SPACE SURVEILLANCE: PAST, PRESENT AND FUTURE.

L. ANSELMO

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Luciano Anselmo

CNUCE/CNR
Via S. Maria 36
56100 PISA - ITALY

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INTRODUCTION

At present the United States Space Command tracks about 7000 orbiting objects which have characteristic sizes typically larger than 20 cm. Even if about 11000 catalogued space objects have reentered in the atmosphere or have been sent into deep space since the launch of the first satellite 30 years ago, the number of catalogued objects still in orbit increased by more than 10% per year during the last two decades (Ref. 1).

Moreover, several investigations indicate the probable presence of 2000 additional objects in the 10-20 cm range and up to 50000 objects in the 1-10 cm range (Ref. 2). These untrackable particles constitute a growing hazard for space operations, mainly when large structures and manned vehicles are involved.

To make the matter worse, collisions between orbiting debris may result in a cloud of many more objects with a dramatic increase in new collisions probability. It has been estimated that we are already in a situation where, even for zero launch rate of new spacecraft, the amount of space debris will continue to grow, eventually creating a "debris belt" around the Earth (Ref. 2).

In the present circumstances over one-half of the tracked objects are the result of about 90 fragmentations. Even if the majority of them were probably caused by propulsion related explosions or by deliberate collisions (e.g. anti-satellite tests), at least three unintentional collision-induced breakups might have occurred (Ref. 3).

Therefore the space surveillance task will be ever more important in the future, not only to routinely track the largest objects, but also to evaluate the small objects population and to assess how the space debris environment will affect more ambitious space operations.

HISTORICAL BACKGROUND

During the heroic few years following the launch of the first artificial satellite on October 4, 1957, the people involved in astrodynamics computations outnumbered the objects in orbit and often one individual was fully devoted to one or two spacecraft.

Moreover, the optical tracking network made up of Baker-Nunn cameras and managed by the Smithsonian Astrophysical Observatory was fully adequate to provide the observations (to be sent by telex and put in the first electronic computers) needed for orbit determination of cooperative and non-cooperative space objects.

However this easy-to-manage situation was short-lived, due to the rapidly growing complexity and number of space objects. Cooperative operational spacecraft requested tracking systems more sophisticated and demanding than the minitrack radio interferometers and the Baker-Nunn optical cameras. On the other hand, the task to detect, track and possibly identify non-cooperative spacecraft was taken in charge mainly by military agencies.

In the United States the North American Aerospace Defense Command (NORAD) was entrusted with this latter mission. In the Soviet Union the same duty was probably assigned to the Strategic Rocket and Air Defense Forces.

The primary task of NORAD was to provide the U.S. National Command Authorities with tactical warning on an impending missile or bomber (nuclear) attack to the USA territory. To this end three Ballistic Missile Early Warning System (BMEWS) radar sites were established in Greenland, Alaska and England. An array of air defence radars located in Canada and in the Northern continental United States provided detection and early warning against approaching bombers. However, during the sixties and the seventies the space surveillance task began very important, following the growth of military space operations and the increase in spacecraft number.

The space surveillance network then evolved over the past 30 years by integrating new sensor technologies, like the phased array radars, into the older systems, including Baker-Nunn optical cameras and classical mechanical-stearable dish radars.

To process the growing flow of observations there was a parallel improvement of communications links and computing power. This trend is continuing at present.

THE PRESENT SITUATION

UNITED STATES

The NORAD Space Sensor Network, managed by the Space Surveillance Center at the Cheyenne Mountain Complex, near Colorado Springs, currently consists of about 20 sensors located all around the world. Some sensors are classical mechanically-stearable, dish-shaped antennae built over 20 years ago. Others are very sophisticated phased array radars. In addition, optical and electro-optical detectors and the unique radar-interferometric fence of NAVSPASUR are operated.

Several sensors, like the radars of the Ballistic Missile Early Warning System, are primarily devoted to missile attack tactical warning. However, at least seven U.S. Air Force radars are routinely used for space objects tracking (Ref. 4).

Ground-based radars have an effective search range limited to a few thousand kilometers, although some radars can track a satellite out to geosynchronous altitude if the spacecraft's approximate position is already known.

The network performances were dramatically improved by the introduction of phased array radars, that are able to track many objects simultaneously (up to 200-300). This proves to be very useful to track space debris, since mechanical-stearable radars can track only one object at a time in ordinary conditions. To put it in other words, the AN/FPS-85 phased array radar operated at Eglin, Florida, and the Perimeter Acquisition Radar and Characterization System (a phased array as well) operated at Cavalier, North Dakota, together collect one third of the observations received daily at the Cheyenne Mountain Complex (Ref. 5).

