Space Surveillance Network
for
A More Complete Catalog

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ABSTRACT

Currently the U.S. Space Surveillance Network can track and catalog objects as small as 5 – 10-cm in size. However, operational satellites can be damaged or destroyed by debris as small as 0.1 – 1-cm. This creates a need for improved space surveillance for collision avoidance and a more complete catalog of resident space objects. A number of studies or initiatives were undertaken in the 1990’s to improve the sensitivity of the Space Surveillance Network. Although dated, the methodologies and many of the conclusions are still valid today. This paper will concentrate on two of these studies in which NASA either led or participated. First, it will look at a study done in 1992 which examined the requirements and produced a conceptual design for a Collision Avoidance Network to protect the Space Station Freedom from centimeter-sized orbital debris, while minimizing collision avoidance maneuvers. Second, the paper will summarize a study led by Air Force Research Laboratory, Los Alamos National Laboratory, and Lawrence Livermore National Laboratory, at the direction of the 1998 Senate Armed Services Committee authorization bill, which sought to track and catalog 1-cm debris to an altitude of 1000 km.

Introduction

A major part of the space surveillance task is to perform collision warning for high value satellites such as the Space Shuttle, Space Station, and other critical assets. Recent events have highlighted the need for improved space surveillance and cataloging of man-made orbital debris. Although there have been three known examples of unplanned collisions in orbit involving objects tracked by the U.S. Space Surveillance Network (SSN) (Ref. 1), none have been catastrophic producing only one to four additional pieces of tracked debris per collision. However, in January 2007, an intentional collision of an anti-satellite (ASAT) weapon with the Chinese Fengyun 1C spacecraft showed just how damaging to the environment collisions between resident space objects can be. The Fengyun breakup produced more than 2500 trackable debris fragments and increased the size of the SSN catalog by over 25%.

In addition, the current SSN can only catalog and track objects larger than 5 to 10-cm, while operational satellites can be seriously damaged or destroyed by collisions with orbital debris larger than about 0.1-1.0 cm. The increase in population and the continued gap between the object size that can be tracked and the size which can damage satellites shows a need for significant improvements to the current SSN. Current efforts to improve the SSN can leverage past studies which had similar goals. These initiatives include:

- A 1992 NASA study (Ref. 2, 3, and 4) to determine if collision avoidance could be provided for the Space Station Freedom for objects down to 1-cm in size. The proposed network would have cataloged 1-cm objects to 600 km altitude.
- A 1996-97 study by the Space Debris Task Team (SDTT) (Ref. 5) consisting of NASA and the Air Force Space Command (AFSPC) personnel who were given the task to “examine Space
Surveillance Network capabilities to enhance orbital debris data collection and processing on objects (as small as 5 cm) not currently in the satellite catalog."

- A 1997-98 study (Ref. 6) led by Air Force Research Laboratory, Los Alamos National Laboratory, and Lawrence Livermore National Laboratory, at the direction of the 1998 Senate Armed Services Committee (SASC) authorization bill, which, “directs the Secretary of the Air Force to undertake a design study of a system that could catalogue and track debris down to 1 centimeter in size out to 1,000 kilometers in altitude.”

- A U. S. General Accounting Office (GAO) report released in December, 1997 on Space Surveillance (Ref. 7) which recommended that “the Secretary of Defense and the Administrator of NASA, in consultation with the Director of Central Intelligence establish a consolidated set of government-wide space surveillance requirements...” and that they “develop a coordinated government-wide space surveillance plan ...”

Although these studies date back as far as 15 years, the methodologies and many of the conclusions are still valid today. This paper will concentrate on the 1992 Space Station Freedom study and the 1997-8 SASC mandated study.

The 1992 Space Station Freedom Study

Background In August 1992, NASA was designing the Space Station Freedom. Plans for protecting the station from meteoroid and orbital debris (M/OD) included shielding it against penetrations from objects as large as 0.8 cm and performing collision avoidance maneuvers against objects in the USSPACECOM catalog, which then included objects as small as the nominal size of 10 cm. This left a gap in debris size to which the station was vulnerable. In August, the NASA Administrator directed that the Space Station Program Office undertake studies which would effectively eliminate this gap. Two study teams were formed in September. The first team studied enhanced or augmented shielding for the station. The second team studied improved tracking techniques.

