An Overview of Space Situational Awareness

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***Abstract*— Space Situational Awareness (SSA) means different things to different people, but in its broadest view refers to a knowledge of our near-space environment. This includes both a natural and man-made component. SSA is a term that has become prominent lately due to several collisions of orbiting space objects. This paper will briefly review the realm of SSA, the means by which we gather and process SSA, and the expected increase in a wide variety of SSA sensors that will result in large and diverse data streams that will require data fusion techniques and better data display methods to render more complete our knowledge and predictability of our immediate space environment**

***Index Terms* — Space Surveillance Network, Space Debris, Space Situational Awareness**

1 DEFINITIONS

In the broadest sense, Space Situational Awareness (SSA) may be defined as a knowledge of the energy and particle fluxes in near-Earth space, natural and artificial objects passing through or orbiting within this space, including the past, present and future state of these components. The realm of near-Earth space may be left rather vague at this stage. It is definitely within cis-lunar space, but extends to an Earth-radius of at least 100,000 km to include nearly all man-made objects currently in orbit.

Not everyone agrees with this definition. Some reserve the term only for macroscopic objects in near-Earth space. The Space Foundation states that “Space Situational Awareness (SSA) refers to the ability to view, understand and predict the physical location of natural and manmade objects in orbit around the Earth, with the objective of avoiding collisions”[1]. Not only is this very restrictive, but it is not very useful, as most natural objects do not orbit the Earth, but rather transit through near-Earth space.

The European Space Agency (ESA), however, uses the fuller definition, and specifically lists three segments of knowledge in SSA: “SST - Space surveillance and tracking of objects in Earth orbit (Watching for active and inactive satellites, discarded launch stages and fragmentation debris that orbit the Earth). SWE - Space weather (Monitoring conditions at the Sun and in the solar wind, and in Earth's magnetosphere, ionosphere and thermosphere, that can affect space-borne and ground-based infrastructure or endanger human life or health). NEO - Near-Earth objects (Detecting natural objects that can potentially impact Earth and cause damage).”[2]

The US Strategic Command, which possesses the largest SST assets on the planet, defines SSA as "the requisite current and predictive knowledge of space events, threats, activities, conditions and space system (space, ground, link) status capabilities, constraints and employment -- to current and future, friendly and hostile-- to enable commanders, decision makers, planners and operators to gain and maintain space superiority across the spectrum of conflict."[3] This includes not only the knowledge of the space segment, but also the ground based capabilities that enable the knowledge, as well as specifying the reason that SSA is important to this organisation.

A good SSA is invariably linked to threats and hazards, but SSA can also provide opportunities to both mitigate or reduce the hazards, and even to benefit from the potential resources present in both man-made and natural debris.

2 HISTORY

On January 10, 2007, the Chinese launched a KT-2 missile toward an old non-functional Chinese weather satellite (Feng-Yun 1C). The resulting hypervelocity collision demonstrated that China was now the third nation with anti-satellite (ASAT) capability (behind Russia and the USA). It also created the largest cloud of space debris in our space-faring history – debris that will remain in orbit for hundreds of years and debris that routinely threatens the International Space Station several times a year.

The US followed this in 2008 with the destruction of a failed reconnaissance satellite due to re-enter the Earth’s atmosphere with a load of highly toxic fuel. Fortunately the debris from this collision was all gone within a few months. The low altitude at which the fragmentation occurred insured that atmospheric drag removed the debris very quickly.

The above two collisions were intentional. However, in February 2009 a collision occurred between an active Iridium communication satellite and a defunct Russian satellite. This was at an altitude that will ensure a long life for the resultant debris cloud. It was really this totally unexpected accidental collision that catapulted the concept of Space Situation Awareness to the fore.

3 THREE COMPONENTS OF SSA

The three components of SSA are shown in figure 1. These components are a knowledge of space weather – the electromagnetic and sub-atomic particle fluxes incident on the Earth, and which are mainly derived from solar activity; a knowledge of the current man-made orbital space object population and the means to propagate this state into the future; and a knowledge of the flux of natural space debris that transits through and/or impacts upon the near-space environment, including the Earth.

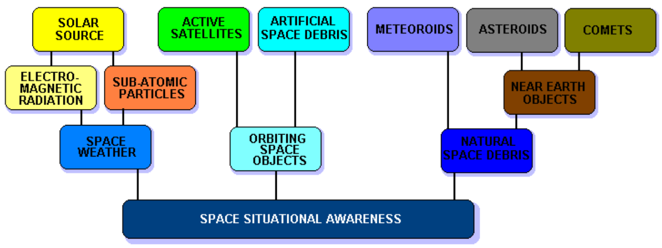

Figure 1. Three components of SSA

4 SPACE WEATHER

The source of most of our space weather is the Sun. We can separate this into a background and a transient component. This division and the classification of the sub-components is illustrated in figure 2.

