PROSPECTS FOR IMPROVING THE SPACE CATALOG

Paul W. Schumacher, Jr.

ABSTRACT

For more than thirty years, United States Space Command (USSPACECOM) and its predecessor organizations have maintained a continuous surveillance of space and a complete catalog of trackable Earth-orbiting objects. The total number of satellites in the historical catalog is now almost 25,000. Most of these have decayed, though the number of trackable objects in space at any time continues to grow at a long-term rate of about 300 objects per year. USSPACECOM and its component commands now provide daily tracking and element set updates on more than 9500 objects. Besides being global in scope, this catalog maintenance process is a prime example of non-cooperative tracking of multiple targets with multiple sensors of different type. Therefore, not only is it one of the largest-scale tracking enterprises in the world, it also belongs to the most difficult category of tracking problems. Nevertheless, the U.S. space surveillance network has always achieved a high level of reliability and completeness in the catalog using straightforward methods. This paper describes, for the newcomer to the field, the basic process of catalog maintenance at Naval Space Command (NAVSPACECOM) and also offers some reasons why the straightforward techniques in use now have worked so well to solve what is fundamentally a very difficult tracking problem. Simple arguments will show why the current surveillance system works well for updating an already established catalog but would be inadequate for reconstituting the catalog ab initio. In fact, there must be some daily observation count above which the current cataloging system would begin to fall farther and farther behind real time, so that the whole process would eventually fail. This fact raises the question of what basic changes to the space surveillance system might be necessary or desirable as the catalog grows. For example, a variety of proposed satellite constellations such as Iridium, Teledesic or any of several missile defense systems, would increase the trackable orbiting population by up to several hundred or even several thousand objects in a short period of time. Would such deployments strain the satellite cataloging system? For another example, concerns about the risk to payloads from small space debris have led to various proposals for extending the catalog to include objects as small as 1 centimeter in size. But there may be as many as 400,000 objects that are 1 centimeter in size or larger in Earth orbit below 1500 kilometers altitude. Is it feasible to build a catalog of this size with the current space surveillance system even if the objects can be detected reliably? While complete answers to these questions are not yet possible, this paper outlines some basic issues and problems that have to be addressed in order to maintain a much larger and more rapidly growing space catalog.

1 Presented as Paper Number AIAA 96-4290 at the AIAA Space Programs and Technology Conference, Huntsville, Alabama, 26-29 September 1996.
2 AFRL/AMOS, 535 Lipoa Pkwy., Kihei, HI 96753
This paper was presented by Terry Alfriend.
This paper is declared a work of the U.S. Government and is not subject to copyright protection in the United States.
INTRODUCTION

The USSPACECOM satellite catalog exists primarily to provide global situational awareness of threats from on-orbit space systems. For example, when the first satellite was launched in 1957, one of the first Naval concerns was to be able to warn fleet units when enemy satellites might be capable of targeting them or collecting intelligence. Nowadays, besides the basic tactical purpose, the catalog serves a variety of peacetime uses, both military and civilian, both public and private, both domestic and foreign. For example, the catalog is used to predict when trackable objects will come dangerously close to any manned or mannable spacecraft or any launch from a U.S. launch site. However, maintaining the space catalog itself remains a mission of the U.S. military. Agencies such as NASA rely on USSPACECOM to operate the tracking, communication and data processing facilities that support the catalog, and to supply analysis and reports in a timely manner. In fact, no other country except Russia attempts to maintain an equivalent catalog of space objects. For this reason alone, the USSPACECOM satellite catalog should be considered a national treasure. It is one of the most important artifacts of the space age.

The catalog is a database of orbital elements from which it is possible to calculate position and velocity at any time for any trackable object in Earth orbit. Predicted positions of these objects are essential data for all analyses, including threat assessments. But since the prediction accuracy of each element set degrades more or less rapidly with time from the last tracking contact with the object, all objects must be tracked continually and element set updates calculated frequently (usually daily) if the threat assessments and other analyses are to be valid.

