US NAVAL SPACE SURVEILLANCE UPGRADE PROGRAM 1999-2003

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INTRODUCTION

This paper reviews some of the main objectives, constraints and lessons learned in a particular US Navy program that ended in 2003 with the transition of the space surveillance mission, personnel and funding to the US Air Force. Because of changing needs for space situational awareness both for national security and global commercial reasons, the Air Force sensor program that is now emerging must necessarily be different in scope from the Navy program. However, the Navy program was the first US space surveillance sensor acquisition that addressed the problem of building a large catalog of small space objects. This problem was, and remains, a new one, because the existing catalog of space objects has been maintained since the launch of the first satellite, Sputnik I, on 4 October 1957. To date, it has always been possible to maintain a complete inventory of space objects without ever re-building the catalog *ab initio*, because of the relatively slow rate at which new satellites are launched into space. Now, with the probable introduction of new and very sensitive space surveillance systems in several countries in the coming years, the apparent satellite population will grow instantly by orders of magnitude as the previously invisible small-debris background population becomes visible. The problem of building a large catalog of possibly faint objects in a short time has become unavoidable. Yet, all existing methods of managing sensors, associating tracking data and predicting orbital uncertainties are inadequate for this task. For this reason, reviewing from a historical point of view the Navy's attempts to address some of these problems in a conceptual system design may give us a useful perspective, even though that particular program is defunct.

My personal involvement with the Navy program included the entire duration and almost all aspects of the effort. Beginning in 1999, I participated in the formal identification of the need to improve the capability of the existing system, wrote the basic specification of system performance requirements, helped develop the Navy's Request for Proposals from industry, served on the source selection panel, reviewed the conceptual and preliminary designs of the new system, and finally assisted in the transition of the old system and mission to the Air Force in 2003-2004. Subsequently, in 2005, I joined Air Force Research Laboratory to work on projects related to space surveillance. Today, essentially all persons with first-hand technical knowledge of the Navy upgrade program and its background are either retired or work somewhere in the Air Force.

THE CURRENT VHF SYSTEM

The historical image in Fig. 1 dates from the early 1960s, and portrays the then-future configuration of the Naval Space Surveillance System (NAVSPASUR, also known as NSSS, also known as the Fence) before all the receiver stations came online in the mid-1960s.

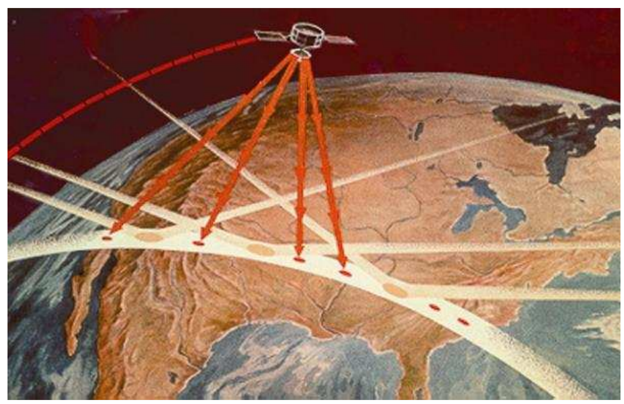

Figure 1. Naval Space Surveillance Concept

As conceived originally by researchers at Naval Research Laboratory (NRL) and built with help from Advanced Research Projects Agency (ARPA, now Defense Advanced Research Projects Agency), the NSSS field system consists of 3 transmitters and 6 receivers deployed along a great-circle arc across the southern US. The system is a continuous-wave fully multi-static Very High Frequency (VHF) radar interferometer: any receiver station can receive signals reflected from a satellite illuminated by any transmitter, subject only to horizon and signal-strength limitations. At present, the coverage of the system is such that, on average, a satellite having reflected signal strength above the detection threshold is simultaneously visible to 4 receivers and 2 transmitters. This redundant coverage provides the system with robust detection capability and very high overall reliability. The system detects more than 60% of the current catalog on any given day, and over time detects more than 85% of the catalog, as has been described many times in the open literature.