The tracking team set out to answer the question “was performing collision avoidance for Freedom against objects \( \geq 1 \) cm diameter within current technology?” The team reported to the head of the Space Station and the Associate Administrator for Space Flight on December 4, 1992 that it was within the available technology and they proposed a conceptual network of sensors which could perform the job. The estimated cost of $450-550 million to design and build the network was considered too high and no further work on the concept was performed.

Summary of Findings

Current vs. New Sensors

One of the significant findings, which shaped the 1992 study, was that the existing sensors of the SSN could not be readily upgraded or modified to meet the goals of the study. Radars in the SSN generally operate at UHF wavelengths of ~70 cm. Figure 1, based on the NASA Size Estimation Model (Ref. 8), shows that at the 70-cm wavelength, objects ~12 cm and smaller are in the Rayleigh scattering regime. In the Rayleigh regime, the radar cross section (RCS) of an object falls off as the 6th power of the diameter. Therefore, in order to upgrade a UHF radar so that it will have the same sensitivity for a 1-cm object that it currently has for a 10-cm object, the power/sensitivity would have to be improved by 60 dB. This was deemed to be an unacceptable solution. Similarly, existing optical sensors in the SSN were not capable of detecting 1-cm objects. Therefore, new sensors were needed to catalog 1-cm debris.
Having eliminated existing sensors, the team started from the ground up looking at the requirements that a new network optimized for the SSN collision avoidance network must meet.

Network Requirements and Tasks

A collision avoidance system (CAS) must perform three tasks: 1) it must generate the catalog of small debris objects; 2) it must maintain the catalog for all objects in the orbital space of interest; and 3) it must reduce the orbit uncertainty for the subset of objects predicted to collide with the high valued target. A fourth, non-mandatory task is to provide imminent collision warning against objects, for which a collision avoidance maneuver is not, or no longer, possible, but for which other mitigating options exist.

In order to generate a debris catalog, a search volume must be established. That volume must search all orbital space within a time period that is short when compared to the lifetime of the objects to be cataloged. In the 1992 study, the SSF was to have flown as high as 450 km altitude during periods of high solar activity. 600 km was chosen as the top of the altitude band of interest. Studies of area-to-mass of debris and orbital lifetimes indicate that some debris can reenter from 600 km in 13 days (area-to-mass of 1.0 m²/kg) during periods of high solar activity. Therefore, the complete orbit space between these two altitudes should be searched in a time span that is shorter than 13 days. If the probability of detection is less than 100%, then it is desirable to search the volume more than once in the allotted time. Once an object is detected and identified as an “unknown,” or uncorrelated target (UCT), the detecting sensor must be able to predict the orbit far enough ahead to be able to locate and track the object at the next track opportunity. The next track opportunity may be by the detecting sensor or by another sensor in the network. After a sufficient number of tracks are performed, an orbit can be determined and the object can be entered into the catalog.

When a sensor updates the location of an object, that location is known to within some error ellipsoid. Subsequent to the measurement time, the error ellipsoid grows due to such things as uncertainties in atmospheric drag or errors in the propagators until the next time that the object location is updated by another sensor. The lower an object is in altitude, the faster the error ellipsoid grows due to the increase in the effects of the atmosphere on the object. If the error in predicted position at the time of the next sensor observation approaches the mean distance between objects, the catalog will fail because re-identification will be impossible. In other words, to perform catalog maintenance, the orbital elements must be maintained well enough to correlate an observation. This is a much less restrictive requirement than the conjunction update task, which will be discussed next, but this requirement applies to all objects in the catalog. The study concluded that in order to maintain a catalog of 1-cm debris, the orbits would have to be updated at least daily. Since this had to be done for the entire catalog, capacity of the sensors was a driving issue. It was determined that one or more of the radars in the network needed to be either a phased array radar or an interferometer fence radar in order to accomplish this task.