The operators of active payloads usually use some kind of cooperative tracking scheme to determine the orbits of their satellites. Radio beacons, on-board sensors, laser retroreflectors, on-board GPS receivers and other systems are commonplace. They provide accurate orbits very economically. Cooperative tracking also neatly identifies which satellite is being tracked in a constellation of several objects, since each payload can, for example, be assigned a unique frequency. However, for space surveillance, non-cooperative tracking is mandatory, for at least two reasons. First, one cannot assume that enemy satellites will emit signals that are usable for orbit determination. Second, 90% to 95% of cataloged space objects are inert, anyway: dead payloads, empty rocket bodies, a variety of objects deliberately jettisoned from payloads and rocket bodies, and miscellaneous debris from satellite break-ups and other inadvertent causes. It is essential to track and maintain current elements for everything that has a reasonable probability of detection, including debris, if the catalog is to serve its purposes. However, non-cooperative tracking tends to be more expensive and less accurate per observation than a cooperative method, especially for radars, the mainstay of surveillance tracking. Moreover, there is now the problem of determining from which object a given measurement originates. This problem of data association is one of the most difficult aspects of multitarget, multisensor tracking. It is potentially severe if the main or only means of target identification are the kinematic tracking data themselves, the case in space surveillance today.
In recent years, multitarget, multisensor problems other than space surveillance have spawned a vast and sophisticated literature, to which references [1], [2], [3], and [4] are only an introduction. Practically nothing has been done to apply the new techniques to space surveillance. Yet it is hard to overstate the practical difficulties of a large multitarget, multisensor tracking problem and the importance of overcoming them somehow. One of the first lessons of research related to ballistic missile defense was that the processing needed for data association and sensor coordination (command and control) always increases exponentially with the number of objects being tracked, and rapidly becomes unfeasible for any current technology when the number of targets rises to a few thousand. Uhlmann [5] has described this situation with a familiar baseball analogy. Three outfielders usually have no trouble catching a single fly ball. They would have noticeably more difficulty catching three simultaneous fly balls. However, the 3-on-3 problem is easy compared to the problem of ten outfielders trying to catch ten simultaneous fly balls. And it is hopeless to expect 100 outfielders to be able to catch 100 simultaneous fly balls. From the position of one of the 100 outfielders, it is easy to see why. The problems of distinguishing and labelling the individual balls, communicating that information among the players and coordinating the actions of the players have increased far out of proportion to the number of balls in the air. With this analogy in mind, we might compare the current Space Surveillance Network (SSN) to 24 outfielders (sensors) trying to catch 9500 fly balls (satellites). Of course, space surveillance is really easier than that. For one thing, satellites orbit the Earth repeatedly, and each sensor has many chances to "catch" them. But the actual difficulty of the space surveillance problem is real enough and is potentially overwhelming. Fortunately, there are a few mitigating circumstances:

(1) An essentially complete and up-to-date database of orbital elements of all trackable space objects has been maintained at a central facility since the first satellite was launched. Currently, this central facility is the Space Control Center (SCC) at Cheyenne Mountain Air Station in Colorado Springs and the Alternate Space Control Center (ASCC) at Naval Space Command in Dahlgren, Virginia. Moreover, the database has always been available to all of the sensors, so that, at any time, almost all of the objects being detected by a particular sensor are already cataloged and known to all other sensors. In other words, we have never had to generate the entire catalog of (now) more than 9500 objects ab initio. Such a massive task of data association and sensor coordination may be unfeasible with the current space surveillance infrastructure.

(2) Satellite orbital motion can be modeled and predicted much more accurately than the motion of other high-interest objects such as missiles and aircraft (or even baseballs). Moreover, the timescale of orbital motion is such that a tracking network response to an event within tens of minutes is adequate for many surveillance purposes, allowing opportunity for sophisticated computation.

(3) The vast majority (at least 95%) of currently cataloged objects do not maneuver, split into several distinct satellites, or use evasive measures to prevent detection.

(4) The space environment provides a relatively low-clutter background for most of the sensors, so the number of false detections reported to the SCC/ASCC is extremely low.
(5) The current catalog size implies a low enough spatial density of objects to prevent frequent confusion of targets. As a result, each sensor can reliably associate individual observations into single-object tracks.