The transient components of space weather can impact the orbital population of active satellites and space debris. Global ground-based and space sensors continually monitor space weather. This data and forecasts derived from it are made available by regional space weather centres.

In the USA this space weather information is available from the Space Weather Prediction Center [4], in Australia from IPS Radio and Space Services [5] and in Europe from the European Space Weather Portal [6].

5 NATURAL SPACE DEBRIS

At the beginning of the space age, there was considerable concern about the natural meteoroid flux and its possible impact (literally) on satellites that were placed in Earth orbit. Some of the first scientific sensors on early satellites were meteoroid detectors.

Fortunately the natural space debris flux transiting orbit is small enough not to cause serious problems, although a few Space Shuttle windows were replaced due to impacts from small pieces of natural debris (most window replacements however, were due to artificial space debris impacts).

Figure 4 shows the average meteoroid flux through low Earth orbit. It normally requires a particle of at least one centimetre to cause major spacecraft damage.

This flux translates to the expected loss of one satellite every 20 years, given a current active satellite population of around 1000.

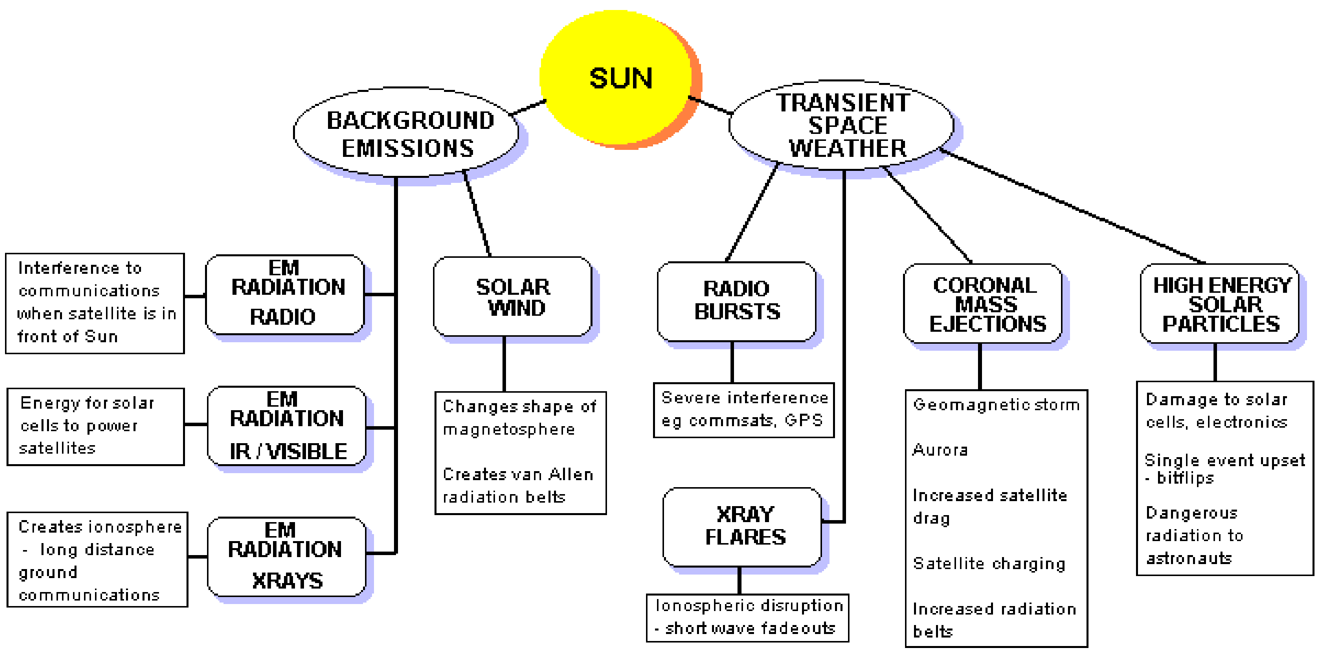

Figure 2 An Overview of Space Weather

Figures 2 and 3 indicate some of these and other effects of severe space weather. Increased and variable atmospheric drag can impact the ability to propagate satellite orbits to future times. Single event upsets can influence the ability to control a satellite's attitude, and in extreme cases, ability to station-keep in geosynchronous orbit. Radiation damage to solar cells can reduce the useful life of a satellite, and thus the income such an asset produces commercially.