All detections of satellites are made at one or more of the six receiver sites without any *a priori* knowledge of the satellite catalog. The raw signals are sam-

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pled at high rate and the discrete time-series data are forwarded in real time to the Operations Center in Dahlgren, Virginia, where they are processed by interferometric algorithms into the basic observable quantities: a pair of direction cosines of the line of sight from receiver to satellite, reckoned at time of maximum signal strength during the pass. The direction cosines are then associated with cataloged objects in real time and used to update the orbits of those objects.

Fig. 2 shows a plot, to correct scale, of actual NSSS Fence beam penetrations obtained from the satellite population near the beginning of the Fence upgrade program. The low-altitude penetrations, out to about one Earth radius of altitude, were accumulated over a 4-hour period. The higher-altitude penetrations were accumulated over several days. The heavy circular arc of detections at several Earth radii of altitude is from the GLONASS satellite constellation.

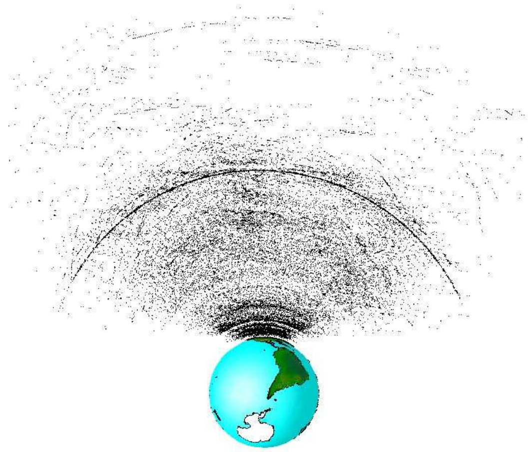

Figure 2. East-West Coverage of the NSSS

The East-West coverage turns out to be quite extensive at satellite altitudes. However, with limited transmitter power, the Fence beam has to be concentrated somehow in order to maintain sensitive detection at large ranges. Consequently, the Fence beam is confined very near to the great-circle plane containing the ground stations, and this is the plane shown in Fig. 2. Were this plane rotated to be seen edge-on, the North-South distribution of detections would be much narrower than the pixels used to make the diagram at this scale. Note also that the NSSS field systems were neither designed nor deployed to be able to detect geosynchronous equatorial satellites: the great-circle plane is inclined at about 33 degrees from the equatorial plane. However, as indicated in Fig. 2, the system is sensitive enough to detect routinely many of the larger objects in the catalog, such as rocket bodies and some payloads, which happen to pass through the beam at and even beyond geosynchronous distances.

The redundant design of the NSSS has allowed it to keep pace with the growth of the catalog without any major modifications of the field systems. Although the antenna systems have been refurbished over time, and the antenna layout at each station was changed in the late 1980s, no changes in the basic design or operational concept have been made since the field systems were first deployed. Of course, more processing capacity has been added over time at Dahlgren in order to accommodate the growing number of detections and the growing number of orbits to be updated.

REASONS FOR THE UPGRADE PROGRAM

For many years, the NSSS has provided both the main un-tasked detection capability of the Space Surveillance Network (SSN) and also more observations than any other SSN sensor system. The original reasons for the upgrade program were the age and obsolescence of the field systems, which threatened to degrade the detection capability, especially the unique high-altitude un-alerted detection capability. However, by the time the upgrade program started in 1999, there were added incentives to make the refurbished NSSS able to detect much smaller space objects than called for in the original design. Consequently, the program soon came to involve both the field radar systems and the mission processing systems.

Before 1999, computer capabilities always grew faster than the number of objects in the catalog, so it was possible to keep up with the ever-increasing data flow from the NSSS system. In fact, the catalog grew by 4 orders of magnitude in the first 40 years of the Fence's operation, but the data processing capacity grew by 5 or 6 orders of magnitude.