(6) Since the cataloging operation was started, computer and communication capabilities have continued to grow faster than the catalog size. As a result, the SCC/ASCC has always had some processing performance margin and has usually responded well to stressing events such as satellite break-ups or solar storms.

The essential problem of space surveillance is data association. The space object catalog is maintainable only to the same extent that sensor observations can be associated with the correct satellite. All of the above factors combine to simplify the problem of data association enough for straightforward processing techniques to work. In fact, the entire concept of operations for the space surveillance system depends on such simplifying factors, and the entire system infrastructure has evolved accordingly. If any of the above fortuitous circumstances were to change for the worse in the long term, we would have to both re-think the current concept of operations and invest in major technical improvements throughout the system. Sometimes one or more of these circumstances does change temporarily and in those cases we do face special difficulties maintaining the catalog. For example, solar storms disturb the upper atmosphere and temporarily degrade our ability to model near-Earth orbits accurately. On at least one occasion (March 1989) the integrity of the catalog was endangered because of unmodeled atmospheric perturbations affecting an unprecedented number of orbits. Fortunately our ability to model satellite orbits is not going to degrade in the long term. Also, some procedural changes at the SCC/ASCC have reduced the chances that a similar problem would recur with the present catalog size and SSN. For another example of temporarily changed circumstances, satellite break-ups may instantly increase the trackable orbiting population by 500 or 600 objects. In that case, a substantial fraction of the objects detected by a sensor may be uncataloged and therefore unknown to any other sensors. Moreover, in the early stages of a break-up the spatial density of objects can be high enough to cause confusion between targets. Both of these effects must be overcome through extra association processing at the SCC/ASCC. Once the break-up pieces have separated sufficiently, typically after a few hours, orbits for all trackable pieces can usually be determined within a few days or several weeks.

One consequence of the above-listed factors which has special practical importance even in routine, "non-stressing" operations is that each individual sensor can, with high probability, associate the correct satellite catalog number with a new observation before the data are forwarded to the SCC/ASCC. Only a small fraction of the associations needed for catalog maintenance has to be made at the central facility. This avoids a serious bottleneck. The SCC/ASCC does not have enough processing capacity to do all, or even a large fraction, of the data association centrally. The association processing that is done at the SSC/ASCC consists mainly in verifying the satellite numbers supplied by the sensors, which may involve detecting and correcting the occasional mis-association, plus identifying the relatively small percentage of observations that the sensors could not associate. The latter identification process is the first
phase of so-called "uncorrelated target" (UCT) processing. Once associated, observations for each satellite are merged into a cumulative central-level track file which is used to update the orbital elements of the satellites. Then updated elements, along with sensor-specific tracking assignments ("tasking"), are distributed to all the sensors for use in acquiring future observations.

This two-tiered sensor-level-plus-central-level approach to data association has always been a fundamental feature of the satellite cataloging operation. In general, it has been very successful. It permits the necessary autonomy and flexibility at remote sensor sites, most of which have a primary mission other than space surveillance. It also allows the initial association processing to be tailored to the characteristics of each individual sensor without increasing the central-level processing load. It turns out that, in the current SSN under routine operating conditions, at least 90% of the observations are correctly associated by the sensors, making the central-level verification process relatively fast. Of the 10% or fewer remaining, as many as 94% turn out to be already in the catalog after all. Hence, a refined search of the entire catalog is always made at the SSC/ASCC to try to identify these observations before declaring that the data belong to one or more uncataloged objects. The high association success rate at the sensor level is what makes it feasible to do the refined search at the central level. Of course, it may happen that at least one new object has appeared, and that one or more new element sets must be created and examined for inclusion in the permanent catalog. This is the second phase of UCT processing. It involves track-to-track association for an unknown number of targets, plus initial orbit determination, and will be discussed in more detail later.

DATA FLOW FOR CATALOG MAINTENANCE

The logical flow of data for catalog maintenance at the SCC/ASCC is not a simple linear sequence, but it can be broken down into the following interrelated steps:

1. verify the sensor-level data associations;
2. identify unassociated or mis-associated observations with known satellites;
3. update the database of elements;
4. generate elements and associate data for the remaining UCTs;
5. release updated elements to the SSN and external users.

