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NAVSPASUR ORBITAL PROCESSING FOR SATELLITE BREAK-UP EVENTS

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ABSTRACT

Satellite break-ups via explosion or collision can instantly increase the trackable orbiting population by up to several hundred objects, temporarily perturbing the routine space surveillance operations at U. S. Space Command (USSPACECOM) and the Naval Space Surveillance Center (NAVSPASUR). This paper is a survey of some of the procedures and techniques used by NAVSPASUR to respond to such events. First, the overall data flow at NAVSPASUR is described, highlighting the places at which human analysts may intervene with special processing. So-called manual intervention is required in a variety of non-nominal situations, including break-ups. Second, a description is given of some of the orbital analysis and other software tools available to NAVSPASUR analysts. These tools have been developed in-house over the past thirty years and can be employed in a highly flexible manner. The basic design philosophy for these tools has been to implement simple concepts as efficiently as possible and to allow the analyst maximum use of his personal expertise. Finally, several historical break-up scenarios are discussed briefly. These scenarios provide examples of the types of questions that are fairly easy to answer in the present operational environment, as well as examples of questions that are very difficult to answer.

INTRODUCTION

NAVSPASUR has conducted space surveillance operations for almost 30 years. The primary product of such work is a satellite database containing orbital element sets and associated observations for all trackable objects. Many military, scientific and engineering enterprises depend on the accuracy and timeliness of this database. Although most of the satellite cataloging operation is completely automated, a variety of situations can occur in which a human analyst must intervene with special procedures. A break-up event is just such a case. Historically, NAVSPASUR has been quite successful in deriving orbital elements from observations of new debris fragments, even when the event involves several hundred trackable objects. This fact has come into special prominence since 1985 when NAVSPASUR was designated as Alternate Space Surveillance Center (ASSC), back-up to the Space Surveillance Center (SSC) operated by USSPACECOM at Cheyenne Mountain AFB. A dozen major break-ups have occurred since then [1]. Currently, NAVSPASUR provides identifications for almost all of the unassociated observations reported to the SSC by the worldwide surveillance network.

NAVSPASUR contributes two main resources to the space surveillance effort. The first is the NAVSPASUR "fence", a radar interferometer deployed on a great circle coast-to-coast across the southern United States, which provides unusually wide geographical and altitudinal coverage. It is an all-weather, dedicated space surveillance instrument that does not have to be "tasked" (scheduled in advance for aiming) as do tracking radars. Rather, 3 transmitters provide a continuous-wave fan beam in the great-circle plane. Satellites penetrating the beam reflect signals to one or more of 6 receiver sites. At each receiver site, signal phases and amplitudes are measured on arrays of antenna elements and this data is relayed in real time to Dahlgren for processing. The second main resource is less tangible, namely, human expertise. NAVSPASUR employs civilian orbital analysts for operational work and requires them to have at least 6 years' experience. There are several staff members with over 20 years' experience. The result is that the analysts' subjective judgment becomes well tuned to the problems of orbital element maintenance. In the present system, human expertise is indispensible, especially for infrequent but stressing situations such as break-ups.

NAVSPASUR DATA FLOW

In order to understand the special processing needed for break-up analysis, it is necessary to understand something of the routine processing that occurs in maintaining the satellite catalog. NAVSPASUR is continually receiving a mixture of observations and element sets from the SSC and other surveillance network sensors, besides raw data from the fence (Fig. 1).

OBSERVATION & ELEMENT DATA FLOW

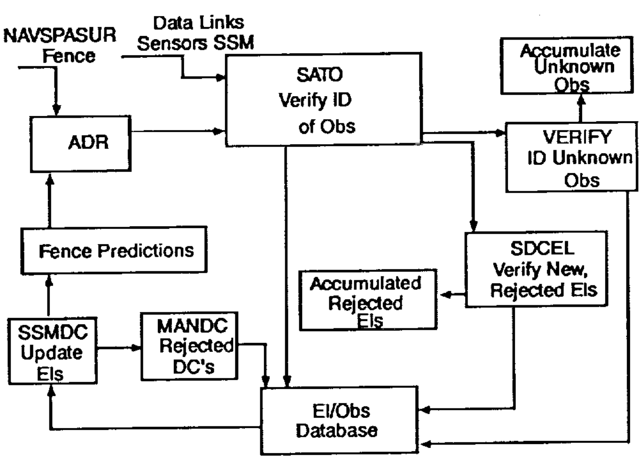

FIGURE 1

ADR is the real-time program which reads the incoming fence data and converts the phase measurements into direction cosines as seen from each receiver site. Doppler measurements are also extracted from the raw data. ADR attempts to associate these single-station sightings with known orbits based on comparisons with a time-ordered list of predicted time, cosine and Doppler values for fence crossings of known satellites. These predicted values will have been computed from the most recent element set on file for each satellite, as described later. In case the sighting cannot be associated within nominal tolerances, ADR performs a triangulation of time-correlated single-station sightings to arrive at a position estimate for the object. Various other programs will use this position in a more refined attempt at association, but in a non-real-time manner.

