Orbital Elements Determination for Breakup and Debris

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This paper describes the general procedures and resources required for a determination of specific orbits of space debris resulting from satellite breakups and other causes. The initial coincidence of all pieces combined with the limited discrimination ability of tracking radars causes confusion in this process. The Naval Space Surveillance Center uses a technique called blast-point analysis to analyze the orbits of specific debris pieces as rapidly as possible. The details of this procedure are described, together with practical factors involved in actual breakup events. Evidence of fragment behavior is presented from the breakups of COSMOS 1823, TIROS N, and two other COSMOS satellites. Typical numbers of trackable pieces are 100–300. Typical fragment relative velocities range from 5 to 125 m/s, with an average value near 50 m/s. Evidence is presented to confirm the generally accepted model of near-term debris behavior that shows a secular dispersion in the along-track direction, with more strictly cyclical behavior in the cross-track component.

Introduction

IN recent years there has been a great deal of emphasis on the statistical description of the orbital debris environment. Although this is sufficient for some purposes, for collision avoidance and the full characterization of the space environment, a discrete cataloging is necessary that would require the orbit of every piece to be known. This latter task is obviously a much more difficult one. It is undertaken by a limited community that consists, in the United States, entirely of the military components of the U.S. Space Command. (Although NASA distributes orbital data to civilian users from its Projects Operations Branch at Goddard Space Flight Center, it does not maintain its own tracking facilities for noncooperative satellites.) It requires continuous operation of a radar tracking network, and near-real-time updating of all orbits at a computational/operations center. The Naval Space Surveillance Center (NAVSPASUR) is tasked, together with the Air Force Space Command, with fulfilling this responsibility for keeping track of everything in orbit. Because of this responsibility, NAVSPASUR has consistently maintained, since the first recorded breakup of 1961 Omicron, an interest in determining the orbits of all detectable pieces resulting from a breakup. As a result, we have extensive experience in the "how-to" of determining in near real-time the orbits of debris fragments diverging from a breakup. This paper discusses in general terms these procedures, as well as the characteristics of space debris as observed in real breakups with a system such as the U.S. Space Command's radar network. It will describe the procedures in use at the NAVSPASUR Alternate Space Surveillance Center (ASSC) in Dahlgren, Virginia. Although the procedures at the U.S. Space Command/Air Force Space Command Space Surveillance Center (SSC) in Colorado Springs, CO, are generally similar, there are differences in performance due to computer resources and communications constraints. In addition, the general characteristics of space debris as observed with the national Department of Defense network will be described. It should be noted that the U.S. Space Command's primary mission of protection against threats does not lead to a great emphasis on doing a thorough job of characterizing debris.

It is useful at this point to provide a brief overview of certain characteristics of the U.S. Space Command's radar network. The system consists of a global network of sensors; this distribution is necessary in order to obtain a satisfactory representation of an orbit over all longitudes. There is no sensor located exactly on the equator, which has led to requests for a debris-characterization radar that will provide observations of strictly equatorial near-Earth orbits. However, this has little effect on the principal mission of determining the orbits of all space objects, since most are launched into orbits with significant inclinations.

The nominal sensitivity of the surveillance system is shown in Fig. 1.[1] This sensitivity limit is a "soft" one, and objects near the sensitivity limit may or may not have an orbit determined. Radar sensors are used as the primary low-altitude tracking method, supplemented by optical sensors for geostationary orbits. The NAVSPASUR maintains a radar fence across the southern United States that is a part of this network and has traditionally played a major part in the determination of orbits for breakups and other unidentified objects because of its capability for unalerted (i.e., "guaranteed") detection of objects passing through the fence. In NAVSPASUR's breakup determinations, we make extensive use of observations from this fence, as well as those from other sensors when appropriate. Particular mention should be given to the phased array sensor at Cavalier, North Dakota, which is the most sensitive in the Space Surveillance Network (SSN), and to that at Eglin AFB, Florida, which has historically played a large part in the orbit determination of unidentified objects.

