to generate sufficient power to operate the satellite. This increases the reliability and considerably decreases the cost of the satellite.

This concept is intended for use with a distributed ground station network which gives operational flexibility and reduces the downlink rate required, further simplifying the spacecraft.

For orbit maintenance and end-of-life deorbit we have selected SSTL's standard xenon resistojet. This is a very low cost solution for orbit control in LEO.

9.2 SSTL-MINI

The second example is based upon the Precision configuration of the SSTL-MINI platform with a mass in the region of 280 kg, this concept is highly capable both in agility and detection sensitivity. It can capture 20.9 magnitude 18 tracks per hour, each spaced apart by 40 degrees, with a pointing accuracy of 0.5 arc-seconds over an exposure. There is provision for the cooling of the payload via a passive radiator to further improve the performance if required. Three star trackers are used in a redundant arrangement to maximise accuracy. Like the SSTL-MICRO platform example, this concept is placed in a dawn-dusk orbit which maximises the power generation and the visibility of the geostationary ring. Its target range is from MEO to GEO which has led to the large aperture. This magnitude range approximates to a 30 cm diameter sphere with ideal illumination in GEO. The design is also capable of performing precise observations in LEO.

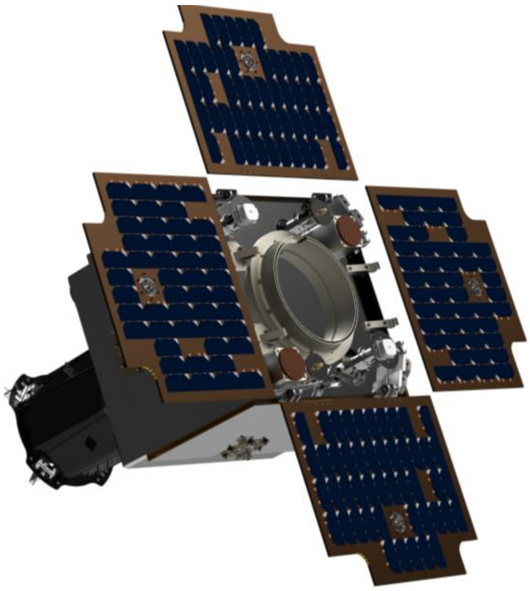

Figure 18: The SSTL-MICRO platform modified for SSA

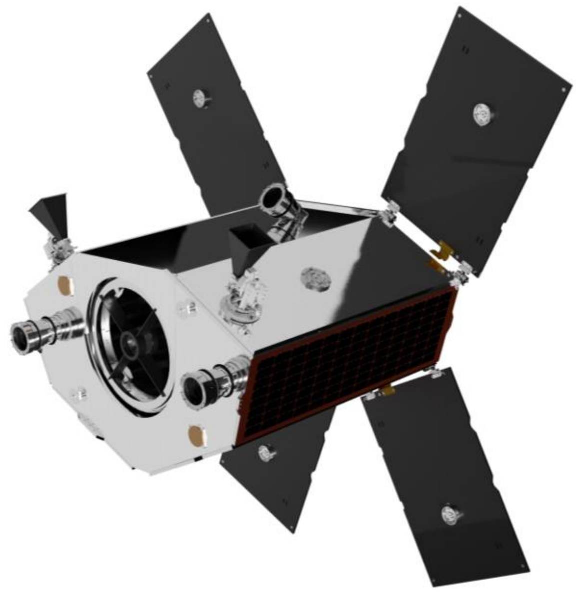

Figure 19: The SSTL-MINI platform as an SSA asset

Intended as a national (or shared multi-national) asset, this satellite has been designed with high-rate X-band downlinks so that it can make the most of a smaller number of downlink opportunities. For urgent commanding an Inter-Satellite Data Relay System is used, which would transmit encrypted commands to the satellite. This arrangement minimises latency while maintaining sovereign control over the spacecraft. Control and reporting latencies can be kept below 2 hours depending on ground station location. The maximum observation latency is 4 hours for an object in the GEO ring.

It is also important that the platform be sufficiently well controlled to be able to avoid any incoming collision threats, so this platform is equipped with a monopropellant propulsion system.

This platform has the capacity to host additional secondary payloads, for example an RF listening payload would synergise well with its main role, optical SSA observation for defence. This would allow it to determine if a threatening object is an active satellite or not.

10 Other Possible Concepts

This section will briefly outline a small number of other possible solutions to a space SSA mission. These are presented to demonstrate that not all missions need be optical missions in LEO.

Note that an SSA payload as a secondary payload on a GEO satellite is possible and may be very beneficial, but such a payload may need more precise pointing and a more controlled microvibration requirement than a GEO telecommunications satellite can provide.

10.1 GEO Inspector

This concept uses a small satellite placed outside the GEO protected belt. A satellite which is above the belt would be able to observe targets in GEO at the times when no other optical observatory would be able to, when the satellites are between the Earth and Sun. This orbit would also allow the satellite to detect much smaller debris than is currently possible. However an orbit near the GEO ring must ensure that it does not risk crossing the ring.

10.2 IR Sensors

Highly sensitive IR sensors are beginning to become popular on small satellites. All satellites require radiators to reject waste heat, which can often be at quite high temperatures. Sunlight will also warm satellite surfaces, particularly solar arrays. This would show up to an IR detector as a slight increase in the temperature of a pixel.