The transition from meteoroid to asteroid is ill-defined but is often given as around 10 metres in diameter. The size range of comet nuclei is even less well known. As object sizes increase so does the number of known objects decrease. It is estimated that there exist around 1000 asteroids with diameters of one kilometre or greater that could pose a hazard, not to satellites, but to the Earth itself (or rather human society). Most of these objects have been detected and have

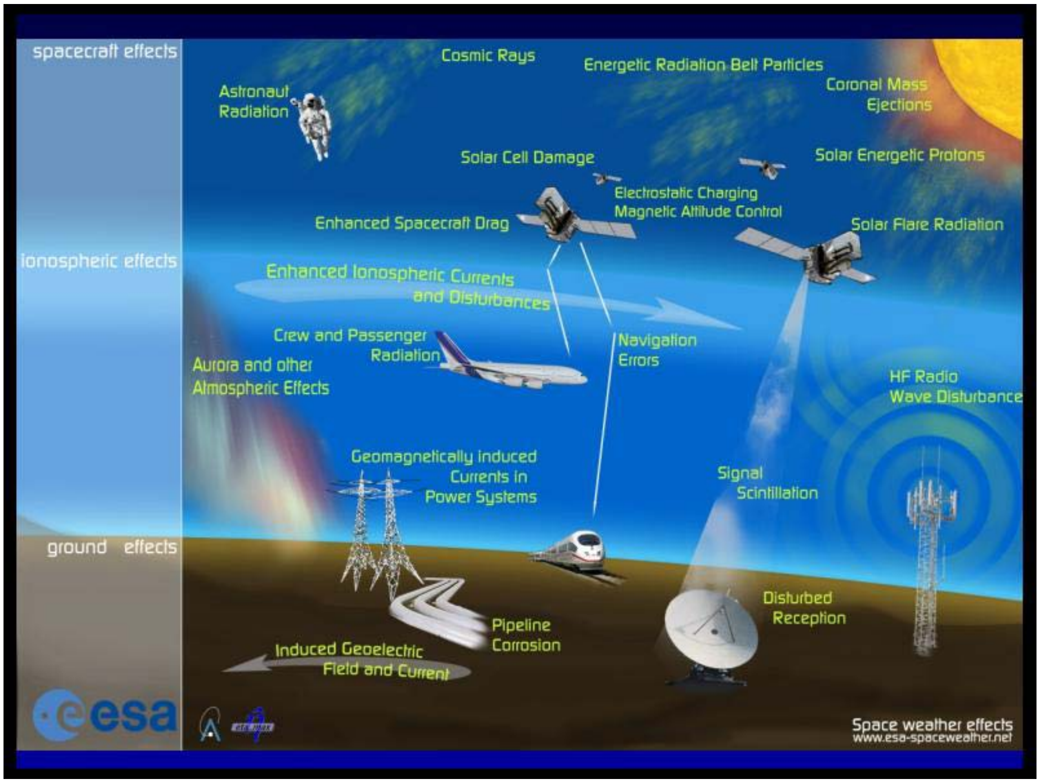

Figure 3 Some Effects of Space Weather (Credit: European Space Agency).

reasonably well-known orbits. Objects above 100 m in size are believed to be much more plentiful (~10,000) but only a fraction of this population has been detected. Objects less than 100 m in size are virtually undetectable with current technology, unless the body approaches close to the Earth. Due to their hypervelocity, such pieces of rock have kinetic energies measured in multiple megatons of TNT, and are quite capable of destroying a city if a direct impact occurred. On February 15, 2013 a meteoroid of around 15 m in size with a mass of 7000 tons, deposited 300 kT TNT energy over a Russian city in the Ural mountains, shattering windows and injuring around 1000 people. On the same day a larger (about 45 m) asteroid passed below geosynchronous orbit with an energy of around 2.5 MT TNT.

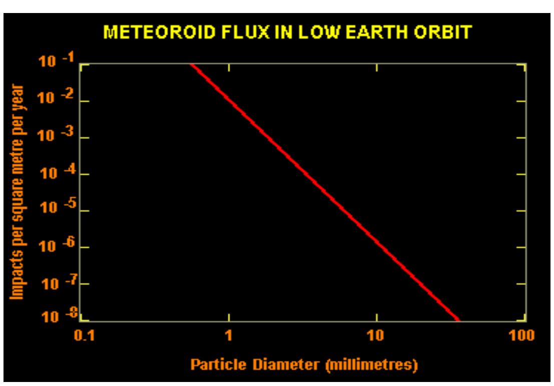

Figure 4 Natural Space Debris as a Function of Size

Many observatories, including many amateur astronomers are devoted to the detection of near Earth objects (NEO), and routinely provide positional data to the Minor Planet Center [7]. Orbital dynamics and predictions of NEOs are computed and made available via JPL [8] and the University of Pisa NEODYS site [9].