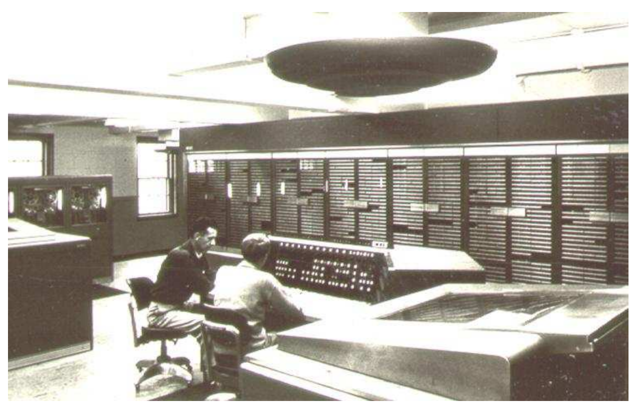

Figure 3. Naval Ordinance Research Calculator (NORC), 1958

Fig. 3 shows the first computer used for US Naval space surveillance, the NORC, located in Dahlgren at the Naval Weapons Laboratory (NWL, now Naval Surface Warfare Center). It was one of the largest and fastest computers in the world at the time: 2000 "words" (8k) of memory and capable of 10,000 multiplications per second. The famous Dr. Edward Teller once tried to get this machine for his own programs but failed to convince the Navy to give it up[1,2]. During the day, NWL used it to support the Polaris missile program as well as to design naval guns. At night, NAVSPASUR used it to update the satellite catalog. In those days, it was easier to move engineers and technicians to the computer, rather than vice versa, which is the reason why the NSSS project was headquartered at Dahlgren. By the time of the upgrade program in 1999, the surveillance mission processing system consisted of a distributed computing environment with about 240 computers, every one of which was better in every respect than 3000 NORC machines! Nevertheless, even this impressive capacity was not nearly enough to handle the job of building a catalog of more than 100,000 objects in a reasonable amount of time, and the Fence upgrade program included in its plans a complete replacement of the mission processing system.

The most visible and costly part of the upgrade program involved the replacement of the antenna systems and associated facilities at each field station. The antenna systems are arrays of half-wave dipoles arranged as sub-arrays with each sub-array deployed in a simple linear configuration. The high gain needed for creating a narrow beam and detecting weak signals comes from the long length of the sub-arrays and the ability to maintain correct relative phase in the combination of signals from all antenna elements. In fact, the dipole elements in these sub-arrays have to be aligned mechanically in three dimensions across the entire antenna field to within a very small fraction of a wavelength in order to keep the apparent phase noise of the system at an acceptably low value. However, the long NSSS wavelength, which is desirable from a signal-processing point of view, results in distances between antenna elements of up to 3200 meters for the transmitters and up to 1200 meters for the receivers. Maintaining precise antenna alignment over such distances has always been challenging and potentially expensive, especially because all these arrays are entirely exposed to the weather.

Many other maintenance problems were becoming apparent by 1999, when future plans for the Fence were being reviewed. Examples of these problems, familiar to every radar engineer, can be listed:

- Corrosion and electrical material-property changes with age.
- Spare parts for electronics no longer available from commercial sources.
- Detectors, phase controls, frequency controls, and amplifiers becoming obsolete.
- Close to end of design life of high-power transmitter electronics.

General obsolescence of the field systems demanded an eventual complete replacement of every signal path as many parts and subsystems began to exceed their design life. Meanwhile, a completely different issue emerged when the US Government re-allocated the NSSS frequency band away from space surveillance to terrestrial maritime communications. Although space surveillance operations were allowed to continue in that band as long as they did not interfere with any communications users, this circumstance gave us both the incentive and the opportunity to redesign the NSSS system to operate at some other frequency. Then, with the eventual replacement of the system accepted as inevitable, our single biggest question as the program started in 1999 was, which frequency?

CONSTRAINTS AND REQUIREMENTS OF THE PROGRAM

The original constraints imposed on the program by Navy managers in 1999 were essentially cost constraints: no extra land would be obtained and no essentially new capability would be added to the system. The whole program was tightly cost-constrained from the beginning and was to be handled as a "service life extension" rather than a "new sensor" activity. Any improvements had to be consistent with better maintainability of the system, lower overall life-cycle cost, and so forth. Fortunately, it was appreciated at all levels of management from the beginning of the program that major improvements would have to be made in the computer processing systems in order to keep up with the growth of the catalog, whatever that growth turned out to be. Also, it was directed that the new system should function the same way in the Space Surveillance Network (SSN) as the existing system: that it be un-alerted and un-tasked and that it provide wide-area surveillance of space with approximately the same geographical coverage. The idea was to perturb the operation of the other SSN sensors as little as possible.