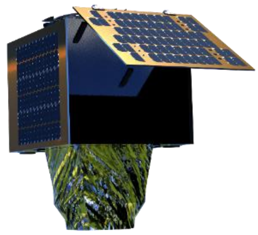

Figure 20: SSTL's DarkCarb MWIR Earth-observation platform

Such a satellite used for SSA would require a sensitive detector, but it would be much harder to obscure a target in the IR as well as the detection being somewhat independent of solar illumination angle.

10.3 High-Frequency SAR/inverse-SAR

Synthetic aperture radar (SAR) is increasing in popularity in Earth-observation due to its immunity to illumination or weather conditions, in addition to the sensor's resolution being independent of range. This detection method has been applied in an SSA context, however it has not yet been used in space. Increasing the frequency would allow higher-resolution images to be captured, however atmospheric attenuation becomes prohibitive.

A space-based iSAR SSA mission would be able to inspect and directly image objects and satellites in orbit at greater distances and higher resolutions than other technologies. However it would be limited by power generation and would be unable to easily detect new objects.

11 Conclusions

In this paper we have provided an overview of SSA and endeavoured to explain the implications of common requirements to all SSA systems, how space and ground based systems differ; and described how these requirements affect the design of space-based SSA systems in more detail.

The discussion has shown the need to carefully consider the limitations of both ground and space systems, while space missions are expensive there are situations which a purely ground-based system cannot observe. Depending on the goals of the system, both a space and ground segment may be needed. It is vital to note the gap between detection sensitivity requirements, the real-world application, and the ease by which a requirement can be designed for and verified.

For space missions, there are some areas with unintuitive interactions, for example the relationship between track capacity and accuracy. The need for a spacecraft to settle to an object tracking rate substantially limits the number of different objects which can be observed.

Finally we have outlined some current missions and emerging concepts for space-based SSA. Due to SSTL's experience and knowledge we have focussed on promising low-cost small satellite systems, which necessarily will not give a full picture of how spacecraft can contribute to SSA as the capabilities of larger systems have not been considered in-depth. However we have shown that small low-cost satellites can be valuable parts of a wider SSA system or ecosystem.

12 References

[1] ESA/ESOC, "Space debris: assessing the risk," 16 March 2005. [Online]. Available: https://www.esa.int/About_Us/ESOC/Space_debris_assessing_the_risk.

[2] ESA, "Space Environment Statistics," 08 January 2021. [Online]. Available: https://sdup.esoc.esa.int/discosweb/statistics/. [Accessed 12 March 2021].

[3] T. Uriot, D. Izzo, L. F. Simões and R. Abay, "Spacecraft Collision Avoidance Challenge: design and results of a machine learning competition," ResearchGate, 2020.

[4] F. Alby, E. Lansard and T. Michal, "Collision of Cerise with Space Debris," in *Second European Conference on Space Debris*, Darmstadt, 1997.

[5] D. Mehrholz, L. Leushacke, W. Flury, R. Jehn, H. Klinkrad and M. Landgraf, "Detecting, Tracking and Imaging Space Debris," February 2002. [Online]. Available: http://www.esa.int/esapub/bulletin/bullet109/chapter16_bul109.pdf.

[6] J. A. Reyes, R. C. Hoffmann, D. P. Engelhart, H. M. Cowardin and D. Cone, "Spectroscopic Behavior of Composite, Black Thermal Paint, Solar Cell, and Multi-layered Insulation Materials in a GEO Simulated Environment," in *The First International Orbital Debris Conference (IOC)*, Sugar Land, TX, 2019.

[7] W. E. Krag, "Visible Magnitude of Typical Satellites in Synchronous Orbits," National Technical Information Service, Springfield, 1974.

[8] Ø. Jordheim, *Angle Dependent Reflectance and Performance of Solar Cells*, Tromsø: The Arctic University of Norway, 2018.

[9] C. Wiedemann, E. Gamper, A. Horstmann, V. Braun and S. Enrico, "The contribution of NaK droplets to the space debris environment," in *7th European Conference on Space Debris*, 2017.

[10] A. Vananti, T. Schildknecht and H. Krag, "Reflectance spectroscopy characterization of space debris," *Advances in space research*, pp. 2488-2500, 2017.

[11] C. L. Stokely, J. L. Forster, Jr., E. G. Stansbery, J. R. Benbrook and Q. Juarez, "Haystack and HAX Radar Measurements of the Orbital Debris Environment," NASA, Houston, 2006.

[12] ESA, "The current state of space debris," 12 October 2020. [Online]. Available: https://www.esa.int/Safety_Security/Space_Debris/The_current_state_of_space_debris. [Accessed 09 March 2021].

[13] D. L. Oltrogge, S. Alfano, C. Law, A. Cacioni and T. S. Kelso, "A comprehensive assessment of collision likelihood in Geosynchronous Earth Orbit," *Acta Astronautica Volume 147*, pp. 316-345, 2018.

[14] eoPortal, "STARE (Space-based Telescopes for the Actionable Refinement of Ephemeris)," ESA, [Online]. Available: https://earth.esa.int/web/eoportal/satellite-missions/s/stare. [Accessed 09 March 2021].

[15] Gunter's Space Page, "S5," 04 06 2020. [Online]. Available: https://space.skyrocket.de/doc_sdat/s5.htm. [Accessed 24 03 2021].

[16] J. Foust, "NorthStar orders three satellites to collect space situational awareness data," SpaceNews, 27 October 2020. [Online]. Available: https://spacenews.com/northstar-orders-three-satellites-to-collect-space-situational-awareness-data/. [Accessed 09 March 2021].