A computer program called the Calculation of Miss Between Orbits (COMBO) determines close approaches between high valued targets and all other cataloged satellites including debris. The 1992 study called these close approaches “conjunctions.” Simulations have shown that only a few objects per day would be predicted to come close enough to the SSF to cause concern. For these objects, it is necessary to update the orbit in order to decrease the uncertainty in predicted location at the time of the conjunction. One of the objectives of the SSF was to perform microgravity experiments. The SSF requirement was to have a 60% probability of achieving 6 periods
of 27-30 contiguous days without maneuvering, giving a maximum number of 10 collision avoidance maneuvers per year. Given the number of objects of size >1 cm, this translated into an error ellipsoid at conjunction of 400-m downrange and 80-m radial and crosstrack. The error ellipsoid would be smallest at the time of an observation by a sensor, and, at the low altitudes of SSF, this would grow quickly due to atmospheric drag uncertainties. It was estimated that an observation would need to be made within two orbits of the predicted conjunction to meet the 80 x 400 x 80-m maximum error ellipsoid requirement. Since there would only be a few objects per day with predicted conjunctions, these could be handled by lower cost “pencil” beam, dish antenna radars. Optical sensors were rejected because of the probability of not having the correct lighting or weather conditions when an observation was needed.

An observation too close in time to a predicted conjunction would not be useful for collision avoidance. There is a minimum time required to process the data, make the decision to move the station, make the maneuver, and for the maneuver to take effect. This time was likely to be from ½ to ¾ of the period of the SSF orbit.

Proposed Network

The conceptual collision avoidance network developed during the 1992 study is shown in Figure 2. It utilized two radars that were being developed at the time. The first was the Ground Based Radar X-band (GBR-X) which was an X-band (3-cm wavelength) phased array radar that was planned for deployment on Kwajalein Atoll in the Marshall Islands. As a phased array radar, GBR-X would have been capable of erecting a debris search fence while simultaneously tracking several targets. Therefore, it could contribute to all three of the CAS tasks. GBR-X was never built as designed, but a variation of the design was developed and deployed as the GBR-P (Ground Based Radar - Prototype) (Figure 3).

The second radar under development was an X-band radar with a mechanically steered, dish antenna design. As a dish radar, it could only track one object at a time and, therefore, was limited to the conjunction update task, which involved tracking a small number of objects. This radar has now been deployed as the Globus II radar in Norway (Figure 4). Globus and GBR-X were being built by the same contractor and shared many of their major components, including transmitter tubes.

GBR-X and four dish radars were to be located with roughly equal spacing within 180° of longitude and as close as practical to the equator. GBR-X was to be located at its planned site at Kwajalein, while the dish radars were to be located at South Point, Hawaii, Vandenberg AFB, California, Kennedy Space Center, Florida, and Kourou, French Guiana. With this arrangement, the five radars could see any low Earth, near circular orbit on either its ascending or descending passage and guaranteed that an object could be seen at least once every 2 orbits (in fact, for most orbits, the objects could be seen on every orbit).

GBR-X would not, by itself, have the capacity to maintain the orbits of all of the 1-cm debris below 600 km. An additional sensor was planned. At the time of the study, the U.S. Navy operated a VHF interferometer radar called NAVSPASUR, which erects a fan beam in an east-west orientation across the continental U.S. (Although still in operation today, the radar has undergone two name changes. From NAVSPASUR, the name was changed to the Navy Space Surveillance System, or NSSS. Later, the radar was turned over to the Air Force and is currently known as the Air Force Space Surveillance System, or AFSSS.) Orbits are determined by the location and time between penetrations of the fence. The interferometer concept can inherently
handle a very large number of satellites. It also sets up a very large detection volume. If the fence covers $15^\circ-17^\circ$ of longitude (earth center angle), then each object is guaranteed of being detected at least once per day. The 1992 study proposed replacing the VHF interferometer with an X-band system (called the Debris Interferometer Fence Radar [DIFR]) using as many components in common with GBR-X and Globus as practicable. The CONUS location limited the radar to detecting orbits with inclinations $>33^\circ$.