All of the sensor-level associations are verified at the SCC/ASCC as the observations arrive. This is a relatively fast process since only the element set indicated by the sensor needs to be retrieved from the database and propagated to the time of the observation. Well over 99% of the sensor-level associations agree with the central-level verification and are judged to be correct.

The few sensor-level mis-associations, plus the 10% of total observations that could not be associated at the sensor level, are passed to the identification process. Here some kind of comparison with the entire database of elements must be made for each observation. In practice, we retrieve and propagate element sets for only those orbits that come near the observed altitude. However, the identification process is still much slower (per observation) than the verification process. Usually about 94% of the observations presented for identification can be associated.
with objects that are already in the database, so the extra effort is worthwhile. The observations that fail the identification step are passed to the UCT processing step.

As new observations become available, or at least once per day, an attempt is made to update each element set. The automatic update is a least-squares differential correction (DC) process using the most recent element values as the *a priori* estimate. On average, about 98.5% of the element database is updated successfully without human intervention. The least-squares process may fail or produce poor results for a variety of reasons, so the analysts must examine about 1.5% of the database elements daily. The main tool that they use to do this is "manual differential correction" (MANDC), which gives them complete discretion over the least-squares fitting process. Using it, they can accept or reject individual observations, update only a subset of the complete element set, adjust the number of iterations, and so on. We find that new analysts acquire proficiency with MANDC only after considerable learning time, so that human expertise is an essential part of the cataloging system.

It should be noted that the orbit models used to generate catalog element sets are not highly accurate compared to most orbit models in operational use in the space industry. The best accuracy would be obtained with numerical-integration (special perturbation, or SP) models, and most satellite programs use such models for operations. Space surveillance is one of the few space activities that relies mostly on analytical (general perturbation, or GP) models. The reason is that GP models can be made to execute faster than SP models by one or two orders of magnitude, though with much reduced prediction accuracy. Until recently, the greater speed was essential if the catalog was to be maintained at all, because of computer limitations, and the accuracy penalty was simply a fact of life. Nowadays the basic computer capacity does exist to use SP models for maintaining the space catalog. NAVSPACECOM is investigating the details and special considerations involved in using advanced orbit models to fit current SSN data. It is not yet clear what actual improvement in prediction accuracy can be achieved when model errors are no longer the limiting factor in our orbit determination. What is clear is that the need for highly trained and experienced analysts will increase as the models improve. The reason is that more of the orbital phenomena that are actually observable in the SSN data will be represented in the element sets and will call for analysis and explanation. Even now a variety of hard-to-understand phenomena are on record for individual satellites [6]. Some of these cases, such as apparently maneuvering debris, are of such a nature that no automatic system is likely to be able to handle them satisfactorily, so the analysts will have to stay fully engaged in the entire cataloging process no matter how good the models are.

**FENCE OBSERVATION PROCESSING**

The NAVSPASUR fence operated by NAVSPACECOM is a continuous-wave multistatic radar interferometer deployed along a great-circle arc across the southern U.S. Raw signals detected at the receiver stations are sampled at an effective rate of 55 Hz for up to one second as the satellite passes through the fence beam, and then forwarded in real time to NAVSPACECOM. Interferometric processing of each signal produces a pair of direction cosines reckoned at the time of peak signal strength at each individual receiver station. Then the cosines are associated
with cataloged objects in real time by comparing them with pre-computed fence crossings of all objects in the database. This scheme is feasible because, by design, the fence beam is confined very near to the great-circle plane. Therefore it is possible to predict, to within nearly the accuracy of the element sets, when and where each satellite in the database will be detected by the fence. Predictions based on the most recent element set for each satellite are computed for 36 hours into the future every time the element set is updated, or at least once per day. These predictions are sorted in time order and merged with the predictions for all other satellites in a single prediction database. The fence data association then proceeds in time order as the observations arrive. Normally, at least 97% of the fence observations can be associated with known satellites. This is a noticeably higher percentage than can presently be associated at the sensor level by the other tracking sensors in the SSN, which makes the NAVSPASUR fence an especially important asset for UCT analysis.

