LEO Space Surveillance and Tracking Through a Non-Traditional Lens

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1. ABSTRACT

From the earliest days of space activity space surveillance and tracking (SST) has predominantly been provided by the military, using systems developed to support other priorities such as Missile Warning. With the dramatic changes that have occurred on orbit in recent years this paper advocates a fundamental change is needed. The reliance on military systems not only fails to adequately address current challenges of the 'new' space environment but also undermines international developments. This discussion advocates the establishment of a civilian led; global facing organisation dedicated to the coordination of space traffic. Furthermore, it will discuss the need to re-evaluate the current space situational awareness (SSA) approach through the introduction of the LEO Optical Camera System (LOCI), a potential market and mindset disruptor.

2. INTRODUCTION

It is axiomatic to state that the use of LEO has increased dramatically since the start of the 21st Century. This has necessitated an attitudinal shift in the approach to the way that space surveillance and tracking is undertaken, with current legacy systems struggling to provide the persistence of coverage needed for the dramatic increase in the orbital population particularly in LEO. This discussion will not only seek to provide some context to illustrate why SST is configured in its current form. This will then allow consideration of the nature of the data that is received from and about the orbital environment.

Having set the broader context, this paper will then examine the possible utility of adapting an 'air traffic' model from the UK. The paper will strike a timely note of caution about the cost of monitoring before examining the developments brought about by the European Union SST network. The paper will conclude with a novel technological proposition, the LOCI system pioneered by Northern Space and Security Ltd. This, it will be suggested, represents a low-cost, high yield solution which should be considered by all stakeholders.

This paper offers novel findings, both in respect of the technological solutions posed and the need for a shift in mindset. The paper is significant and timely, given the speed of the changes that are happening in LEO. The first element that this discussion will examine and needs to be established is how the current system of SST has evolved.

3. CONTEXT

Since the launch of Sputnik 1 on 4th October 1957, resident space objects (RSO) have been predominantly tracked by military owned and operated sensors and systems. By far the greatest contributor to global SSA has been the US Space Surveillance Network (SSN) which is a combination of optical and radar sensors used to support the Combined Space Operations Centre's (formerly Joint Space Operations Centre) mission to detect, track, identify, and catalogue all manmade objects orbiting the earth [1]. Evolution of the SSN occurred in several phases [2] and continues as an ongoing process adapting to meet the ever-changing near-earth environment. But how much of the ongoing process is dictated by the needs of the US Department of Defense [DoD] and what influence is leveraged by the needs of the international space community? Furthermore, can large government organisations adapt quick enough for the rapid changes occurring in space operations?

US planning for satellite tracking began as early as 1955, in preparation for the International Geophysical Year [3], scheduled from July 1957 through to December 1958, and over the following half century the SSN developed in 4 significant phases ultimately shaping how we monitor and support orbital operations today. Phase 1 focused on the fundamental requirement to detect, track and identify what was perceived as the ever-increasing number of RSO, both active satellites and debris. The second phase focused on the development of an operations centre in Cheyenne Mountain Airbase, Colorado Springs USA to meet the more demanding requirements for computational precision, better network communications, improved tracking capacity, accurate decay predictions, and anti-satellite (ASAT) support [4]. Phase 3 was initiated through an increase in foreign [to the USA] space launches and associated need for greater accuracy/precision; additionally, in association with space surveillance the US needed more timely warning and verification of attacks on US assets. Of note, a re-

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entering RSO has the same characteristics as a re-entering warhead and if the location of satellites is not monitored the consequences of a false response could be catastrophic. Finally phase 4, leading ultimately to the development of the Joint Space Operations Centre (JSpOC) on the west coast of the USA which was guided via a need for greater SSA to support the US Space Control agenda. Without doubt, the development of the SSN has been intrinsically linked to a developing US militarisation of space and a desire for space control/superiority.