Another very sensitive sensor is the Naval Space Surveillance System, NAVSPASUR in the military jargon. One main and two auxiliary very powerful transmitters erect an electronic fence across the United States (latitude 33 deg North). Space objects going through the fence interfere with the radio beam which is continuously monitored by six separate receivers in the continental United States (Refs. 4 and 5). This system is claimed to have a fine discrimination capability and it is at present considered, together with the two above mentioned phased array radars, as the basis for developing a small debris catalog (Ref. 6).

For the detection of spacecraft in deep space the USA rely upon passive optical sensors. Two systems are currently used by NORAD: classical 0.5 m Baker-Nunn cameras, first deployed in 1957, and the state-of-art Ground-based Electro-Optical Deep Space Surveillance system (GEODSS). The conventional photographic Baker-Nunn cameras require about 90 minutes for film processing and data reduction. They will be finally phased out when the GEODSS network of 5 observation sites will be completed and declared operational.

GEODSS sites I, II and III each have two main 1 m telescopes and one 40 cm auxiliary telescope, while both sites IV and V should have three main telescopes. The equipment is designed to be relocatable at another site within 2 weeks (Ref. 7).

All the main telescopes, characterized by a 2.1 deg field of view, carry a 36 cm radiometer to measure light variations of the targeted space objects. The system, due to powerful light intensifiers, is designed to detect objects as dim as a star of visual magnitude 16.5 (two magnitudes fainter of the Baker-Nunn cameras limit), corresponding to a reflective sphere about the size of a soccer ball in geosynchronous orbit (Ref. 4). With all the sites operational, the coverage of the geostationary ring will be complete.

A further advantage of GEODSS over Baker-Nunn cameras is the "speed" of the system. The telescopes can move from one observation to another in one second with a pointing accuracy of 1.5 arcsec and a maximum slew rate of 15 deg/sec (Ref. 4). Moreover, on-line computers process the tracking data in real-time for immediate transmission to the Cheyenne Mountain Complex.

In addition to the systems already described, the U.S. Air Force also maintains and operates laser tracking stations and a network of cameras for close-up photography of satellites for intelligence purposes.

At least two such a cameras, code named Teal Amber and Teal Blue and located, respectively, at Malabar (Florida) and Mount Haleakala (Hawaii), are operational. These large telescopic cameras should be able to produce computer enhanced high resolution images of orbiting objects combining together successive electronic scans of the target (Ref. 8). During the maiden mission of space shuttle Columbia, on April 1981, it was claimed that at least the camera located at Malabar was employed to assess the status of the spacecraft underside thermal protection tiles before reentry (Ref. 8).

The observations performed continuously by the complicated network of radars, telescopes and cameras are routed, by a high rate communications system, to the Space Surveillance Center inside Cheyenne Mountain. On the average, 40000 observations are received and processed every day. However, on February 1, 1987, the Space Surveillance Center processed a record 71891 observations (Ref. 6).

The NORAD Resident Space Object Catalog, routinely updated to take into account the continuos flow of tracking data, includes at present about 7000 space objects (of which about 50 with radioactive material onboard). Of this number, the 23% are payloads, the 10% are rocket bodies and the 67% are debris (Ref. 1). Only the 5% of the catalogued objects are active satellites and probes. Unfortunately, the actual amount of debris exceeds of several order of magnitude the numbers indicated by the catalog. In fact, the sensor network is not able to track small particles, as shown in Figure 1 on page ix (Ref. 9).