When fence observations (directions cosines) cannot be associated immediately with known satellites, an attempt is made to convert time-correlated lines of sight from all participating stations into a position fix for the object. Additionally, a crude velocity estimate is available as a by-product of the interferometry. Therefore, a complete state vector can be passed to other SSN sensors if we want special tracking coverage of the object. Meanwhile, the position fix is passed to the automatic identification process.

**UCT PROCESSING**

"UCT" stands for "uncorrelated target", an observation or track that has not been associated with a known satellite. For this part of the discussion, we consider UCTs to be those observations that fail to associate in the automatic identification process. Ultimately, we must dispose of UCTs either by (1) associating them with a cataloged element set or an existing analyst element set, or (2) creating a new analyst element set from the UCT data. Option (1) is still possible after the automatic identification step because the most recent element set may have been corrupted or because the element set has not been updated recently and no longer provides accurate predictions. Of course, it may be that no association will ever be made for some observation, perhaps because the data is corrupted or because the object has such low probability of detection that no element set can be maintained. The current practice is to retain all UCT data for up to 60 days for high-altitude orbits and up to 30 days for near-Earth orbits. Beyond these timespans, the prediction accuracies available from the standard orbit determination methods have degraded so much that the chance of making correct associations with known satellites is practically nil.

Whenever the automatic system cannot associate observations with known satellites, orbital analysts must use special software tools to make the proper data association. Although the analyst work is inherently slower than real-time, it is still essential to make the correct data associations as soon as possible. Human expertise built up through long experience has always been indispensable for this analysis. Moreover, satellite break-up events present special challenges because many unassociated observations and an unknown number of new satellites are involved. The number of association hypotheses that may have to be investigated always goes up exponentially with the number of unassociated observations and rapidly becomes
unmanageable without human expertise to identify the most probable associations *a priori*. Recently, advanced computation and parallel processing techniques have made it possible for the analysts to consider many more association hypotheses than in the past. Nevertheless, human expertise is still crucial in the overall management of the cataloging system.

When the automatic identification fails to make associations, the analysts usually try a "manual identification" first. This involves relaxing the association tolerances in some systematic way to account for known or expected inaccuracies in the element sets and observations. The tool SID identifies position observations (including fence position fixes) by comparing all observations with each selected element set. The tool IDUAOB identifies angles-only observations (including fence direction cosines) by comparing all element sets with each selected observation. If any new associations can be made with these tools, the analysts may use MANDC to update the respective element sets in the database of known satellites.

If the manual identification cannot associate observations with known element sets, the analyst must generate new element sets from the UCT data. These candidate element sets are handled differently from the "analyst" element sets on known objects, because they have little statistical support. They are really only working hypotheses that may make it possible to associate data from different sensors or data that are widely separated in time. The candidate element sets are generated differently, depending on the sensor type.

For radar tracks with sufficiently many observations, it is relatively easy to generate a candidate element set. The main tool for creating single-track element sets is FORCOM. It can also compare other tracks and observations with predictions from the candidate element set, and can differentially correct the element set using observations that do associate with the predictions. Once FORCOM produces a candidate element set with reasonable statistical support, two other tools can be used to compare it with element sets on known objects or other candidate element sets. FNSORT compares two element sets by comparing their predictions. COMEL compares two element sets by comparing their element values directly. By one tool or the other, the analyst can usually decide whether two element sets belong to the same object. If they do, then the observations can be merged and a more refined element set produced via MANDC.