The term "debris" is used by the space community to refer to all Earth-orbiting objects other than active payloads. There is a significant influx of natural debris (i.e., meteors) into the near-Earth environment. An occasional piece is of very large size, as evidenced by the remnant meteor craters located around the globe. However, the natural population at any time is kept relatively low by the fact that meteoric material always has a relative orbital velocity greater than the Earth orbit escape velocity and, thus, is normally present in the near-Earth environment for only a matter of minutes. Man-made debris, which encompasses the majority of large objects, can be divided into several morphological classes. There are satellites that have outlived their operational lifetime, and, of course, many rocket bodies. In the category of smaller debris, there are various pieces shed during launches, and also genuine physical disintegrations. There are at least two known instances of collisions. Although the exact cause of most breakups is unknown, they are most often due to a low-grade fuel explosion in some guise. The space catalog at the present time consists of about 7000 objects. Of this number, approximately

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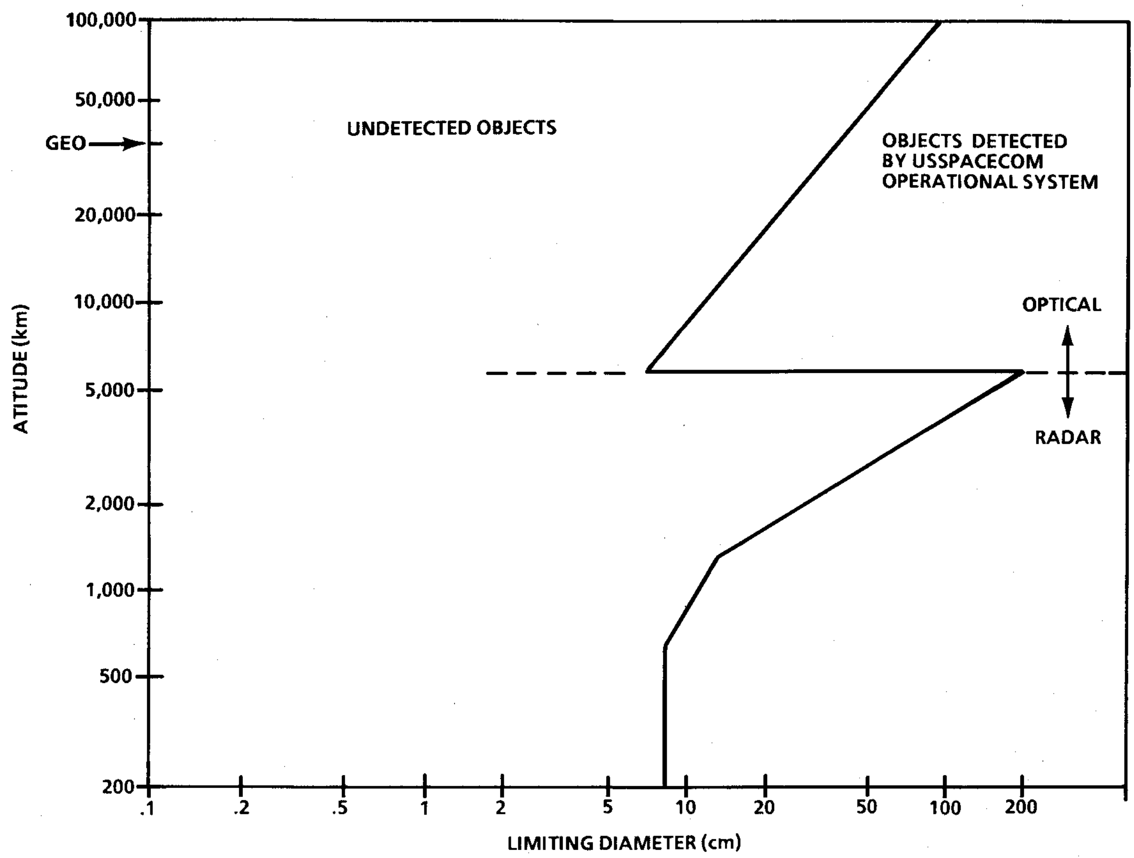

Fig. 1 Space Surveillance Network (SSN) nominal sensitivity as a function of satellite altitude (figure courtesy of Donald Kessler, see Ref. 1).

400 are active payloads, 1300 are inactive payloads, and the remainder are debris of various types.