SATO is really a set of programs which are cued every 15 minutes to add incoming element sets and observations to the database. Unassociated observations and tracks are written to a holding file. Elements that are new or out of tolerance with the existing sets are written to another holding file.

SDCEL is executed once each day to re-examine incoming element sets rejected by SATO. A more thorough comparison with existing sets is made and those sets still rejected are saved for review by analysts.

VERIFY also is executed once each day to re-examine the unassociated tracks rejected by SATO. If, after more extensive checking, the track still cannot be associated with a known orbit, it is saved for analyst review.

SSMDC attempts a batch least-squares differential correction of each element set in the database using the associated observations, if new observations have become available since the last epoch. The new epoch is placed at the time of the last observation. The fit interval is chosen by an empirical formula containing the satellite's mean motion and rate of change of mean motion (the latter is mainly a decay effect). If the fit interval has fewer than 5 observations, or if new elements change by more than prescribed tolerances from the earlier values, or if the residuals in the fit are too high, the orbit is declared "not fit" and is noted for attention by analysts. However, SSMDC is able to fit about 98.5% of the database automatically under routine conditions; that is, of 6500 orbits, only about 100 will need further work by the analysts.

Finally, another set of programs uses the updated orbital elements to produce a time-ordered list of all predicted fence penetrations for the next 24 hours.

SOFTWARE TOOLS

Observations that cannot be associated with known orbits by VERIFY must be associated by the analysts. Likewise, incoming element sets that were rejected by SDCEL (for any of a variety of reasons) can be entered into the database only under direct analyst supervision. Moreover, there are always a few correctly associated observations that still do not produce an acceptable differential correction in SSMDC. These cases also require analyst attention. There are tools designed to aid in all these processes (Fig. 2).

General UCT Processing

The abbreviation "UCT" stands for "uncorrelated target", that is, an unassociated observation or track. The initial association attempt can fail for a variety of reasons, even for well known objects, and, in fact, about 94% of all UCTs turn out to be finally associated with some already-cataloged orbit [1].

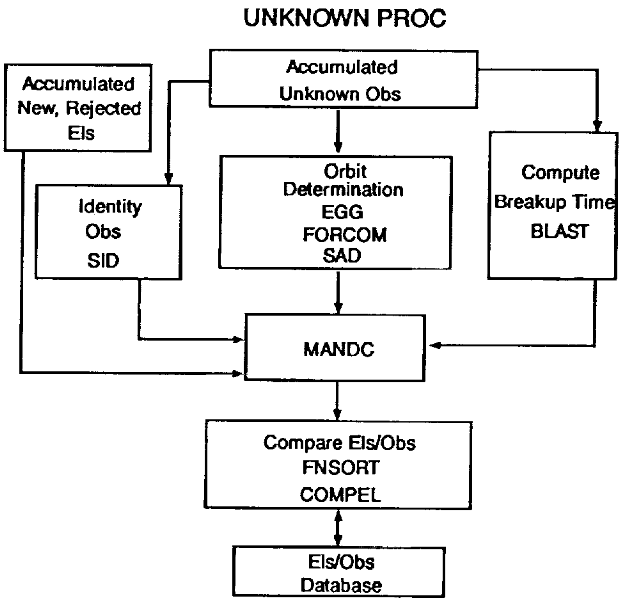

FIGURE 2

Hence, one should try to associate a UCT with an existing element set before assuming that a new orbit has appeared. If only a few observations or tracks are to be considered, the analyst can address them essentially one by one. There are several programs designed to operate on this category of problems.

SID seeks to associate observations and tracks with known orbits through a systematic relaxation of tolerances. Here, the analyst's knowledge of such things as lunar/solar effects, decay behavior and maneuvers is used to compensate for the incomplete representation of these effects in the orbital model.

FORCOM and EGG produce an element set from a single track and attempt to associate other tracks to this candidate orbit.

FNSORT compares each element set from FORCOM and EGG to the catalog to see if it matches an existing set (perhaps locating a "lost" satellite) or if it is an entirely new orbit.