With only fence position fixes or sparse radar tracks, it is not possible to generate sufficiently accurate single-track element sets. Therefore data that are widely separated in time must be associated before candidate element sets can be produced, and the processing is necessarily more complicated. In principle, one could consider generating all possible candidate element sets from the entire database of UCT observations. The tool SAD implements this approach. It takes a set of UCT observations selected by the analyst and generates an orbit through every possible pair of positions. Essentially, it solves Lambert's problem, including secular perturbations, for each pair. SAD also refines each candidate orbit in the same way that FORCOM does, so that finally some candidate orbits with reasonable statistical support are produced. These can be examined more closely with FNSORT and COMEL. Ultimately, the analyst may be able to produce some refined candidates via MANDC.
The only difficulty with SAD is that it generates a combinatorially large number of candidate orbits and compares each of these against the entire set of UCTs presented to it. In its original form, it required so much computation time that the analysts could not use it for the entire 30-day or 60-day collection of UCTs. The simple expedient of limiting the input to 5 days of UCT data (which still required several days of execution time!) did not work well. With such a short span of data, few orbits with reasonable statistical support could be produced. Instead, the analysts had to find ways to manually select UCT observations from the 30-day or 60-day time span that had high probability of originating from a small number of objects. Several graphical tools were created to help with this selection job. PLUME allows the analyst to select observations based on visual correlation in a plot of time differences relative to predictions from a reference (or "parent") element set. TRIPLT allows the analyst to select fence position fixes based on visual correlation in a plot of fence data. RAQUAD allows the analyst to group fence position fixes together by helping him find sequences of constant difference in right ascension with altitude constraints. Of the three, PLUME finds the most use and works fairly well (in skilled hands) for finding pieces that have separated at low relative velocity from a parent satellite. But the real problem has always been that SAD inherently requires vast computations. Recently, a parallel version of SAD was implemented at NAVSPACECOM on a cluster of 11 medium-performance workstations. It is able to process 30 days of UCT observations in about half a day and always produces a large number of candidate orbits with good statistical support. Reference [7] describes the parallel algorithm. As of September 1996, the tool is still being tested and qualified for operational use, but is already considered a breakthrough in UCT processing. It was used to process the Pegasus upper-stage break-up which occurred on 3 June 1996, a very timely application because that event turned out to be the largest satellite break-up to date (over 670 trackable pieces).

There are two other tools which are especially useful for satellite break-ups. COMBO finds the times and locations at which the distance between selected satellites is a local minimum. COMBO is used routinely when a break-up is suspected to see if the satellite in question could possibly have collided with a known object. Similarly, BLAST computes the time and position of a satellite break-up once sufficiently many element sets for the pieces have been produced. It straightforwardly searches for the times at which the predicted positions cluster together and gives a statistical characterization of each cluster. Once the break-up time and position have been found, SAD can produce elements quite rapidly for all the remaining pieces that have been tracked. It does this by constraining all the candidate orbits to pass through the break-up position (and time) so that the number of candidate orbits is no longer combinatorially large.

Finally, some relatively new tools have been developed for historical analysis of the element set database. GOBS displays time histories of cataloged elements with analyst elements or UCT-derived elements superimposed. This allows the analyst to identify lost or mistagged objects. GOBS can also make reasonably accurate long-time predictions (on the order of years) for geosynchronous satellites, which aids UCT processing for that orbital regime.
POTENTIAL FAILURE MODES

It is possible in principle for the cataloging system to fail because, fundamentally, no orbit model can make accurate predictions indefinitely far into the future, regardless of the number and quality of the observations available. The accuracy inevitably continues to degrade with time from the last observation included in the orbit determination. Therefore, without periodic updates of an element set, it will become increasingly difficult to associate recent observational data with the element set. Eventually it becomes effectively impossible to make the associations, and after that the element set can never be updated. That particular satellite would be "lost". Notice that "lost" does not mean that it is no longer being observed. Sensors may actually be detecting it occasionally. But without a current element set there is no way to associate the observations together so that we know the same object is being detected at different times and places. Hence, it is essential for the catalog to be always as current as possible.

We can say that the cataloging process is failing if the proportion of lost satellites is increasing with time, meaning that, on average, element set updates are falling farther and farther behind the flow of incoming observations. How might such a failure get started? There are two basic ways. One way is if there were a general communications failure so that observations cannot reach the SCC/ASCC fast enough to be included in the next element set update and element sets cannot reach the sensors fast enough to permit high association success rates, and for this situation to continue for several update cycles. Such a general and sustained slowdown of all communications paths is a rather contrived scenario, however, and unlikely to occur in practice. The other way for the failure to get started would be for a central-level processing bottleneck to develop. This situation has actually happened on a limited scale, as in March 1989, and deserves some attention.