Breakup Detection and Processing

How are breakups detected? Occasionally there is advance information that a breakup is expected because of anomalies in the satellite's performance. In any event, the first detection of a breakup normally happens when one of the surveillance network's tracking radars detects several pieces in place of the one that is expected. At this point, the orbit determination and cataloging process begins. There are several important factors that bear on this process.

The velocity distribution of a breakup has a major bearing on the orbit determination process. The orbital speed of a near-Earth satellite is about 7500 m/s. This speed, which exceeds that of a speeding bullet, results in a very large amount of kinetic energy. The breakup process will normally not result in adding or subtracting kinetic energy, and thus velocity, that is more than a fairly small fraction of this amount. Within this limitation, studies of actual breakups have shown that the fragments will typically have a fairly wide range of differential velocities. The two recorded cases of collisions have shown a tendency for the pieces to remain in two velocity groups corresponding to the velocities of the original colliders.

The discrimination ability of the various radars used is also a factor in breakup analysis. This discrimination ability has two dimensions, in the position plane and in the velocity plane, and depends on the radar. The multitarget discrimination ability is not fully developed in the typical satellite tracking radar because the normal distribution of satellite targets is rather sparse; many radars can only process one target at a time, even if the radar electronics itself is capable of more. The discrimination problem is obviously worst immediately after breakup, and gradually becomes more manageable as the pieces spread out according to their differential velocity. As an example, the NAVSPASUR radar system has a velocity-discrimination interval of 25 m/s, but can only measure one piece at a time within a separation interval of 15 kms due to data processing limitations. This performance gives relatively high velocity discrimination ability compared to range discrimination ability. Note, however, that, with typical separation velocities, pieces will be separated enough to track individually after a small fraction of an orbit. Although the total number of trackable pieces will depend on a number of factors, the total number trackable with our existing radar network has tended to be about 200–300.

The primary difficulty for most breakup solutions is the determination of orbits for the large number of debris pieces. The determination of orbits for breakups is a semimanual operation at both computation centers, with little software devoted specifically to disentangling breakups based on the identifying morphology. A central problem is that an individual orbit must be computed from the observations for every trackable debris piece. The number of possible reconstructions that can be made follows the general rule of *n* factorial, so that the amount of analyst work and computer loading rapidly multiplies. Additional complications are caused by the fact that the pieces are close together and, thus, easily confused immediately after a collision, and by the fact that, for pieces small enough to be near the limiting sensitivity of the network, tracking will be unreliable, with the piece not detected at all possible passes. The result of all this in practice is that a very significant amount of elapsed time is required to determine unambiguously the orbits of all trackable pieces. Up to one or two months is typical before all piece orbits of a large breakup are completely under control.

Let us follow a typical scenario for a breakup analysis, as performed at NAVSPASUR. First comes a notification of a breakup. This is often prewarned by external information from the news services or other sources, but the first actual warning comes when it is noticed that one of the network of sensors has observed several "satellites" in its coverage where only one was expected. This is typically noticed within a few minutes of the radar pass, although no completely automatic method of detection exists either at NAVSPASUR or at the SSC in Colorado Springs. During the first 12 hours, NAVSPASUR normally does not attempt to seriously determine individual orbits for debris fragments, preferring to wait for the confusion factor to diminish as the pieces spread out. We often track a few outlier or fringe pieces, however, that have been ejected with especially high in-plane velocities and, thus, have spread out more along the orbital plane. These are used primarily to determine the blast point, or point along the orbit (together with time) at which the breakup occurred.

After a few hours have elapsed, debris piece orbit identification begins in earnest. The primary tool used for this at NAVSPASUR is blast-point analysis, using a program called SAD. In the blast-point technique, a sequence of passages of all of the observable pieces through a sensor is recorded a few hours after the breakup. The NAVSPASUR sensor system is well suited for this because all detectable pieces are automatically tracked. For each detected piece, the orbit computed from the two observations consisting of the blast point and the reference time is extended and compared with other observations. When one more observation is obtained within the tolerance limit, an orbit is declared for that piece. Thus, two individual observations plus the blast-point information are used to determine an orbit for a piece.