COMPEL helps insure close correlation between the satellite databases at NAVSPASUR and at the SSC. Elements sets generated at the two centers are compared and and a list is generated of those orbits for which NAVSPASUR has a more recent epoch. Occasionally, NAVSPASUR has a current epoch for a satellite reported by the SSC as "lost". (By convention, a satellite is "lost" if it has had no observations associated to its orbit for a specific time span: 5 days for near-Earth objects or 30 days for deep-space objects.)

MANDC (Manual Differential Correction) allows the analyst complete control of the fitting process. This program is identical in concept with a program of the same name used at the SSC. The user may specify the fit interval, the tolerance used to accept observations, and the starting value of any element. Any subset of an element set can be corrected, and the user can reject observations at will.

COMBO (Computation Of Miss Between Orbits) is also conceptually identical to a program of the same name used at the SSC. It computes the times and locations of local minima in the distance between any two specified satellites in a given time span. A straightforward option allows a list of satellites to be compared against another list. The method uses analytic procedures to identify the distance minima that are less than a specified value, and then numerical integration is used to compute these close encounters as accurately as possible. The SSC version of the method has been described in the open literature [8]. In either version, the program can require long execution times, so some analyst discretion is needed to employ it effectively.

Break-up Processing

When a break-up occurs, one is faced with a large number of UCTs plus actual new orbits. The analyst workload always tends to go up geometrically with the number of UCTs because, in order to determine the orbits, observations have to be associated between successive passes of the debris cloud through the fence or other sensor coverage. The above programs by themselves would not be adequate for this task, but special software has been devised to help the analyst sift through the vast number of possible association combinations that must be checked.

SAD (Search and Determine) operates on an analyst-specified subset of the whole UCT list [2,3]. The analyst may suspect, based on his experience and intuition, that some particular observations all belong to the same break-up. SAD selects pairs of positions and computes candidate orbits by solving the secular-perturbed Lambert boundary-value problem for each pair. The size of the family of candidate orbits is constrained by user-specified limits on inclination, period and eccentricity. The analyst may also enforce an a-priori decay rate on the orbits. For each candidate orbit, the full orbit model is used to try to associate other observations with the candidate, based on position tolerances in radial, transverse and normal directions. If enough associations are found, the orbit is refined via differential correction. The fit statistics are compared with previous differential corrections for the family and the best orbits are saved. When no more observations can be associated, another pair of positions is selected and the whole process is repeated. When all pairs of observations have been checked, the analyst has a list of element sets with which to begin MANDC processing. The list is likely to contain many spurious orbits, but an experienced analyst will be able to "separate the wheat from the chaff" in a reasonable amount of time. Of course, the running time of SAD is potentially very long and the analyst must exercise discretion in presenting data to this program. Besides time span and element value limits, the user can select association tolerances and the number of associations which must be found before a differential correction will be performed. One more option, crucially important, will be discussed below after a different program has been described.

BLAST attempts to solve the special problem of locating when and where the break-up occurred, assuming an instantaneous event [3]. A list of candidate element sets is used to calculate the position on each orbit at equal time increments (initially 7 minutes) using the full orbit model. Conjunctions in these ephemerides are detected and recorded for analyst review. Presumably, the positions will show definite clustering near the actual break-up location, even given the inaccuracies in the element sets. It is quite common for several candidate "blast points" to appear, and the analyst must choose between them on statistical grounds and based on a-priori information.

Once the blast point is known, that time and position can be used to constrain the selection of orbits on which the remaining unassociated observations are assumed to lie. An additional option in SAD is to force the blast point to be always one of the pair of positions to be processed. This is the crucial step in sorting out the whole mass of unassociated observations; not only is the SAD processing time drastically reduced, but also the results generally contain fewer spurious orbits. The new SAD orbits can be used to refine the estimate of the blast point in another run of BLAST, which in turn increases the efficiency of subsequent SAD searches. The temptation in this type of processing is always to try to determine the blast point too soon, that is, before enough data is available. If an inaccurate blast point is adopted then the subsequent searches may go astray. SAD might appear to be confirming this wrong point when, in fact, the fits are not nearly as good as they would be if the correct point were being used.

EXAMPLE BREAK-UP EVENTS

It is difficult to classify any given break-up as "typical", either in terms of orbital behavior or processing sequence. However, several examples will illustrate the degree of success which can be achieved in the current system.