In recent years the Combined Space Operations Centre [5] (CSpOC), has led the mission of detecting, tracking, identifying, and cataloguing all human made objects orbiting the Earth. The CSpOC replaced the JSpOC in 2018 to improve coordination between the US and its allies [6] and incorporates military operators from the US, UK, Canada, Australia, New Zealand and more recently France and Germany. To date the CSpOC continues to expand its collaboration but the focus is predominantly on the military mission to 'execute operational command and control of space forces to achieve theatre and global objectives' [7]. The space surveillance element of command and control is achieved through the operational management of a combination of optical and radar sensors predominantly operated by the US military. The CSpOC oversees the programming of the sensors and recovering and analysing the data to compile and manage the 'space catalogue'. Furthermore, the CSpOC has continued the US DoD tradition of sharing space object data, including SSA services with external entities.

The space surveillance sensors across the rebranded Allied Space Surveillance Network (Fig. 1) are divided into 3 categories: dedicated, collateral and contributing [8]. A dedicated sensor is a US Strategic Command (USSTRATCOM) operationally controlled sensor with a primary mission of space surveillance. For example, the newly commissioned Space Fence and Eglin Space Surveillance radar to name but 2 for LEO surveillance. A collateral sensor is a USSTRATCOM operationally controlled sensor with a primary mission other than space surveillance – historically missile warning and missile defence. Usually, the sites secondary mission is to provide space surveillance and therefore the sensor/system is optimised to support its primary mission. Finally, contributing sensors are those owned and operated by other agencies that provide space surveillance support upon request from the CSpOC. This may include systems such as the Haystack radar at MIT Lincoln Labs. With the advent of commercial SSA capabilities such as ExoAnalytic Solutions and Leolabs, one can assume that, depending on the service they are contracted to provide, the capabilities will fall between dedicated and contributing.

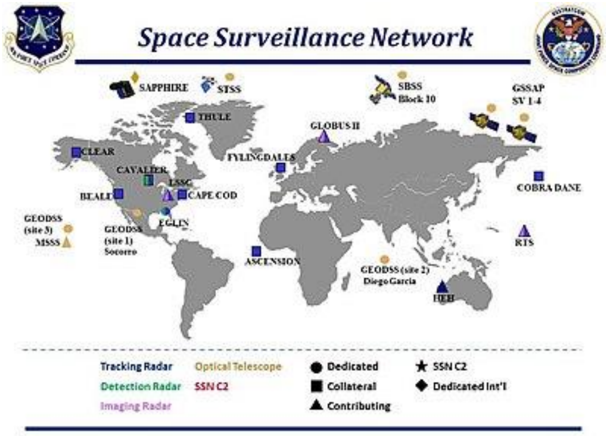

Figure 1 – Allied Space Surveillance Network

Although an 'international flavour' has developed across the operations centre its operational procedures have been shaped by a historic 'nagging concern' of US Presidents and their National Security Advisers – shaped through nuclear-armed, openly confrontational Soviet and post-Soviet governments [9]. Moulded since 4th October 1957 with military arsenals including intercontinental ballistic missiles (ICBM) and earth-orbiting satellites the military mission's priority is to secure space and therefore not necessarily funded to sustain space operations.

US political leaders remain acutely sensitive to a "Pearl Harbour" from Space and the collapse of the Soviet Union did little to dampen this sensitivity. In recent years the divergence of geopolitical tension has further stoked the fear of aggression in/from space which ultimately concluded in the admittance that space was no longer a benign environment and that, to gain space superiority a new paradigm of Space Domain Awareness (SDA) was born. In November 2019, prior to the official formation of the US Space Force, US military leaders announced "the implications of space as a warfighting domain demands we shift our focus beyond the SSA mindset of a benign environment to achieve a more effective and comprehensive SDA" …the US military has changed its posture regarding outer space and now considers it a domain of warfare [10]. Naturally this permeates across its allies also and whilst the focus is upon space superiority. This leaves the SSA needs of space operations safety, the needs of space traffic management in something of a hinterland. Certainly, data security classifications will hinder not help the sharing of data of RSO and this discussion will now consider the nature of the data that needs disseminating.