Meanwhile, the emerging issue of detecting and cataloging sub-decimeter-scale space objects began to affect the Navy's deliberations. Changing the system's frequency meant, in practice, increasing the frequency, thanks to the ionosphere's blocking or refracting most lower-frequency signals. Of course, as the frequency increases, the required detection bandwidth necessarily increases also. Considering the many competing uses for the radio-frequency spectrum, the Navy found that it had to go rather far up in frequency simply to find enough open bandwidth for un-alerted Fence-type space surveillance. As described later, even frequencies well above the eventual 3.5 GHz recommendation were considered. Of course, at such frequencies, if large objects are being detected at long range in an un-alerted manner, then it can be difficult *not* to detect very small space objects at shorter ranges. It must be admitted that, at first, many persons in the program viewed this as a problem rather than as a solution. However, even though the question of the military utility of cataloging objects as small as 5 cm had not been resolved by this time, NASA had articulated in August 1997 very specific requirements to predict conjunctions with such small objects to support the safe operation of manned spacecraft. For this and other reasons, in the several-year period around the beginning of the Navy program, attaining more comprehensive "space situational awareness" began to be seen as important by other government agencies as well as by industry and commercial interests. By the end of 2000, the Navy's own Analysis of Alternatives for the upgrade program was concluding that building an S-band replacement for the NSSS was feasible, both technically and economically, and that it might be able to detect objects even smaller than 5 cm at low orbital altitudes. The S-band alternative came to be seen more favorably by Navy managers as time went on, especially when it was realized that no other program for the SSN was addressing the 5-cm cataloging problem.

The system performance parameters specified to industry by the Navy turned out to be rather ambitious. A few examples of these can be listed in simplified form as follows:

- <u>Frequency</u>: S-band (~3.5GHz), based on target size and bandwidth availability.
- <u>Sensitivity</u>: 5 cm target size up to 1000 km altitude, with specified probability.
- <u>Accuracy</u>: Same as VHF Fence.
- <u>Precision</u>: Same as VHF Fence.
- <u>Coverage</u>: Number of detection opportunities per day for each object.
- <u>Capacity</u>: Maintain at least 100,000 objects in the catalog.
- <u>Continuity of Operations</u>: No degradation in catalog timeliness.
- <u>Catalog Completeness</u>: No degradation in data association rate.

As described later, these specifications were actually developed in collaboration between industry and the Navy. This was done to ensure that the desired performance would be achievable with high probability. The highest risk appeared in the requirement to maintain the catalog of small objects at the same level of completeness as the present catalog. Although many persons appreciated the potential difficulties with this task, there was no "off the shelf" solution or analogous program to turn to for guidance.

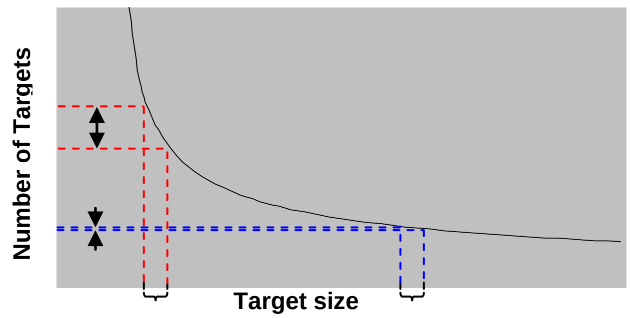

Figure 4. The Problem of Marginally Detectable Objects

Fig. 4 shows how the essential difficulty of maintaining a catalog of small objects stems from the size profile of the space object population. It is well established theoretically and empirically that, in a mean sense, both the absolute number of objects and the proportion of marginally detectable objects increase exponentially as the lower bound on size decreases. This means that the number of objects that can be maintained with unique identifications in the catalog becomes progressively more uncertain at smaller limiting sizes. Most multiple-hypothesis tracking approaches become inefficient in this circumstance, because false hypotheses cannot be eliminated rapidly. The difficulty is compounded by the very large basic size of this tracking problem. Some analysts had suggested that a catalog of small, marginally detectable objects would have to be statistical or probabilistic in nature, rather than discrete and deterministic as at present. However, it was not clear then and it is not clear now how we would build or use a "catalog" of that type.