The first example illustrates the simplest type of break-up, one in which only a few small pieces appear singly over an extended period of time and depart from the parent body at low relative velocity [1]. TIROS N, a fourth generation Television and Infrared Observation Programs satellite, was launched on 13 October 1978 into a sun-synchronous orbit at 99 degrees inclination. The altitude of 451 x 460 nautical miles gave the satellite a long orbital lifetime estimated at 350 years, and the payload remained active until 1 November 1980. Seven years later, NAVSPASUR analysts discovered and cataloged two small debris pieces which were shown to have originated recently from TIROS N. Break-ups at this altitude, whatever the piece count, have intrinsic interest because they contribute to the growing problem of long-lived orbital debris. Analysis showed the first piece to have separated at 1658UT on 28 September 1987 and the second at 2107UT on 4 October 1987. High probability attaches to these times, and hence to the corresponding locations, because of the simplicity of the scenario. Only one orbit at a time had to be identified, and the low-eccentricity, low-decay orbits could be propagated quite accurately.

The second example is more complicated [1]. Cosmos 1823, a second generation geodetic satellite, broke up on 17 December 1987. The satellite had been in an orbit of 73.6 degrees inclination at an altitude of 785 x 823 nautical miles, so again much of the debris would become part of the permanent orbiting population. The event aroused extra interest because this type of satellite has not been prone to break up. COMBO analysis demonstrated that the original satellite had experienced no conjunctions as close as 25 nautical miles to any known orbiting object. The first observations were made by the PARCS phased array at Cavalier, North Dakota. 22 pieces were detected between 2105UT and 2115UT. Two hours later, the cloud passed through the NAVSPASUR fence. 36 pieces were detected between 2305UT and 2319UT. On 18 December, after additional observations had become available, NAVSPASUR analysts were able to generate 10 element sets and a blast point. The main debris piece was identified by determining which orbit was most similar to the parent orbit. This identification, supported by a high observation count, allowed the SSC to renumber the main debris piece to the parent number. Over the next several weeks, NAVSPASUR analysts continued to discover additional pieces associated with this break-up. By 7 January 1988, a total of 175 element sets had been sent to the SSC, and of these, 33 had been cataloged. The main complication in this scenario was the large number of objects. The orbits were mostly low-decay and so could be propagated accurately, while the pieces persisted long enough that many observations could be taken and reliable orbits computed.

The third example indicates that low-altitude break-ups can be more difficult to assess operationally than higher-altitude events [3]. Cosmos 1405 had been deployed originally in an orbit of 65 degrees at an altitude of 168 x 181 nautical miles, but broke up on 20 December 1983. From later analysis, the event was believed to have occurred at 1214UT at 23.7 degrees S latitude, 44.9 degrees E longitude, 182 nautical miles altitude, with a standard deviation of 3.5 nautical miles. The first NAVSPASUR observations were not made until more than 7 hours later. 67 pieces later associated with this event were detected between 1929UT and 1936UT, spread geographically between longitudes 102 degrees and 95 degrees W and altitudes 133 and 233 nautical miles. In one 2-minute period, at least 20 objects were detected, however. This tight clustering meant that NAVSPASUR analysts had to wait until the cloud had passed through the fence for the third time, late on 21 December, before before meaningful element sets could be generated. Time had to be allowed for the cloud to disperse sufficiently so that new observations could begin to be associated correctly with previous observations. By then, though, the analysis proved to be difficult for a different reason. All the pieces were in high-decay orbits. The orbit model could not propagate the orbits as accurately as for higher-altitude events, and pieces were already beginning to reenter, eliminating opportunities for further observations. Moreover, the differential decay rates among pieces were rather high, amounting (in-track) to 30 seconds in a 12-hour prediction and apparently due to different pieces having different area-to-mass ratios. Therefore, not only were predicted fence crossing times uncertain, the predicted order of pieces passing through the fence also was unreliable. Only 24 element sets were produced, and some of these are likely to have been spurious. In the end, BLAST produced several candidiate event locations. The accepted time-and-location quoted above was selected based on its marginally higher statistical weight and the fact that no element sets were rejected in this solution. The solution also happened to be near the middle of the various candidate solutions. By two weeks after the event, the number of UCTs that could be associated with the break-up had dwindled to 1 or 2 per day, and all the cataloged pieces were being seen regularly. Without the complications due to high decay, an event of this magnitude would probably have ceased to be an operational problem within one week, even using only NAVSPASUR fence data [3].