4. DATA OF SPACE

To manage the catalogue the SSN uses 2 different orbitography models: General Perturbations (GP) and Special Perturbations (SP) [11]. Access to GP data can be gained through the portals of Space-Tarck.org [12], maintained by the US Space Force elements at 18 Space

Defence Squadron, and Celestrak [13]; the latter being a direct conduit of catalogued information from Space-Track with some additional support from operators of the portal. Celestrak was originally set up to focus on satellites and astronomy by Dr T.S. Kelso and has morphed into a not-for-profit company with a mission focused on making data and other resources freely available to the space community to facilitate understanding of our orbital environment and how to use it safely and responsibly [14].

There is no legal requirement for States to collect or provide data about space. The Outer Space Treaty of 1967 talks in vague terms about States having 'due regard to the corresponding interests of other States Parties to the Treaty' This in no way can be seen to be imposing a duty for SST upon States. Whilst the 1967 Treaty talks about exploration and use of space being guided by 'the principle of cooperation and mutual assistance' [15], the military nature of SST means that the more precise SP data is not freely available. Differing levels of access can be achieved through signing SSA Sharing Agreements with the US DoD, specifically US Space Command (US SPACECOM).[16] This, therefore, means that even if the data becomes more ubiquitous and widely shared, the systems in place to manage that data need to be carefully considered. The discussion will now consider one possible model for operationalising the data of space.

5. The AIR TRAFFIC MODEL FOR THE UK

From the 1950s, as radar became sufficiently advanced to support wider coverage, the UK has operated an integrated and coordinated Air Space and Air Traffic Control System [17]. Separating the military air traffic needs from those of civil air traffic in 1962, the UK developed a National Air Traffic Service (NATS) working alongside the military air traffic controllers and coordinating with the national air defence needs. As the decade progressed, and jet aircraft became more prevalent, Britain and nations of western Europe coordinated air traffic control to prevent collisions. Although Eurocontrol was established as early as 1964 to coordinate aircraft movements across Europe as a single entity, individual nations struggled to form agreements and much of the coordination remains at the national airspace level with close links between countries to support the safe and efficient passage of aircraft across European airspace and beyond.

UK air space is regulated by the Civil Aviation Authority (CAA) of which NATS form a part – incorporated in 1996 it became a wholly owned subsidiary of the CAA. The NATS mission is to "make the skies an even safer and more efficient environment for aviation" [18] and their day-to-day role is to provide air traffic control services to support local and national airspace needs. Since its inception in the 1960's NATS has worked closely with the UK military, particularly with the air defence community of the nation. Recognising that airspace is a crucial part of the UK's infrastructure [19] the basic structure of UK airspace developed over more than 40 years, alongside the development of sensors and systems to support the needs of different elements of the community.

Civil air traffic control employs secondary radar surveillance systems to control the airspace. This requires aircraft to be equipped with a radar 'transponder'. The civil radars transmit an interrogation signal to which aircraft 'reply' with identity codes and additional information; and most transiting aircraft will comply with the requirement to actively respond. But what if an aircraft is trying to avoid detection? Military Air Defence systems still use primary radar to monitor national airspace/territory and to respond accordingly to aircraft trying to avoid detection; to police and deter nefarious actors. UK Air Defence elements closely coordinate with NATS to ensure airspace integrity, safety and efficiency are maintained and any response to nefarious actors is controlled across the territorial airspace. In other words, in the UK NATS takes care of the "day-to-day traffic" - the background noise – whilst the military can identify and respond to nefarious actors as needed. This ensures safe airspace management whilst facilitating efficient funding allocation to support the different needs of military and civil/commercial air traffic. The question remains as to whether this model can be duplicated for space traffic safety/management.