PROGRAM SUMMARY

The whole Navy program was structured to identify and mitigate risks, both before and after contract award. The sequence of program phases was straightforward, ending in contract award at the end of Phase 3:

- NSSS Acquisition Strategy
- Analysis of Alternatives
- Phase 1: Independent conceptual designs from industry answering a general problem statement offered by the Navy.
- Phase 2: Award of contracts to industry partners, based on Phase 1 results, to help develop a complete NSSS Performance Specification prior to formal Request for Proposals.
- Phase 3: Contract award by open competition.

The Navy solicited industry participation in developing conceptual designs and performance specifications before the formal contract bidding process began. This strategy had the effect of educating industry about this challenging new problem, better identifying certain risks early in the program and helping to ensure that the Navy's expectations would actually be met after contract award. The Navy's strategy of "partnering" with industry prior to the final contract award achieved its goal of building strong industry interest in the design problem early in the program. However, it did require special measures to ensure fair and open competition, and objective evaluations, at each stage of the process. For example, the Navy held "Industry Day" briefings regularly. These were open to any interested company, not merely the ones engaged to date. The Navy also provided a "Virtual Program Office" website that was accessible to all industry partners and allowed them to communicate "on the record" but that was designed to protect each partner's proprietary information. One of the most important steps that the Navy took was to develop a comprehensive Program Life Cycle Cost Estimate early in the program and to update it throughout Phases 1 and 2 as better information became available from industry or the Navy's own analysis. This allowed the best possible objectivity in assessing the cost estimates in each proposal in the final contract award phase.

The Navy's Analysis of Alternatives had as its goal the identification of technically and economically feasible radar designs for detecting and tracking various small target sizes, based on the best information that the Government could assemble without any specific inputs from industry. Subject-matter experts analyzed a variety of radar designs at VHF-band (200-300 MHz), L-band (1.2 GHz), S-band (3 GHz), C-band (5 GHz) and X-band (10GHz), all in a variety of site locations and beam configurations. Some current cost data solicited from a survey of industry leaders was used with the Navy's own figures to arrive at projected manufacturing costs for each alternative.

The choice of frequency band was much debated. The basic difficulty here is that as one searches upward in frequency, the required detection bandwidth increases because of increasing Doppler shifts from the targets of interest. At the same time there is ever-increasing commercial pressure to dedicate more bandwidth for private business use. Starting at VHF, it is not easy to find sufficient interference-free bandwidth for space surveillance until L-band. However, at L-band it is difficult to detect 5-cm targets reliably. The detection probabilities improve as the frequency increases through S-band. Above S-band (~3.5GHz), the transmitter efficiency begins to drop off, greatly increasing the procurement and operating costs of the system. The Navy's conclusion was that the S-band alternative turned out to be feasible both technically and economically for 5-cm targets at 1000 km altitude. In fact, the S-band systems were expected to be comparable in overall cost to simply re-building the existing system at VHF-band, and to offer much better performance per unit cost. The Analysis of Alternatives even recommended that the upgrade program adopt as a long-term goal a 2-cm limiting target size. In Phase 3 of the program, the Navy did assess industry's proposals partly on how easily their nominal designs could be extended to the 2-cm and 1-cm target sizes. As it turned out, in the final bidding for the contract, companies were free to propose any frequency whatever; however, all proposed an S-band system of some type.

Phase 1

In this first public phase of the program, the Navy announced its intention to replace the VHF Fence and solicited preliminary design concepts from industry for deploying new radar equipment and building the small-object catalog. Very few constraints were imposed at this stage, not even explicit cost constraints. These design concepts would be developed and offered at no cost to the Navy; however, the companies with the best concepts would be awarded contracts to participate with the Navy in Phase 2 of the program. The concepts would be reviewed and ranked by a panel of experts from NNSOC (Naval Network and Space Operations Command, the operational unit), NRL (Naval Research Laboratory, the research unit), SPAWAR (Space and Naval Warfare Systems Command, the acquisition headquarters unit) and SSC (SPAWAR Systems Center, the engineering unit). The result of this phase was that four companies, with four very different designs, were awarded contracts for Phase 2.