This operation can be straightforward under perfect conditions; however, at NAVSPASUR, the process is performed under control of an analyst so that ambiguities in the data can be easily resolved. An example of this is pieces that are of marginal size so that they are not detected on all sensor passes. Another problem that can make orbit determination difficult is low-altitude breakups where the pieces have significant drag. The drag adds complications to the analysis in two ways. First, each piece will have a different, and unknown, drag coefficient due to the randomness of the surface area to mass ratio created after the breakup. Second, the dispersion of the pieces into different orbits will of itself result in different drag effects. To the extent that drag is significant over a few hours, basic mathematical theory says that one additional observation will be required in order to determine each piece orbit. The additional work is balanced for debris analysis by the consideration that high-drag pieces will have only a limited orbital lifetime.

The process of differentiating all of the piece orbits is laborious and time consuming, and is typically not completed satisfactorily for two weeks to one month after the breakup. During the initial determination process, also, it should be noted that there is a period during which NAVSPASUR is reasonably sure of orbits but not yet willing to release them due to the high degree of reliability required for a public orbit release. Throughout this process, NAVSPASUR uses a unique set of in-house developed software, described in more detail in Knowles et al.[2] This software has been developed over many years to solve the particular problems associated with "cold-start" orbit determination, and generally involves a quite sophisticated least-squares process with variable tolerances to optimize accuracy of data use.

Between 1985 and 1989, there were 12 major breakups. Of these, 8 were intentional and 4 were assumed to be accidental (Table 1). Two interesting examples of NAVSPASUR analyses are the breakups of COSMOS 1823 (SSC 17535) and TIROS N (SSC 11060). COSMOS 1823, a second-generation geodetic satellite, broke up in orbit on December 17, 1987. The first observations were from the Cavalier radar between 2105Z and 2115Z with a piece count of 22. The debris cloud penetrated NAVSPASUR's fence between 2305Z and 2319Z with a piece count of 36. Because this type of satellite had not been previously known to break up, NAVSPASUR checked for collision possibilities by means of its COMBO program, but found none. On December 18, NAVSPASUR analysts initially generated 10 element sets and a blast position. On request of the SSC, an attempt was made to identify the main debris piece. Programs were run to determine the orbit most similar to the original orbit. Based on these results, a likely candidate was identified and passed to the SSC. The object was then renumbered to the parent number. All of the initial elements on this breakup were produced by NAVSPASUR. By January 7, 1988, 175 element sets had been sent to the SSC and 33 of those had been cataloged.

Table 1 Major breakups, 1985–89

Satellite no.	Name	Event date	Cause	Number of pieces
14064	COSMOS 1461	May 13, 1985	Intentional	220
11278	SOLWIND	Sept. 13, 1985	Intentional	330
13259	COSMOS 1375	Oct. 21, 1985	Accidental	68
15167	COSMOS 1588	Feb. 23, 1986	Intentional	100
16937	USA 19	Sept. 5, 1986	Intentional	350
16615	SPOT-1 (RB)	Nov. 13, 1986	Accidental	468
16054	COSMOS 1682	Dec. 18, 1986	Intentional	150
17297	COSMOS 1813	Jan. 29, 1987	Intentional	400
15653	COSMOS 1646	Nov. 20, 1987	Intentional	49
17535	COSMOS 1823	Dec. 17, 1987	Accidental	175
11087	COSMOS 1045 (RB)	May 9, 1988	Accidental	33
20136	COSMOS 2031	Aug. 31, 1989	Intentional	42

A second example is the piece ejection of TIROS N. TIROS N was launched on October 13, 1978. It had sensors on board to measure temperature and humidity in the Earth's atmosphere, surface temperatures of land and sea areas, cloud cover, and near-Earth proton and electron flux. It had a near-polar sun-synchronous orbit, enabling it to observe nearly the entire Earth's surface twice a day. It remained operational until November 1, 1980. Because of the extremely long on-orbit life (350 years) of this type of satellite, any major breakup of a TIROS could only increase the problem of long-life space debris. During September and again in October of 1987, small fragments that originated from TIROS N were discovered and cataloged by NAVSPASUR. The first debris piece separated on September 28, 1987, at 1658Z. The second debris piece separated on October 4, 1987, at 2107Z. This type of piece separation is actually fairly common in the space environment. Another example of this type of incident was a piece of debris from TRANSIT SB-1, discovered in October of 1989. Analysis revealed that the object most likely separated on September 11, 1989, but further information was unobtainable.