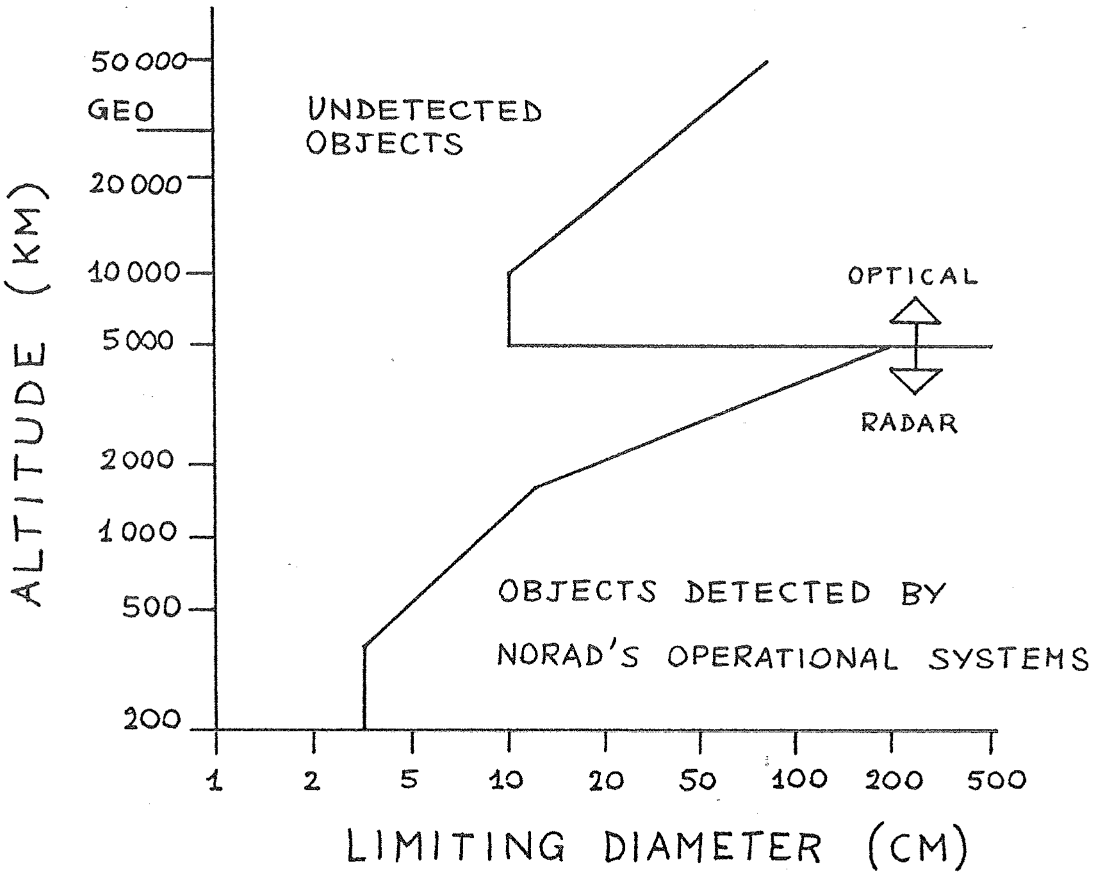

Figure 1. NORAD Tracking Capability

On the other hand, even a 0.2 mm fleck of aluminium oxide paint was able to produce a small crater in a window of the Challenger space shuttle during the STS-7 mission (Ref. 6). The window had to be substituted at a cost of $ 50000. Some estimates evaluate the number of these sub-millimeter sized debris particles as high as 10 billion (Ref. 6). Hyper-velocity collisions with debris in the 1-10 cm size range (50000 objects estimated) could severely damage or completely destroy a spacecraft.

Both NASA and the U.S. Space Command are concerned about this situation that rapidly grows worse. NORAD is considering the creation of a separate debris network of sensitive sensors like phased array radars and NAVSPASUR to develop a small debris catalog (Ref. 6). NASA is funding a dedicated debris radar able to detect objects down to 1 cm in diameter (Ref. 1). The goal of these efforts is to evaluate the global altitude/size densities of space debris for collision risk assessment.

SOVIET UNION

The Soviet Union operates military and civil networks of radars, LIDARs (LIght Detection And Ranging) and photographic sensors linked to the central processing facilities by satellite and terrestrial communications systems.

Radio and radar ground stations can detect and track satellites in low Earth orbit as well as track satellites in higher orbits. In addition, the radars of the ballistic missile early warning and the anti-ballistic missile systems, e.g. the 11 large HEN HOUSE and the new powerful phased array radars located at Pechora and Krasnoyarsk, can be used to detect, track and characterize satellites in low orbit (Refs. 7 and 10). Unlike the USA, that operate several foreign-based space surveillance facilities, the Soviet Union heavily rely on specialized oceanic ships for tracking and communications purposes.

Deep space detection capabilities are necessarily based on passive sensors, primarily telescopic cameras roughly comparable to the Baker-Nunn's introduced by the United States on 1957. At present at least two dozen telescopic cameras are operational. Furthermore, deep space surveillance relies upon radiotelescopes and ground-based military signal intelligence collection systems. Such systems perform direction-finding and signal intercept functions and are known as electronic support measure (ESM) systems (Ref. 7).

Radar returns from satellites in high orbit are generally too weak to be detected by a device performing a rapid scanning of the sky. However, if the approximate position of the satellite is already known, the radar can scan slowly, accumulating signal energy for an extended period of time. This technique is particularly suitable for the radar tracking of geostationary spacecraft.