Phase 2

In the next phase of the program, the winning companies from Phase 1 were invited to form a so-called Integrated Product Team (IPT) with the Navy. The purpose was to develop a detailed performance specification for the upgrade program, identify the "best and most affordable" design solutions, and verify with modeling and simulation that the performance specifications were consistent, technically achievable and affordable. It was during this phase that the approach of using "best value to the Government" as the ranking principle began to make sense. In the beginning, the program costs for the design-build procurement were expected to be strictly capped. As time went on, it became obvious that the actual cost of the system was going to be quite uncertain, perhaps even after the contract award, and that this was due to fundamental uncertainties about the space object population. The answer to this problem was (a) to allow the projected design-build cost to increase as long as it could be demonstrated that the life-cycle cost remained affordable, and then (b) to increase the time allotted for the design-build process so that it could be paid for in increments.

It was interesting to see what specifications were advocated by companies that we expected would submit bids on the final contract in Phase 3. In the end, the IPT settled on the ambitious specification of 5 cm as a threshold target size for cataloging for altitudes of 1000 km and below, with a goal of 1 cm in the same regime. The actual Performance Specification was quite short and was limited to only the key performance parameters. A companion document, the Statement of Objectives, contained a discussion of all the desired characteristics of the new system. Some of the Navy's objectives were mutually exclusive, of course, and defined a tradeoff that the industry proposals would have to make in designing a system that offered the "best value to the Government".

Overall, the collaboration between industry and Navy worked well, and at the end of this phase several companies had a substantial base of expertise in the subject that they did not have before the program.

Phase 3

In the last phase, the objective was straightforward: release the final Request for Proposals (RFP) to industry and award the contract for the design-build phase of the program. At this stage, any company, not merely the Phase 2 participants, could submit a proposal. The winner would be chosen based on "best value to the Government", rather than "minimum cost". The Navy assumed that this new S-band system would have a service life at least as long as the original VHF System, 30 years or more. Therefore, cumulative operating cost, rather than initial design-build cost, was expected to be the dominant component of total life-cycle cost. In fact, this expectation was confirmed in all the proposals received from industry. The proposals were received by November 2001, the Navy's technical and cost evaluations were completed by April 2002, and the design-build contract was awarded in September 2002.

NAVY EXPECTATIONS FOR THE PROPOSED SYSTEM

From the time that the 5-cm target size was adopted as a system design goal, the Navy expected that the new system would involve both some kind of detection-fan radar plus some kind of tracking method to produce initial estimates of orbits based on one pass through the system coverage. One example concept is shown in Fig. 5.

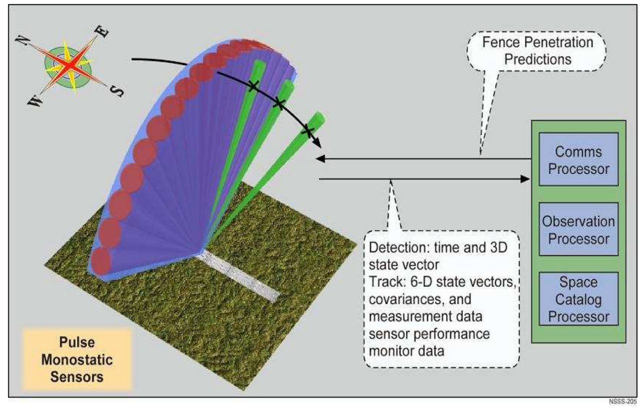

Figure 5. Concept of Detection plus Automatic Tracking

However they would be produced, these initial estimates of orbits would have to be associated with the catalog as it was being built and with each other for the generation of new cataloged orbits. However, developing the detailed concept of operation was part of the design problem posed to industry. At all stages of the program, the Navy sought to "under-specify" the problem and to encourage creative approaches to a design problem that everyone knew to be a difficult one.