6 ORBITING SPACE OBJECTS

6.1 Overview

Orbiting space objects (OSO) consist of active satellites and space debris. The latter are a mixture of defunct satellites, launch vehicles and pieces of space hardware produced by operational activities, deterioration and fragmentation.

A large part of SSA for OSO consists of the tracking of these objects with the aim of creating a catalog of such objects. The catalog then forms the basis of orbital evolution and conjunction assessment; the latter with the aim of protecting active assets from collision. In the future this will also extend to the minimisation of space debris production through collision

SSA also extends to knowledge of the space capability of each space-faring State. Manoeuvre analysis is often necessary in attempts to determine spacecraft functionality. Some states use catalog information to determine overpass times for intelligence spacecraft in order to hide certain ground-based activities from enemy eyes. Figure 5 gives an overview of the areas associated with SSA for OSO.

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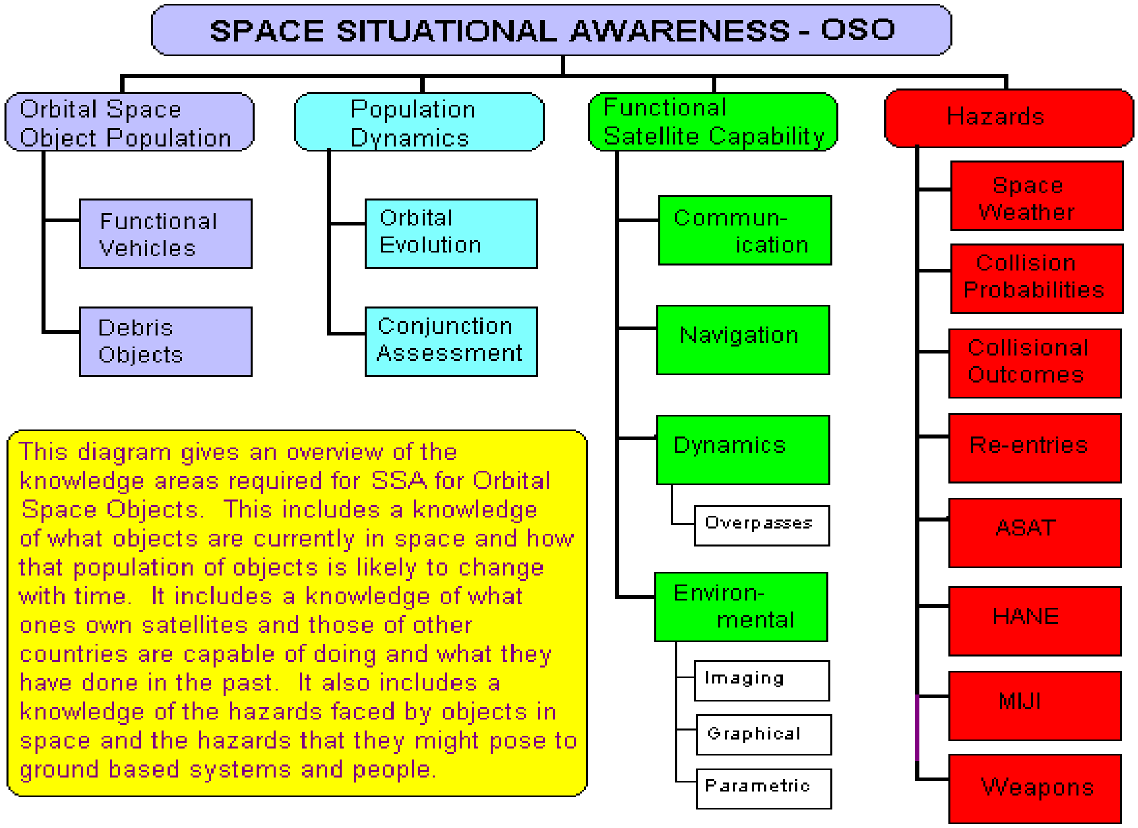