FUTURE DEVELOPMENTS

Both the USA and the USSR are upgrading their network of space sensors at accelerating pace, by filling the gaps in the global coverage and substituting old-fashioned dish radars with more powerful and capable phased array devices. These developments, coupled with the introduction of extensive preprocessing capability at the sensor sites, improved data links and much more powerful computers and software at the control center facilities, will make possible to control the evolution of the space debris population well within the nineties.

Nevertheless, new technologies will be needed in the near future to support existing devices, in particular to sample the small debris population and to track deep space objects. Dedicated space telescopes could be the next step in this direction.

At a typical operating temperature of about 300 deg Kelvin, a spacecraft emits most of its thermal radiation at 10 micrometers. The same may be assumed approximately for rocket bodies, dead satellites and debris. Therefore, a space telescope sensible to the Long-Wavelenght InfraRed (LWIR) radiation could be an optimal sensor, able to perform both day and night observations (ground sensors cannot operate in the LWIR domain due to the lower atmosphere absorbtion).

Such a divice should incorporate technologies similar to those used for IRAS, the ESA-NASA-UK InfraRed Astronomical Satellite, with a very low temperature cooling system to reduce the detector thermal noise. But the LWIR sensor would be much more capable in order to scan the sky more quickly (IRAS needed 6 months for a full survey of the celestial sphere). Moreover, a space object moving unpredictably against the sky requires very short integration times, because the focused radiation collected by the detector element would move on the sensor's focal plane. For example, a LWIR space surveillance spacecraft, orbiting at 1000 Km of altitude with a 1 m primary collecting mirror, needs no more than 1 millisecond integration time to detect a geosyncronous satellite before the image moves across the telescope's spot size. If the focal plane detector were cooled to 77 deg Kelvin, the system could be able to detect at this range a black-painted satellite 1.5 m in diameter (Ref. 7).

At present only Above The Horizon (ATH) devices seem practicable. In fact the Earth itself is a powerful LWIR emitter and it would be hard for LWIR surveillance sensors to detect a target Below The Horizon (BTH) against the planet's background. Furthermore, the residual atmosphere between the target and the detector should scatter and absorb the radiation. Therefore, if a very complicated image processing system is ruled out, space based LWIR detectors will look generally away from the Earth, spotting spacecraft and debris against the black and cold background of space. Low orbiting satellites will be detected from space by looking just over the planet's limb.

Anyway, the technology necessary for effective LWIR tracking systems is very complicated and expensive. The deployment of a constellation of such a spacecraft with a useful lifetime would cost several billion dollars (Ref. 7). For this reasons visual-range orbiting telescopes have been considered as well (Ref. 11).

The technology for long-duration space missions is already available. Low altitude orbits help to minimize costs, even if the best choice depends on the specific priorities assigned to the mission. Both equatorial and dawn-dusk sun-synchronous orbits are suitable for the task (Ref. 11). Two coorbiting space telescopes 180 deg apart could provide a quite continue coverage of deep space objects. More coorbiting telescopes should be able to create a ring of coverage that each low Earth object must cross twice each orbit (Ref. 11).

Of course the targets would not be detectable when in the Earth's shadow. However, space objects usually spend less than one hour in the shadow (less than 40 minutes for low orbit objects) and deep space objects do so only at given periods of the year.

In addiction at visible and infrared telescopes, radars have been considered as well for space basing. Nevertheless, their role should be to detect and track strategic bombers and other low-flying air-breathing vehicles. Therefore, space based radars are not relevant to space surveillance purposes (at least for the immediate future).

THE SPACE DEBRIS THREAT

As underlined in the previous sections, the space objects population consists of three components:

- Active and disabled payloads.
- Exhausted rocket bodies.
- Debris.

As far as space operations are concerned, the larger threat is represented by the latter ones, due to the number of catalogued and, especially, uncatalogued objects. For large space vehicles and structures the impact probability is already troublesome and well in excess to that foreseen for micrometeoroids of equivalent mass.

Therefore, it is not surprising that during all the space shuttle flights NORAD was charged with the duty to predict possible close fly-bys with the catalogued objects for the overall duration of the mission.

To make the matter worse, several hypervelocity impact tests performed at the ground have shown that collisions produce many more smaller particles (size less than 10 cm down to submillimeter flecks) than low energy explosions (Ref. 6). This means that a few collisions in space may considerably worsen the situation, by increasing the probability of new destructive impacts.

Another concern deals with the uncontrolled reentry of large and/or dangerous objects. In this case the space debris, due to their smallness and relative high area to mass ratio, do not represent a problem. Otherwise, large payloads and rocket bodies can present some risks, because several fragments may survive the reentry conditions.