Table 1. Some Possible Performance Improvements

Current VHF Fence Characteristics	Possible S-Band System Characteristics
Bistatic – Multistatic	Monostatic
9 sites	3 sites
Detects 30 cm objects	Detects 5 cm objects
15,000-object catalog	100,000(+)-object catalog initially
100-person field crew	38-person field crew
Minimum of 1 transmitter and 1 receiver required to generate observations. More sites required for system to be fully functional.	Single site provides significant operational capability.

As indicated in Table 1, certain types of performance improvements came to be expected as merely prudent, given that we were facing a complete replacement of the existing system. For example, some of the early concepts led the Navy to expect that perhaps as few as 3 field stations would be needed if a monostatic radar system were deployed. In that case, the cost savings in facilities and manpower over time might offset the higher initial cost of the monostatic system.

Inevitably, Navy budget analysts asked whether the cataloging job could be done with only two sites.

Modeling and simulation indicated that, in fact, only slight shortfalls in some performance specifications would occur in this case, no matter which pair of existing transmitter sites was selected, although the time to build the catalog would increase. The Navy came to expect measurable but modest degradation in overall performance with only two monostatic S-band sites.

Eventually, based on these results, the original NSSS coverage specification was re-defined to allow a possibly reduced number of field sites as long as the "steady-state" catalog quality and timeliness were not degraded. Of course, in all of these analyses, it was assumed that the upgraded NSSS and its own processing system would have to build the small-object catalog without help from the rest of the SSN. The reason was that no other sensor could detect large numbers of 5-cm objects routinely.

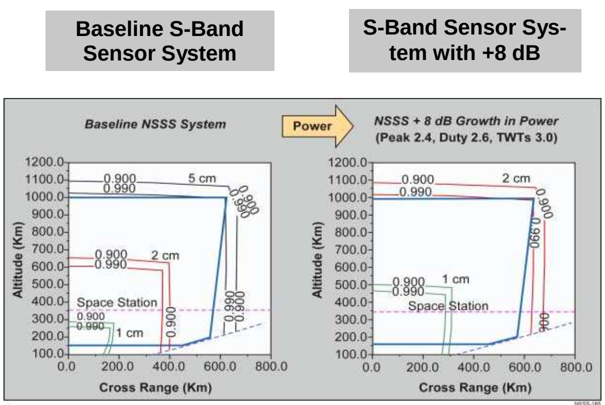

Figure 6. Expected Detection Performance

Even in their conceptual stages, the S-band designs offered some impressive detection capability and interesting performance tradeoffs. An example is shown in Fig. 6, where expected probability-of-detection boundaries are plotted for one proposed design. Regarding this particular tradeoff, most of the Navy analysts believed that merely an increase of radiated power might be sufficient to allow the S-band system to detect the smallest objects of concern to NASA. However, this performance enhancement, though technically straightforward, turned out to be expensive and the enhanced detection performance did not become part of the initial system design.

TRANSFER OF VHF FENCE AND MISSION TO AIR FORCE

Effective in January 2003, the Department of Defense transferred the Navy's share of the space surveillance mission to the Air Force as part of a broader reorganization of military space activities. Over the next two years, all Navy space surveillance facilities and most of the technical staff came under Air Force management.

Even before the transfer of responsibilities, the Air Force was already very interested in the progress of the Navy upgrade program, for obvious reasons. Of course, under new management, the ground rules of the program could be changed. The Navy rule about "no new real estate" was relaxed, once the Air Force recognized the possible performance of an S-band sensor.

In 2004, the Air Force completed a preliminary study to assess the utility of deploying several S-band systems similar to the Navy designs at different locations around the globe. The underlying (and admittedly oversimplified) assumption in this study was that sites could be selected freely to optimize global coverage and overall cost of operation. For example, one of the many possible deployments is shown in Figure 7.