The DIFR would perform the catalog generation and maintenance tasks for objects with orbits $>33^\circ$ inclination, while GBR-X performed the same tasks for objects with orbits $<33^\circ$ inclination. GBR-X and the four dish radars would perform the conjunction update task.

The Senate Armed Services Committee Mandated Study

Study Goals

This study was conducted in response to Congressional language from the 1998 Senate Armed Services Committee (SASC). The SASC directed that the goals of the design study were to catalog debris down to 1 cm in size out to 1000 km in altitude. The SASC further directed that the study be coordinated between the Air Force Research Laboratory (AFRL), Los Alamos National Laboratory (LANL) and Lawrence-Livermore National Laboratory (LLNL). In addition to these laboratories, The Aerospace Corporation, Air Force Space Command, Jet Propulsion Laboratory, MIT Lincoln Laboratory, NASA/Johnson Space Center, and Naval Space Command also participated.

The goal of 1 cm at 1000 km is very stressing. The good news is that at higher altitudes, atmospheric drag effects are less pronounced and the orbits more stable than at low altitudes ($<600$ km). The bad news is that research by NASA using the Haystack radar indicates that there is a very large population of small debris with sizes typically less than 3 cm between 850-1000 km. These objects are most likely liquid metal Na-K coolant leaked from Russian RORSAT payloads (Ref. 9 and 10). Additionally, there appears to be a significant population of centimeter-sized debris consisting of Aluminum Oxide slag from solid rocket motor firings (Ref. 11).

The large number of objects has severe implications for the current method of cataloging. The report found that the then-current SCC was software-limited to a catalog of 16,000 RSOs. This number could be extended to 40,000 with some hardware and memory upgrades. A novel concept was proposed to help alleviate this problem. The concept was to treat all small debris as UCTs and maintain a temporary catalog of only those objects which pose an imminent collision risk with the high value targets of interest.

Optical Systems

The SASC study took a close look at the utility of optical systems, both active and passive, as a potential low cost alternative to radars. However, the report concluded that optical systems could not, by themselves, meet the stated requirements. Optics are not suitable for low altitude collision avoidance. All ground-based optical systems are limited by weather. But, this limitation is compounded by the fact that for passive optical systems, the sensor must be in darkness while the debris is sunlit. For low or moderate latitude sites this only occurs for a short period near dawn or dusk. Although it is conceivable that given enough sites, optical systems
could create a catalog of small debris, such a network would not be able to routinely provide timely orbit updates for collision avoidance against a low altitude target such as the Space Station.

The study did find that there were contributions to the network where optics could and should play a role. Optics could be well-suited for high altitude orbits. High altitude orbits are lit for longer periods each night than low altitude orbits giving more opportunities for observation. Also, because the orbits at high altitude are more stable, they do not have to be revisited as often allowing some accommodation for weather outages. Similarly, optical sensors might also provide coverage for high eccentricity orbits where the object spends much of its time at high altitude.

Also, if an optical sensor/site is cheaper than a comparable radar, it might be cost effective to supplement a radar network with optical sites to handle special orbits, such as Molniya orbits whose perigees are in the southern hemisphere (assuming that the object can only be detected at short slant ranges) or low inclination orbits (if all of the radars are located at high latitudes).

Other discussed uses of optics included the detection of objects which may be bright optically, but which exhibit small radar cross sections, space object identification, and high accuracy observations.

Radar Systems

The principal finding of the study was that radar systems offered the best approach to detecting and cataloging debris at low altitudes. In particular, the study recommended that an upgraded VHF interferometer fence be designed and fielded. The upgrade primarily lay in the radar frequency – either S-band or C-band. Either of these would be able to detect 1-cm debris out to 600 km. altitude and 2-cm sized debris at 1000 km altitude. However, the C-band, if designed with adequate power, could get down to 1 – 1.5 cm size in debris detection. Further, the major advantage of the interferometer fence was its guarantee of detecting debris in orbits above 33º inclination at least 5 times a day. Thus, the major requirement of timeliness in cataloging could be satisfied. Additional radars were needed to track and establish precise orbits on debris that posed a threat to the International Space Station. These could consist of existing radars like Haystack, Globus, Millstone, TRADEX, TIRA in Germany and upgraded C-band radars like the ones at Kaena Point and Ascension.