In the last few years world-wide attention was payed to the reentry of some spacecraft. Many observers pointed out that the number of significant space objects reentering on the Earth is quite larger (of the order of one-two reentries per week) and that the attention raised by selected spacecraft was driven by political and propagandistic reasons.

However, if the reentry history of the last ten years is analyzed, it is easy to show that the publicized events were really the most dangerous:

- S-II Skylab upper stage.
- Skylab.
- Cosmos 954.
- Pegasus I, II and III.

- Cosmos 1402.
- Cosmos 1625.
- Cosmos 1714.
- Cosmos 1767.

All the listed cases were characterized by the uncontrolled reentry of very large (several tons in mass) or radioactive objects (Cosmos 954 and 1402).

Of course large objects reenter every week, but it is a matter of controlled reentries in designated areas performed mainly by the Soviet Union (recovery of film capsules from reconnaissance satellites or space station related missions). Up to now, for example, several space stations of the Salyut class (16-20 tons in mass) are reentered without rising worries or concern for the controlled nature of the operation.

Moreover, new launch procedures currently involve the stage discard on selected areas before the reaching of the orbital velocity, as shown, for example, by the space shuttle External Tank disposal. On the other hand, many Soviet payloads remain attached to the orbital stage, preventing uncontrolled reentry.

Consequently, it is possible to conclude that the risk laying down on reentering space objects is still sporadic, even if it will increase in the future.

POSSIBLE EUROPEAN ACTIONS

It is evident, due to the dimension of the problem, that Europe will continue, in the foreseeable future, to rely upon NORAD and NASA data in the space surveillance field. Global networks of sensors with the sophistication of the NORAD's one are awfully expensive to build and operate and find their full justification in the military tasks assigned to them. However, taking into account the considerations outlined in the previous section, some useful and affordable actions could be undertaken.

A very important task will be to evaluate as accurately as possible the dynamical and size distribution of the small debris in low orbit. As shown previously, it is impossible to treat the problem with the same techniques and procedures employed up to now for the tracked population. On the contrary, some sensitive sensor sampling will be needed: NASA and NORAD are working in this direction.

Europe could give an important contribution in this area by funding, bulding and operating a dedicated radar and/or electro-optical facility to perform a continuos sampling of the small debris population. The data acquired would be of paramount importance for mission and operations planning and could reveal themselves an important bargain resource in dealing with NASA for information exchange and full cooperation on this topic.

On the side of reentry predictions of potentially dangerous objects, some useful actions could be undertaken as well. In fact, the NORAD sensor network is conceived to track many thousand objects near simultaneously and promptly detect on-going space activities, as new Soviet launches. But when the orbit of only one or few low orbiting objects must be determined without tight time constraints, a few sensors are fully adequate for the task. Furthermore, because only large payloads and rocket bodies (radar cross-section of 1 sqm or more) are generally dangerous from the reentry point of view, very sophisticated and sensitive detectors are not needed.

To put it another way, a coordinated network of 2 or 3 suitably located classical dish radars, able to unambiguously detect objects with a radar cross-section of 1 sqm at a range of 1000 Km, could be employed by Europe to perform independent tracking and orbit determination of selected reentering spacecraft. On a smaller extent, this was already performed by single European countries, e.g. France (Ref. 12) and Germany (Ref. 13), using existing facilities during some of the above mentioned reentries. In the future this kind of activity could be coordinated by an international body, e.g. ESA, to obtain a standard set of data to be used for reentry predictions.

Finally, when European countries will perform manned operations in space, a preemptive and real-time collision hazard evaluation should be carried out using as input the updated NORAD Resident Space Object Catalog. The aim of this analysis would be to discover in advance eventual dangerous close approaches of known payloads, rocket bodies and debris to the manned spacecraft.

CONCLUSION

Due to the growing number of tracked and undetected space objects affecting the full exploitation of the near Earth space, the importance of the space surveillance task will steadily increase.

At present the top priority is to quantitatively assess the physical properties of the small debris for setting new requirements on spacecraft design and operations. Both NORAD and NASA are evaluating the introduction of new instruments and data processing techniques to sample this large undetected population. Europe could usefully concur to this research by building and operating a dedicated facility for sampling the small debris cloud.

In the field of the reentry predictions of potentially dangerous spacecraft, Europe could already afford, just coordinating existing facilities, a quite independent tracking of the relevant objects. In this case the main problems are probably neither finantial or technical, but political. In fact the radar facilities are operated by independent (often military) agencies.

For a complete snapshoot of the trackable population, however, Europe shall rely upon NORAD data for many years to come. In particular, to assess the collision risk of a manned spacecraft with the objects of the known population, NORAD data will be essential.

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