6. THE COST OF AWARENESS AND THE EUROPEAN UNION SST FRAMEWORK

The US Government Accountability Office (GAO) published a report in 2015 projecting the cost of SSA to the US Government over 5 years at an average of approximately $1BN per year [20]. And this report focused primarily on the DoD and Intelligence Communities "to provide SSA to provide critical data for planning, operating, and protecting space assets and to inform government and military operations. Recognising that the mission focus had expanded from awareness of location and projected movement of RSO to include assessment of capabilities and intent the report did not identify if it were more efficient to separate budgets to support the different military and civil objectives. Of note, this was also published prior to the development of SDA.

In the same year as the GAO status of effort report, the European Commission sponsored the formation of the European Union Space Surveillance and Tracking Framework (EUSST). Initially leveraging significant grant funding from the Galileo and Copernicus programmes for operations and from the Horizon 2020 programme for R&D. The framework brought 5 nations together the EUSST was created on the platform of national MoD supporting the development of civil SST capabilities.

Recognising the importance of space-based applications to the safety and security of Europe the European Commission established the SST Support Framework in 2014 [21]. The framework consisted of networking existing national assets (sensors and data processing capabilities) to provide operational services to European users. The overarching operational objective is to contribute to ensuring long-term availability of European and national space infrastructure, facilities, and services whilst politically the framework sought to develop "a certain amount of autonomy" [22].

Figure 2: EU SST sensor network – European distribution

A significant role model in collaboration, the initial configuration of the EUSST consisted of 5 member states represented by their designated national entities/agencies. France, Germany, UK and Italy Space Agencies and CDTI (Spain) supported by their national defence agencies. From 2018 Poland, Portugal and Romania joined the consortium with the EU Satellite Centre acting as the Front Desk of the consortium from the outset.

Operations run by the SST Consortium were structure around the 3 main functions of ground-based sensors, data processing and analysis carried out at a national level to produce SST information and services for the EU user community. Unique to the European Union was the model of national assets remaining fully in the control of member states with the final development of a database and service provision provided on a European level. Of note, 8 newly selected Member states are in the process of joining the EU SST Partnership soon. Austria, Czech Republic, Denmark, Finland, Greece, Latvia, the Netherland and Sweden [22] are all set to add capability and experience to the ever-evolving framework.

Despite all this progress on the European front, the fact remains that space surveillance and tracking infrastructure is still contingent on expensive legacy systems. It is the underpinning hypothesis of this paper that disruptive technology is needed to enable the quantum leap required to have SST capability that is fit for the challenges of the new space epoch. The discussion will now move on to assess one potential solution which uses low-cost optical technology to augment the reliance on radar.

8. LOCI – THE MARKET DISTRUPTOR

In response to the UK Space Agency "Advancing Research Into SST" call for grant funded projects [23] in the summer of 2020, Northern Space and Security Limited (NORSS) – acquired by Raytheon UK in 2022 - successfully proposed industrial research to rapidly design and deploy an extremely low-cost prototype optical camera system for LEO space surveillance. Designed from the ground up, the aim of the research was to focus on tracking and characterisation of RSO at an order of magnitude below the cost of deploying and operating space surveillance radar(s). Additionally, the system was designed to operate commercially at a significantly lower price than that of existing satellite observation telescope systems.

The novel camera system was designed around fixed-mounted cameras (Figure 3), with narrow and wide Fields of View (FoV) lenses, in a synergistic manner to achieve a higher performance than either camera system individually (Figure 4). Utilising cost-effective, efficient and simulation-driven design to take advantage of the rapid growth in consumer and scientific camera systems available commercially off the shelf (COTS).

Figure 3: The ZWO ASI6200M Camera

Figure 4: CAD model of the final LOCI camera mount design

Building on a unique association with public astronomy in the Northeast of England, NORSS were able to locate the first operational **L**ow Earth Orbit **O**ptical **C**amera Installation – LOCI - at Kielder Observatory (Figure 5). The observatory is a public outreach astronomical facility located in the Kielder forest in a remote northern region of Northumberland. As it is located at a favourable observation site within one of the largest International Dark Skies Parks in Europe the images captured by LOCI are of a high quality benefiting from the absence of light pollution and other influential factors.. The prototype LOCI has now been operating from Kielder since December 2021. In parallel with the development of an SST system the aim was also to use our association with Kielder to educate the public on the importance of satellites.