Study Recommendations

In spite of the attention given to optical systems in the SASC study, the study concluded “to design an optical system to accomplish the 1 centimeter cataloging task alone would require hundreds of sensor sites around the world in order to deal with the limitations of optical sensors such as weather (inability to see through clouds), viewing time (twilight or night time) and field-of-view (a larger focal plane, which increases costs). Furthermore, the annual operations and maintenance cost of this optical system would very likely be large, even with extensive use of autonomous systems. Radar with its larger field-of-view and near all weather, 24 hour operation is well suited for the detection of orbital objects. We believe that development of a complete system to detect, track and catalog space objects down to 1 cm in size should include both radar and optical surveillance systems.”

The SASC study estimated costs for three systems. First it used the HIgh performance CO₂ LAser radar Surveillance Sensor (HI-CLASS) system as a cost model for active optical systems.
The study found that to build a comprehensive network would require at least 4 to 7 sites. Due to the extremely small field-of-view, each HI-CLASS system would require an acquisition capability such as the radar equivalent to Haystack in sensitivity. The estimated cost for this network was $1.5B to $2.5B.

Second, the SASC study estimated the cost of a passive optical system. The system examined was comprised of a combination of search systems (one search telescope with a 2 to 3 m mirror and four chase telescopes of 1 m class) and catalog maintenance systems (1 m class). The number of global sites was estimated to be a minimum of 7 search sites and a minimum of 25 maintenance sites. It was noted that this system was not capable of performing the collision warning due to the “vagaries of both debris object orbits and weather” without adjunct radar systems. Acquisition costs of the optical sensors were estimated to be “on the order of $400M,” but the report cautioned that there was large uncertainty in the number.

Finally, the SASC study used the 1992 Space Station Freedom Study network to estimate the radar systems costs. The study estimated that, with inflation, current costs of the radar network would be about $700M.

Conclusions

Both studies discussed above show that construction of a network to perform the collision avoidance task is feasible and within the available technology. However, to reach the size goal of tracking 1-cm objects requires a significant investment in new sensors which seems unlikely in any foreseeable fiscal environment.

In the time since these studies were conducted only modest progress has been made in improving the SSN. The Cobra Dane was reconnected to the SSN in 1999 which provides some capability to track high inclination targets as small as 5 cm. Globus II has also become operational, but as a dish radar, it is can only track a limited number of objects per day and is also located at a high latitude.

Current concepts are to replace the VHF AFSSS with three S-band interferometer fences. S-band was chosen over X-band or C-band, because it was considered to have less development risk. Also, the S-band fence being contemplated is not as sensitive as the one envisioned in the SASC study. The currently conceived fence will only be able to detect 5-cm objects at 1000 km. Also, rather than creating one contiguous fence wide enough to guarantee once per day coverage, the concept is to spread the three fences around the world. Until the locations and dimensions of the fences are finalized, it will not be possible to evaluate the ability of the system to update every object once per day.

Finally, there is growing emphasis on space-based sensors, however, requirements for planned sensors do not include lowering the size limit of the catalog.

References


Figure 1. NASA Size Estimation Model for different frequencies. Most radars in the current SSN operate at UHF frequencies. To improve these sensors from their current sensitivity limit of ~10–cm to 1-cm would require a 60 dB increase in sensitivity.

Figure 2. Conceptual network proposed in the 1992 Space Station *Freedom* collision avoidance study. The proposed network consisted of an X-band interferometer fence located where the current AFSSS is currently located; the Ground Based Radar X-band located on Kwajalein Atoll; and four X-band dish radars located in Hawaii, California, Florida, and French Guiana.
Figure 3. Ground Based Radar-Prototype shown under construction (left) and, in an artist’s rendition, completed (right). GBR-P is a phased array radar mounted on a mechanically steerable platform.

Figure 4. X-band dish radar, Globus II under construction (left) and completed (right) located in Norway.