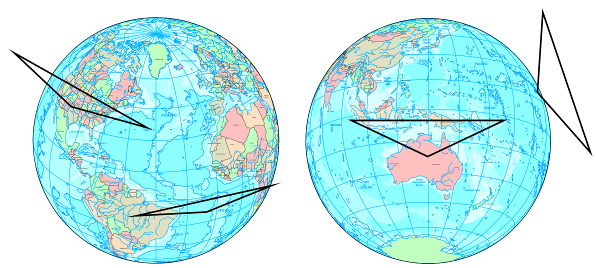

Figure 7. Some Possible Deployment Options (2004)

Since the whole design of the S-band system had been predicated on using the Navy's existing sites, it took a long time to understand the tradeoffs involved in situating a similar system in different configurations elsewhere in the world. In this and other studies, it became apparent that the S-Band sensors could indeed be integrated efficiently into the current SSN. Such a conclusion might not be obvious *a priori*, because the S-band sensors would, for some years into the future, be the only ones able to detect 90% of the upgraded catalog. The key to the conclusion was the high degree of automation that would be required in order for the S-band system to build its own small-object catalog in the first place. Given that feature, and the implied data processing capacity, one can list some important advantages of incorporating the new sensors along with the existing SSN sensors in a single integrated network:

- Does not require SSN tasking and reduces tasking load on other SSN sensors.
- Metric observations would be available for every penetration of S-band coverage.

- Independent catalog maintained within the S-band system for all objects.
- Automatic object processing reduces human workload dramatically.
- S-band system could provide catalog data whenever requested by user.
- S-band system could supply alerts for detected anomalous events of several types:
  - Breakups
  - Multiple object discrimination
  - Maneuvers
  - New foreign launches

LESSONS LEARNED

The Navy upgrade program had produced a number of useful lessons even before the Naval space surveillance mission was transferred to the Air Force. In retrospect, these lessons are the real products of that program, and it is appropriate to end this historical summary by listing a few of the most important ones:

- Detecting all 5 cm objects routinely and with high probability in low Earth orbit is practical.
- The S-band radar design, including signal processing and tracking, was easier than we thought. All the main manufacturing problems for the end-to-end system had been addressed satisfactorily by 2003, though practically none of the software existed.
- The catalog processing design was as hard as we thought, and perhaps harder.
- The complete cataloging problem at 5 cm is bigger than can be addressed in one sensor improvement program.
- Extended tracking of each "small" (low signal-to-noise) target on each apparition is probably required in order to achieve sufficient accuracy and precision for reliable data association and catalog maintenance.

Cataloging 5-cm objects is practical, though somewhat expensive at present. On the other hand, not cataloging these small objects may someday be considered an expensive option too, if for no other reason than the hazard to navigation that they can pose to other, high-value satellites. Moreover, highly capable satellites may eventually appear in this size regime. Already we have "cubesats" at exactly one decimeter. In that eventuality, the value of cataloging all small objects goes up in a way that should be obvious even outside the international space surveillance community.

The method of building a "complete" small-object catalog has not been discovered yet. It is a fertile area of research. Whatever means is finally adopted to do this job will almost certainly involve several different types of sensors, wide geographical coverage, and a new level of coordination among sensors. Of course, the upgraded NSSS was expected to be able to build a catalog of objects visible to that system, but its geographical location prevented it from seeing the whole 5-cm population.

Accuracy and precision are paramount in building the catalog, because the data association job is inherently difficult in the denser 5-cm space object population. Very brief or sparse sampling of target state, as is done by the current NSSS, is almost certainly not adequate for building the small-object catalog. This might have been guessed from first principles, but was confirmed by essentially all analyses in the design phases of the Navy upgrade program.

CONCLUSION

Given that more than 90% of the 5-cm-and-larger population is invisible at present, we are confronted with a problem that is very nearly the equivalent of reconstituting the whole catalog *ab initio*. Today, we have no practical means to do this, though we will need to develop the means before the relevant sensors come online. In 2002, Navy program managers expected that the complete software and processing system for the S-band Fence upgrade would be needed by 2007. We have had a reprieve from this very stringent requirement, thanks to delays inherent in the transfer of the Navy's part of the surveillance mission to the Air Force. However, the reprieve is obviously temporary and, in the meantime, not much work has been done on the problem of building the catalog.

The Navy upgrade program did reveal the face of the future in space surveillance, if only in barest outline. A most encouraging aspect of that face is that we have the means to devise solutions for even the most challenging unsolved problems that still face us. Doing so is mainly a matter of assembling the right people at the right time.

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