It is always possible (again, in principle) to use up the central-level processing margin by sending enough observations from the sensors. The margin is used up at least an order of magnitude more quickly if many or most of the observations have not been associated correctly by the sensors, that is, if the central-level UCT processing becomes extensive. Of course, a sufficient delay in producing updated elements for the sensors tends to increase the proportion of data that the sensors cannot associate because they continue to make observations while they wait for the new elements. The result is that the rate at which the catalog is failing will tend to accelerate, because the UCT processing load gets worse on every update cycle, leading to longer and longer delays in the element set updates. The only safe answer to this problem is to give the central-level processors a far larger capacity than they need for "routine" operations. On those few occasions when they need a big processing margin, nothing else will do. Moreover, the necessary margin goes up much faster than the catalog size because of the nature of UCT processing. Unfortunately, we cannot yet put these arguments in quantitative terms for the SCC/ASCC and the SSN. The dynamic behavior of the cataloging process has never been simulated in the necessary detail. Such a simulation facility is needed to make progress in this area.
Is it likely that any planned or proposed deployments of satellite constellations would cause some kind of failure of the cataloging system? We can use the historical success with cataloging satellite break-up pieces as an indicator. The largest break-up to date (on 3 June 1996) produced just over 670 trackable pieces. Within a matter of weeks, the number of UCTs that could be associated with this event was negligible, and at no time was the rest of the catalog compromised because of the extra processing load. This gives us reason to believe that any deployment involving at most hundreds of satellites, such as Iridium and Teledesic, will not compromise the cataloging system. Even constellations of several thousand satellites should not cause any difficulty, as long as the objects are large enough to be trackable and are deployed in batches of at most a few hundred a few weeks apart.

A somewhat different situation arises if we consider the problem of cataloging small debris that is already in orbit but not now trackable. If the threat of collision with debris as small as 1 centimeter is someday judged to be serious enough, it is possible that we might be required to detect and catalog all such objects. There is little data from which to deduce the present number of near-Earth objects larger than 1 centimeter, but the number may be as large as 400,000 in the region below 1500 kilometers altitude [8]. Entirely new sensors would be needed to detect objects that small with reasonably high probability, but let us suppose they were available. Do we also have available, or can we design, sufficient central-level processing capacity to do the UCT processing for this scenario? Clearly, we would need to re-think the entire cataloging process in order to have a reasonable chance of success, and at present we do not even have the tools (simulations) to do the re-design. The most practical approach to cataloging small debris seems to be to build the catalog slowly over a period of years by gradually increasing the sensitivity of the new sensors. The constraint on the schedule would be that, at any moment in time, we have to be able to catalog essentially everything being detected. A slow enough schedule would keep us from having to process, in effect, a 400,000-object break-up.

**IMPROVEMENTS AT NAVSPACECOM**

We have seen so far that improving the cataloging process means improving data association. This, in turn, calls for better accuracy and precision of predictions, and faster processing (better processing margin) to accommodate the growing catalog. Some aspects of these problems are now being addressed in research efforts at NAVSPACECOM.

The new distributed computing system at NAVSPACECOM has the basic computing capacity to use a fairly sophisticated SP model for catalog maintenance. However, there are some technical problems that must be solved before this approach can be made to work operationally. First, the existing computer network was not designed for the extra processing load of SP; rather, the computing capacity is distributed over more than 200 nodes of the network. Second, it is not clear that observational data from the current SSN is always dense enough or well enough calibrated to allow automatic SP updates of the entire catalog. In the past, we have often noticed that the standard Gaussian-type differential correction of orbits is more robust numerically when our GP model is used than when our SP model is used. Whereas we have long been able to update about 98.5% of the catalog automatically with GP processing, in preliminary SP tests
only about 80% of the catalog has been updated automatically. The reasons are not yet well understood. All of these problems are now under active investigation in collaboration with Dr. Shannon Coffey and co-workers from Naval Research Laboratory.