Figure 5 Knowledge Areas for SSA of Orbital Space Objects

Modelling collisional probabilities and outcomes is very important for the prediction of the evolution of the orbital space debris population. Re-entries of large orbital space objects pose a small hazard to humans on the ground. Anti-satellite (ASAT) activities pose a problem not only to the targeted spacecraft, but also to the entire orbital population through the generation of large amount of space debris. High Altitude Nuclear Explosions (HANE) have the potential to cripple large numbers of active satellites through the electromagnetic pulse (EMP) produced and the increased hazard of trapped radiation (which may last for months). Although space-faring states are unlikely to resort to HANE in any war, rogue states and possibly large terrorist organisations (particularly those sponsored by state organisations) may view this as a way to 'equalize' asymmetric warfare capabilities MIJI is a US military term that stands for Meaconing, Intrusion, Jamming and Interference. Ground and space-based MIJI has already been encountered by some space operators. The US military has set up a system to rapidly determine and locate interference to space assets. Weaponisation of space (threatening ground and space assets) is a problem of concern to some organisations, particularly with respect to the enforcement of treaties regarding the militarisation of outer space.

6.2 Orbital Space Debris

Orbital space debris (also referred to as artificial or man-made space debris) is basically any space object of hardware fragment that no longer has a useful function. (Note that some satellites are launched and put in orbital storage until required. These are obviously not pieces of space debris, even though they are currently non-functional).

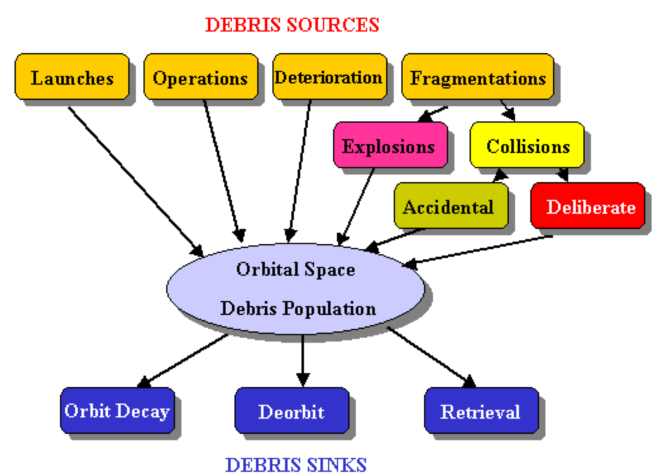

Figure 6 Factors in the Orbital Space Debris Population

The production of space debris started with the launch of the first artificial satellite, Sputnik-1, in October 1957. Typically, every space launch produces around 100 pieces of debris, from launch vehicles which remain in orbit, to discarded shrouds, to smaller fragments produced by pyrotechnic devices used to separate the satellite from the launch vehicle. Figure 6 shows this and other debris sources, as well as debris sinks.

At present most fragmentation debris is produced by explosions that result from stored energy in launch vehicles and defunct satellites. This includes unspent fuel and batteries. Less than half a dozen accidental collisions have been reported up to the end of 2012. However, this state of affairs is not likely to continue.

In 1978, Donald Kessler published a paper [10] in which he showed that continued production of space debris will eventually lead to a chain reaction where accidental collisions will increase exponentially, creating a debris shell in low-Earth orbit that will render further operations in this orbital space impossible. This condition has even been named the Kessler Syndrome. Because of this, together with the damage thus have more in common with explosive events than they do to low speed collisional events. Even specks of paint can be dangerous. Over 100 windshields of the NASA Space Shuttle had to be replaced due to damage by hypervelocity collisions with paint specks created by degradation of painted surfaces on other satellites.

Figure 7 is a NASA graphic showing the sizes of impactors and the typical effects of a hypervelocity collision of such an object with the Space Shuttle.

A particle size of one centimetre is typically regarded as the transitional size above which severe damage to a satellite or spacecraft is produced. The current dedicated sensors or the US Space Surveillance Network are not able to track or provide orbital information on particles this small. Collision with a 10 cm sized object will generally result in total destruction of an active space asset.