The final example is, to date, unique in NAVSPASUR records of break-up processing [4,5,6]. Three satellites were involved in the analysis, and at the time some suspicion was raised that an inadvertent on-orbit collision had occurred. Before it broke up, Cosmos 1646 had been deployed in an orbit of 65 degrees inclination at an altitude of 216 x 234 nautical miles. The accepted time and location of break-up were determined by NAVSPASUR analysts to be 0131UT on 20 November 1987 at 64.9 degrees N latitude, 60.3 degrees W longitude. Early piece counts were about 50, while later estimates ranged up to 150. On 21 November, TVSAT-1, key payload in a cooperative European venture, was launched due east from Kourou, French Guiana, aboard the Ariane V20 vehicle. 3rd stage injection into geosynchronous transfer orbit commenced at 0235UT and payload separation occurred on schedule at 0238UT. 30 seconds later, the payload and the spent 3rd stage crossed the Cosmos 1646 orbit plane near the west coast of Africa at approximately the altitude of the debris. At about 0244UT it was discovered that one of the solar panels on the payload had failed to extend. Between 0530UT and 0726UT the 3rd stage was tracked from Kwajalein (by ALTAIR) and observed to have an anomalous low thrust. Launch plans had called for the 3rd stage to remain in orbit, but instead the low thrust caused reentry on the first revolution at about 1249UT. The coincidence of these two malfunctions led debris scientists at NASA/Johnson Space Center to speculate that collisions with small particles, even millimeter-scale ones, from the Cosmos break-up could have punctured the pressurized 3rd stage and damaged the solar panel. (The relative velocity was about 9 km/sec.) NAVSPASUR was asked to investigate the orbital conjunction. COMBO analysis indicated that TVSAT-1 did indeed penetrate the debris cloud but had approached no closer than 103 nautical miles to any of the known pieces. Some uncertainity attaches to this figure because of fairly high decay in the debris orbits. Meanwhile, contractor analysts at NASA/JSC pursued a parallel study. They used NAVSPASUR element sets because the accepted time and location of the break-up had been based on NAVSPASUR calculations. However, not having access to the NAVSPASUR orbit model, they attempted to recreate the scenario using the SSC orbit model. It was found that the latter model would not propagate the NAVSPASUR element sets backwards to a close conjunction at the accepted time of break-up, making any forward calculation of conjunction with TVSAT-1 highly dubious. In retrospect, this failure is not too surprising because the two models differ markedly in their decay terms. When SSC-generated elements were used, a fairly close conjunction with the 3rd stage could be calculated, which showed the stage somewhat below and behind the known debris pieces rather than among them. Either COMBO result could be used to argue for taking the collision risk seriously, but, of course, the actual verdict on collision is at most a weak "not proven". At NAVSPASUR the collision hypothesis is considered very unlikely in view of the fact that the payload was later reported to be functioning normally, while the Ariane itself has not had a trouble-free history.

It is easy to see that early prediction of accurate conjunctions between debris and other satellites will become essential in future space operations. In this connection, the prediction incompatibility between NAVSPASUR and the SSC evidenced in the TVSAT-1 example is certainly of operational concern; however, it is a well known problem [7]. Various work-around procedures have been used for more than a decade, though not always with complete success. The apparently obvious remedy of adopting a common orbit model turns out to create other operational difficulties which are beyond the scope of this discussion, and in any case a common model is only part of the answer. Currently, Air Force Space Command (Directorate of Operations) is taking the lead in developing comprehensive operational standards for astrodynamics, and NAVSPASUR has developed an element conversion procedure that partly compensates for the orbit model incompatibilities.

SUMMARY AND CONCLUSION

Using a variety of special software tools and drawing on a wealth of in-house expertise, NAVSPASUR analysts have been quite successful in deriving orbital elements for trackable debris fragments from break-ups. In the present system, reliable figures can almost always be given for the time and location of a break-up within one day of the event and sometimes sooner. Within a week, most of the observations due to a high-altitude break-up can be associated with element sets. For low-altitude events, the association may take longer because of the complications introduced by high decay.

In the present surveillance network, of which NAVSPASUR is a part, it is difficult to calculate event time and location within, say, 1 or 2 time periods of revolution of the debris cloud by the orbital mechanics techniques outlined here. The cloud must have dispersed sufficiently for correct associations of observations to be possible, and sufficient numbers of observations on each piece must be available to estimate the orbits. Moreover, since initial debris orbits are known with relatively poor accuracy, conjunctions with other satellites of interest cannot always be accurately predicted. As a result, the collision risk from even the trackable debris can be only poorly known in the current system until well after the break-up occurs.

ACKNOWLEDGMENTS

The author is especially indebted to the NAVSPASUR staff members who produced Reference 1. Several of the program descriptions, as well as the first two break-up examples, follow that report.

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