There is an urgent need for realistic error characterization in space surveillance products, especially the prediction error of element sets. Better orbit models are one part of the answer. An equally important part of the answer is better sensor calibration. In over-simplified terms, the errors of the observations are always mapped through the orbit model, which contributes its own errors, and the combined result appears as the prediction error. So it is not possible to derive useful measures of prediction error unless the sensor characteristics are well known a priori. NAVSPACECOM now is examining new methods for calibrating the NAVSPASUR fence data continuously, based on externally-generated reference ephemerides of selected satellites and on laser ranging measurements.

Parallel processing seems to be the most practical and economical way to provide the extra processing margin necessary at the SCC/ASCC. For the past several years, NAVSPACECOM has been developing, again in collaboration with Dr. Coffey and co-workers at Naval Research Laboratory, parallel versions of important space surveillance applications. Three of these applications will be mentioned here briefly. All of them are being developed to run on the NAVSPACECOM computer network under the control of a software system known as PVM (Parallel Virtual Machine). PVM was developed in recent years at Oak Ridge National Laboratory and is available as "freeware". It allows any UNIX-based computer network to simulate a parallel computer by coordinating the simultaneous execution of programs on different nodes of the network. In problems that do not require extensive interprocess communication, the simulated ("virtual") parallel computer can achieve large increases in performance compared to any single node running the same task, even when the network speed is not extremely high. Fortunately, many space surveillance applications, including catalog maintenance, are in this category of problems.

(1) The tool COMBO, which computes when close approaches between selected satellites will occur, has already been mentioned in connection UCT processing. But perhaps the most important use of COMBO is for collision avoidance for the Space Shuttle. To date, during 500 days of on-orbit Shuttle operations, there have been 6 occasions when cataloged objects came within a "warning zone" extending 4 kilometers radial, 10 kilometers along-track and 4 kilometers cross-track, centered on the Shuttle. On 3 of those occasions, the Shuttle has maneuvered to avoid the risk of collision [9]. COMBO analysis at the SCC/ASCC is the means by which USSPACECOM provides notice to NASA sufficiently far in advance for the Shuttle to be able to maneuver. Of course, it is undesirable for any active payload to suffer unnecessary risk of collision. But COMBO becomes computationally burdensome when more than several objects must be analysed for more than 24 hours into the future. The parallel COMBO algorithm now being implemented at NAVSPACECOM is described in reference [10]. Using 11 medium performance workstations, we can analyze the list of all U.S. satellites of military interest (Blue Space Order of Battle, currently 198 satellites) for close approaches to any cataloged object for a period of 7 days, in a total run time of about 80 minutes. For these tests, PVM-controlled
routines were allowed to execute only in the background because the workstations were in regular use for other purposes at the time, so substantial improvement in performance will be available in the final operational configuration. We expect to be able to analyze the entire catalog in an all-versus-all fashion on a regular basis in the near future.

(2) The tool SAD has already been mentioned in connection with UCT processing. The parallel version is now available to NAVSPACECOM orbital analysts, and has been in use for several months. However, much work still remains to improve the efficiency of the implementation and integrate it into routine operations.

(3) The parallel SP catalog maintenance is still in development, though demonstration runs on the NAVSPACECOM network will begin in the fourth quarter of 1996.

In the farther future, we will have to consider how advanced computation, especially parallel processing, allows us to re-engineer the whole catalog maintenance system. For example, should the catalog have to include small debris, we will need a much more robust catalog maintenance process before the catalog begins to grow rapidly, because of the large numbers of UCTs that will have to be processed. Ultimately it is desirable to be able to reconstitute the entire catalog without any prior element sets or data associations. Rebuilding the catalog ab initio on demand in a reasonable amount of time is the "grand challenge" problem of space surveillance. It is probably out of reach to solve this problem in practical terms anytime soon, but by pursuing it we would develop the more robust catalog maintenance process that we do need soon. In particular, we need detailed modeling and simulation of the entire space cataloging operation in order to estimate system sensitivities, risks, performance boundaries, failure modes and relative merits of proposed improvements. High-fidelity simulation of the whole system at both sensor level and central level is probably the only way that a full reconstitution capability can be developed and tested.

REFERENCES