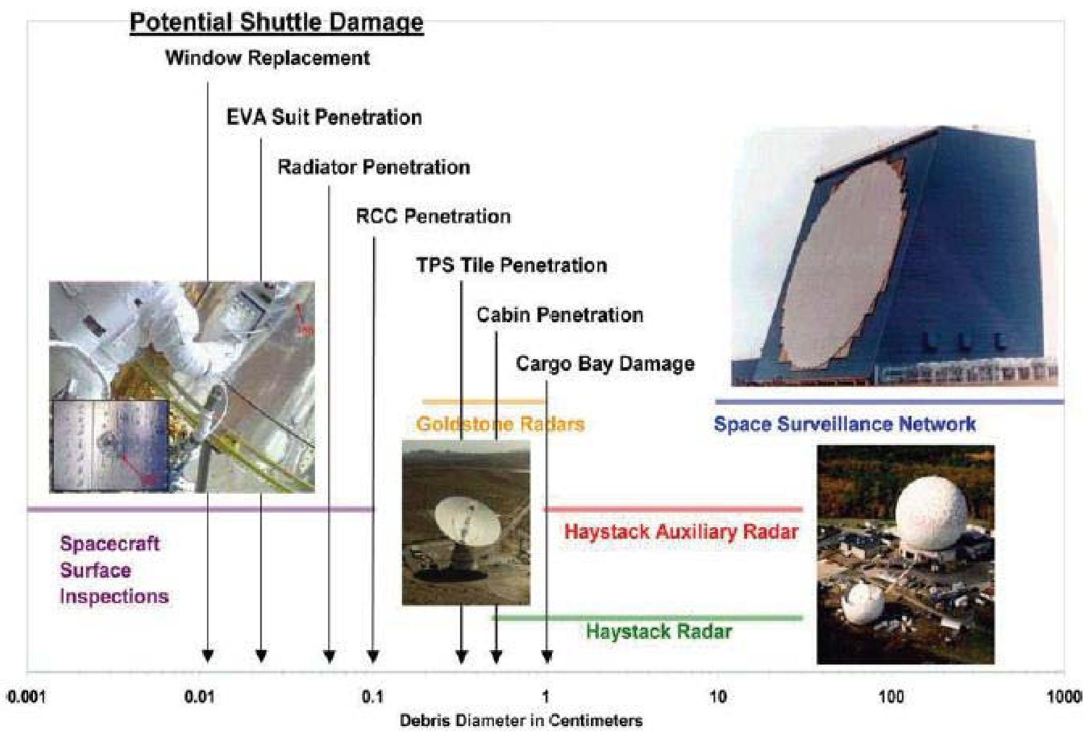

Figure 7 Impact Damage Regimes for the US Space Shuttle (Credit: NASA/ODPO)

that a collision with even a small particle can cause to an active satellite, space debris mitigation is a high priority concern for SSA.

6.3 Hypervelocity Collisions

Orbital velocity in low-Earth orbit is around 7 to 8 km/sec. Obviously, collisional relative velocities can vary from near zero up to nearly 16 km/sec. Because of orbital dynamics the average relative velocity between two colliding objects is around 10 km/sec. These velocities are termed hyper-velocities because the kinetic energy carried by a particle at these speeds is in excess of the energy that the same mass of high explosive (e.g. TNT) would release if detonated. The transitional velocity at which this occurs is around 3 km/sec, when $K/m = \frac{1}{2} v^2 = 4 \times 10^6$ J/kg. Hypervelocity collisions

6.4 The Orbital Space Debris Population

Figure 8 is a graph from the NASA Orbital Debris Program Office (ODPO) showing the increase in the orbital space object population since 1957.

Currently (early 2013) the US Space Surveillance Network (SSN) tracks almost 20,000 orbital space objects above about 10 cm in size. Of these, only 1,000 are active satellites. The step increase in early 2007 is due to the deliberate collision of a Chinese ASAT missile with a defunct weather satellite. A much smaller increase in 2008 is due to the US destruction of a classified reconnaissance satellite. The debris generated in this deliberate collision quickly disappeared from orbit due to the low altitude of the event and the subsequent atmospheric decay of the fragments. The third step increase in 2009 was due to an accidental collision of an active Iridium communications satellite with a defunct Russian communications satellite. The events in 2007 and 2009 occurred at such an altitude that normal decay of the collisional debris will take hundreds of years to occur.

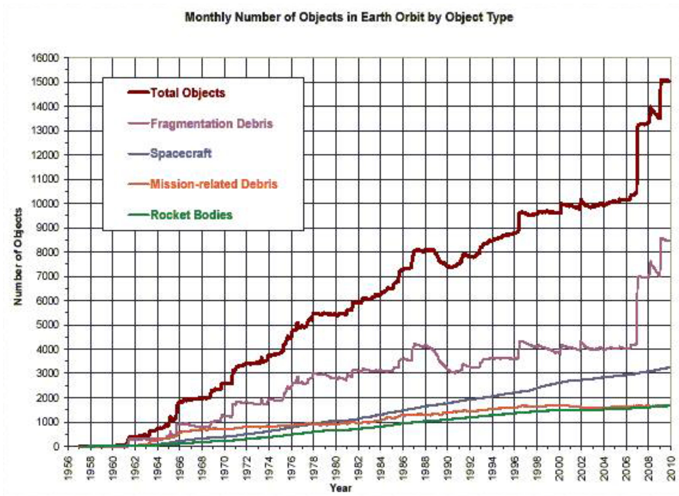

Figure 8 The Low Earth Orbit Object Population in 2010 (Credit: NASA/ODPO)

The NASA OPDO produces a quarterly newsletter [11] with updates on the tracked orbital space object population, together with news of the latest research findings and meetings related to orbital space debris.