Figure 5: Kielder Observatory

LOCI is designed as an 'observation of opportunity' system meaning that the objective is to observe all objects for which the orbital geometry, site location and illumination conditions make detection possible. The system is therefore highly capable of generating large numbers of observations across a large range of objects but unlike a 'tracking system' it is not suited to "tasking". However, as LOCI has been designed as a low-cost autonomous system it can be deployed in significant numbers and locations to provide near persistent coverage of orbits at considerably less than the deployment and operational costs of a single radar.

Figure 6: LOCI Image including light streak

In its simplest form, images generated by LOCI (Figure 6) are autonomously processed to generate track data messages (TDM) and photometric data messages (PDM) to support the cataloguing requirements of SSA customers. The 2 key outputs of the image processing procedure, for each streak detected, are TDM and Light Curve generation (Figure 6). The TDM is a standard format for spacecraft tracking data and consists of the exact location and time at which the observation of the spacecraft is made.

A light curve is a change in measurement of the apparent magnitude of an object as a function of time. Of note the light curve data is beneficial for the characterisation aspect of observation and can be used to support both military SDA capabilities and to support post event analysis if a 'problem' occurs on an operational RSO.

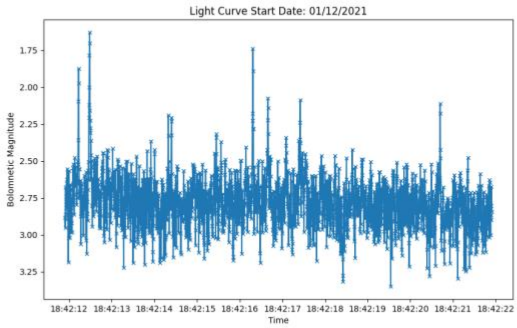

Figure 7: Light Curve generated from a streak

The economic burden traditional SSA data acquisition and processing places on all space actors is significant and yet undeniable [24]. SST is both essential and yet historically expensive. At least it is if one focuses solely on radar operations to support LEO tracking. The placement of a single LOCI observatory can cost as little as £30 000 depending on the system configuration and site at which it is deployed, its running costs negligible. In its basic catalogue supporting role the observatory will autonomously process data to 'transmit' kilobytes of TDM messages to the operations centre. Additionally, the observatories can draw on established power infrastructure or can be operated on fully sustainable energy sources such as solar or wind power. The site at Kielder is supported by the main observatory's wind turbine and energy usage is monitored to ensure there is no conflict between the main observatory operations and that of LOCI.

9. CONCLUSION

The starting point of the discussion was assessing the current context for the development of SST systems. The conclusion is that the space surveillance community is not prepared to meet the challenges of future space operations. In 2013 there were approximately 800 active satellites on orbit [25] whilst in 2019 there were approximately 1700 active satellites. Currently there are now in excess of 5000 active satellites on orbit. This figure is set to increase significantly over the next few years with the full deployment of Starlink and the development of Kuiper (amongst others). The paper has shown that the military origins of SST, coupled with entrenched methods and systems of working has seen only limited gathering and distribution of information about the space environment. It is suggested that this is a recipe for disaster.

In order to counter these difficulties, this paper poses three possible solutions. The first is the creation of a NATS style system to deal with civilian space traffic working closely but not beholden to the military agencies. National agencies need to develop at their own pace before 'amalgamating' into an international entity. Second, it is almost axiomatic to say that all States who are space active, should seek closer and meaningful collaboration with other States to close the capacity and information gap. Finally, it is suggested that disruptive technologies, such as LOCI be actively developed to increase and enhance the capability for persistent SST. Only through these interlinked methods can the current data deficit be addressed. The explosion in the number of satellites in LEO means that 'business as usual' in respect of SST is no longer an option.

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