6.5 Tracking Orbital Space Objects

The United Nations Office of Outer Space Affairs (UNOOSA) maintains an on-line catalog [12] of objects launched into space. This is compiled from information supplied by member states.

The US has by far the largest network of sensors that track orbital space objects, with some 20 sensors deployed globally. These include radar and optical systems. The prime instrument in this network is a ‘space fence’, which is an extremely powerful non-tracking radar system located at Lake Kickapoo near Wichita, Texas and other sites across the USA. Figure 9 shows an image of the 3-km long transmitter array.

This array creates an east-west fan beam with an effective radiated power of 6 GW. Space objects passing through this beam reflect energy back to receiving stations on the ground which record time, intensity and Doppler shift of the echoed signal. This system processes over 10,000 observations per day. Because this system is non-tracking it is able to start the generation of a space object catalog with no a priori information. In contrast to this, other sensors, most of which track, require approximate positional data to provide more accurate orbital information. One such backbone of the US SSN is the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) system. The GEODSS system on the island of Diego Garcia is shown in Figure 10. This employs two one-metre and one 40 cm optical telescopes to track space objects in all possible orbits around the Earth.

Figure 9 The US Space Fence Transmitter Array (Credit: US Navy image)

Figure 10 GEODSS on Diego Garcia (Credit: US Navy image)

The data from the diverse systems of the SSN feed into the Joint Space Operations Center (JSpOC) in California which compiles the US Department of Defense (DoD) space object catalog (SATCAT or SATC). Data for all tracked objects is available in a low resolution format (Keplerian orbital elements). A higher precision catalog is also compiled for a limited set of objects, and this is in state vector format (position and velocity at a specified time). Both of these formats must be propagated forward in time using a particular model which includes perturbational forces due to the Earth’s non-sphericity, atmospheric drag, radiation and lunar and solar gravity. The low resolution catalog is made available publicly [13] for all but US (and some other) military satellites.

While the US SSN and its SATC are by far the largest source of information on orbital space objects, they are not the only ones who track OSO. Russia maintains its own catalog. Most of the Russian sensors lie in the Asian continent, but this is supplemented by mobile surveillance vessels. Figure 11 shows one such vessel.

Figure 11 Russian Space Tracking Ship "Gagarin" (Credit: US Navy image)

The European Space Agency has also begun an initiative to build their own independent space surveillance network [14], having been frustrated by deficiencies (resolution and timeliness) in the sharing of the US SSN data.

A group of around 100 dedicated amateur space observers [15] routinely make observations of the larger space objects in low Earth orbit and produce a catalog of about 100 military satellites that do not appear in the US SATC.

Satellite operators/owners frequently know the location of their assets more accurately than does the US SSN, either through ranging data (GEOsats) or the inclusion of a GPS unit (LEOsats) in their satellite. The US JSpOC has thus set up a Commercial and Foreign Entities (CFE) program to exchange and ingest this data.

The new large array radio telescopes that are coming on line in the next few years may also be a source of space track data, using OSO reflections from existing TV and FM radio transmitters on the ground.

6.6 Catalogs, Accuracy and Processing

The SATC currently does not have the accuracy (spatial position) to perform adequate and routine conjunction assessment (CONASS) on the large number of OSO. It also does not contain information on debris down to the critical size of one centimetre. These limitations are basically due to sensor constraints. The US DoD does have plans to upgrade the SSN with equipment that will provide more accurate positional information on all objects down to one centimetre. One example of this is an S-band space fence. The current space-fence operates at the VHF frequency of 217 MHz. An S-band (2500 MHz) version of this will allow detectable returns from the smaller sized objects. Problems with the current US SSN are discussed by Brian Weeden [16,17], technical advisor for the Secure World Foundation [18].

Duplication of the newer space fence in the southern hemisphere will also provide a greater number of observations with which to compile a more accurate and complete catalog. Space situational awareness operators will require new techniques of data processing and visualization to be able to rapidly monitor and interpret changes in the environment of interest, with data incoming from multiple diverse sensor systems spread around the globe and in space. Some software for SSA is available commercially [19] and there is an effort underway to try to develop open source software for this field.

One of the problems with such an increase in sensor capability is the vastly increased computing power, transfer bandwidth, storage and efficient processing software to deal with this increase in data. The study [20], by the Committee for the Assessment of the U.S. Air Force's Astrodynamic Standards: Aeronautics and Space Engineering Board, identified data association and fusion of information as two key problems in tracking multiple space objects. The recommendation in [20] is based on the traditional view that data association is quintessential to multiple object tracking. Data association refers to the partitioning a set of observations into tracks/orbits and false reports. Information fusion refers to combining information associated with a common object from one or more sources to improve the state or understanding of the object.

From a fundamental estimation perspective, data association is only an auxiliary problem while the main objective of multiple object tracking is to determine how many objects are there and what are their states. Thus it is more prudent to focus on the main problem of estimating the number and values of the trajectories using available data from various sources, rather than focusing on partitioning the data sets and fusing information. While the current data association techniques were sufficient to handle past needs, future demands will require new nonlinear multiple object estimation algorithms. Apart from tracking space objects, the related problem of management or scheduling of available sensors to perform various space surveillance tasks is another key area where new techniques are needed.

6.7 Multiple Object Dynamical System Theory

From a methodological viewpoint, the tracking and sensor scheduling currently used in Air Force Space Command (AFSPC) can at best be described as a chaotic collection of techniques. The data association method currently used in AFSPC algorithms is a deterministic gated association method called Report Observation Association, which worked for widely spaced objects in the space catalog and against a benign background, but breaks down in more challenging scenarios such as LEO breakups and GEO clusters. A top down systematic approach to space surveillance calls for a system theoretic framework for tracking and sensor scheduling.

The system of space objects and sensors (ground-based or air-borne) such as radars and optical sensors, is an example of a multi-object system. Such a system is characterized by stochastically varying sets of states, stochastically varying sets of collected data and stochastically varying sensor parameters. Analogous to conventional dynamical state space systems, optimal estimation control are two fundamental problems. Since the 1970s, a host of multi-object filtering techniques and applications has been accumulated, see for example texts such as [21, 22, 23, 24]. The three major approaches are Multiple Hypothesis Tracking (MHT) [25, 26], Joint Probabilistic Data Association (JPDA) [22], and Random Finite Set (RFS) [23]. MHT and JPDA are classical approaches that dominated the field of multiple object tracking.

The Random Finite Set (RFS) approach is the latest development that provides a general treatment of multi-object system by modelling the multi-object state as an RFS. This abstract state-space representation of multi-object system is an ideal candidate platform for developing top-down algorithmic solutions for space surveillance. The essence of the RFS paradigm is the adoption of a Bayesian stochastic geometric approach to statistical estimation. The Bayesian component is adopted for its suitability to recursive online inferencing as well as the fusion of heterogeneous sources of data. The stochastic geometric component further accommodates a formal and systematic modelling of systems with multiple states and observations. This approach provides a unifying framework for information fusion including non-tradition uncertainty representation and reasoning, estimation, classification and target tracking. It has already produced some remarkably promising results in target tracking and robust Bayesian estimation [23]. Recent development in generalized labelled Multi-Bernoulli (GLMB) RFS is an important result which lead to an analytic solution to the Bayes multi-object tracker [27]. The RFS framework is thus ideally suited to networked multi-sensor multi-object estimation problems, such as SSA.

Research in using the RFS paradigm for SSA are already underway. A prototype large scale tracking system for the US space fence programme that combines both MHT [25] and the GMCPHD filter [28] was developed by Lockheed Martin [29, 30, 31]. DSTO Australia has also developed significant capabilities including robust Bayesian estimation and classification using random set representation of imprecise likelihoods and/or imprecise measurements, sensor scheduling for multiple object tracking, more details can be found in [32]. AFRL has also developed SSA capabilities using RFS for joint detection and tracking of at most one target with significant nonlinearities [33, 34].

7 CONCLUSION

The number of active satellites is increasing slowly, but the number of pieces of artificial space debris is rapidly increasing and may soon reach a critical population size where accidental collisions will cause a runaway exponential increase in the number of orbital space objects. Monitoring of the near-space environment is becoming more critical to enable conjunction assessment with subsequent collision avoidance in cases of high-value space assets. A new generation of space situational sensors together with an increasing number of states who wish to perform independent SSA analysis is projected to give rise to a large and diverse array of measurements and analysis techniques that will require data fusion and innovative display techniques to give a useful tool for planning and operational purposes. This will need to be combined with space weather data and data on near-Earth objects to provide a truly integrated and meaningful approach to SSA.

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