The Gabbard diagram is a representation of the apogee and perigee of a group of orbits vs the period of these orbits. It is in wide use by groups undertaking expostfacto analysis of breakups, since it illustrates well their association and decay behavior over time.[3] The Gabbard technique is not, however, used by NAVSPASUR in breakup work, since the blast-point technique is a much more deterministic way of revealing association for recent events. In the case where pieces were cast off at intervals rather than in a single event, it might provide an important clue.

As part of its discrete analysis of breakups, NAVSPASUR routinely determines the vector components of the differential velocity of each piece at time of breakup. This is often of significant help in analyzing the physical cause underlying the event. As an example, Fig. 2 shows the velocity components for the pieces resulting from the breakup of COSMOS 1405 in December 1983.[4] COSMOS 1405 was a Soviet ocean-surveillance satellite that underwent a breakup typical of its type; most debris fragments re-entered before being officially cataloged. The velocity diagram shows a semirandom distribution of differential velocities with magnitude ranging from 6.9 to 124.8 m/s. The direction of the velocity vectors is spread over the full unit sphere, but there is clearly some order to the distribution that has to do with the mechanism of disintegration. The average differential velocity was 66 m/s for the COSMOS 1405 breakup and 30 m/s for another example—the breakup of COSMOS 1691. It should be noted that in the known instances of collisions, the debris velocities have tended to cluster around the orbital velocities of the two colliding satellites, rather than assuming some mean value in between.

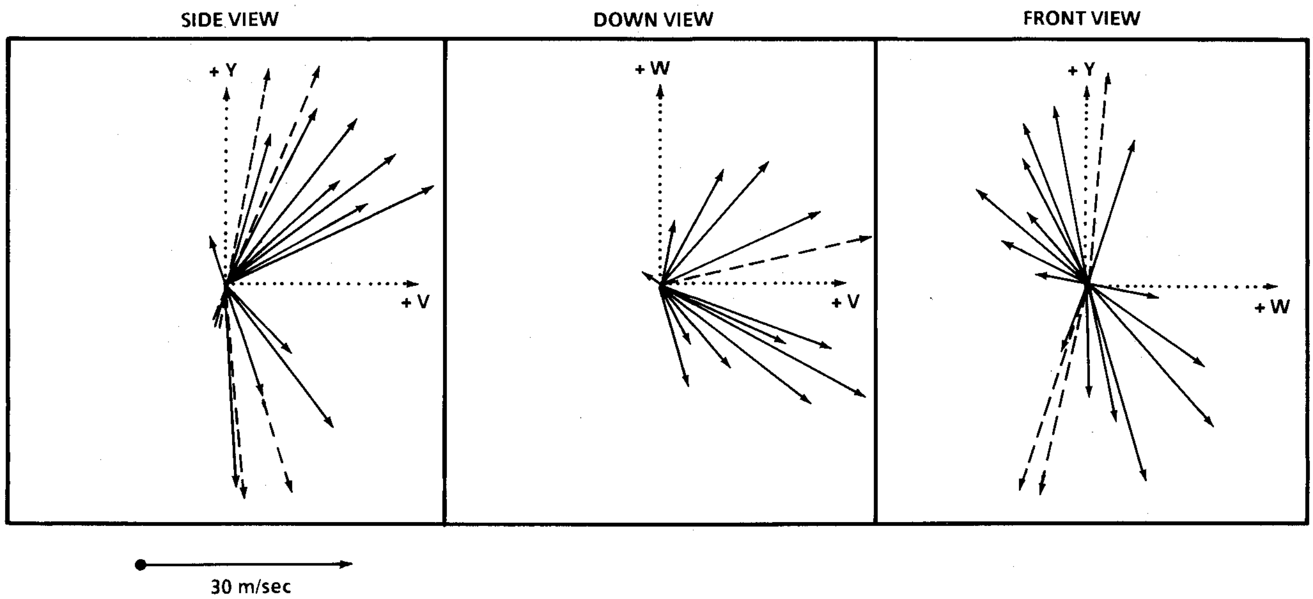

Fig. 2 Rectangular components of relative velocities of fragments from COSMOS 1405 breakup.

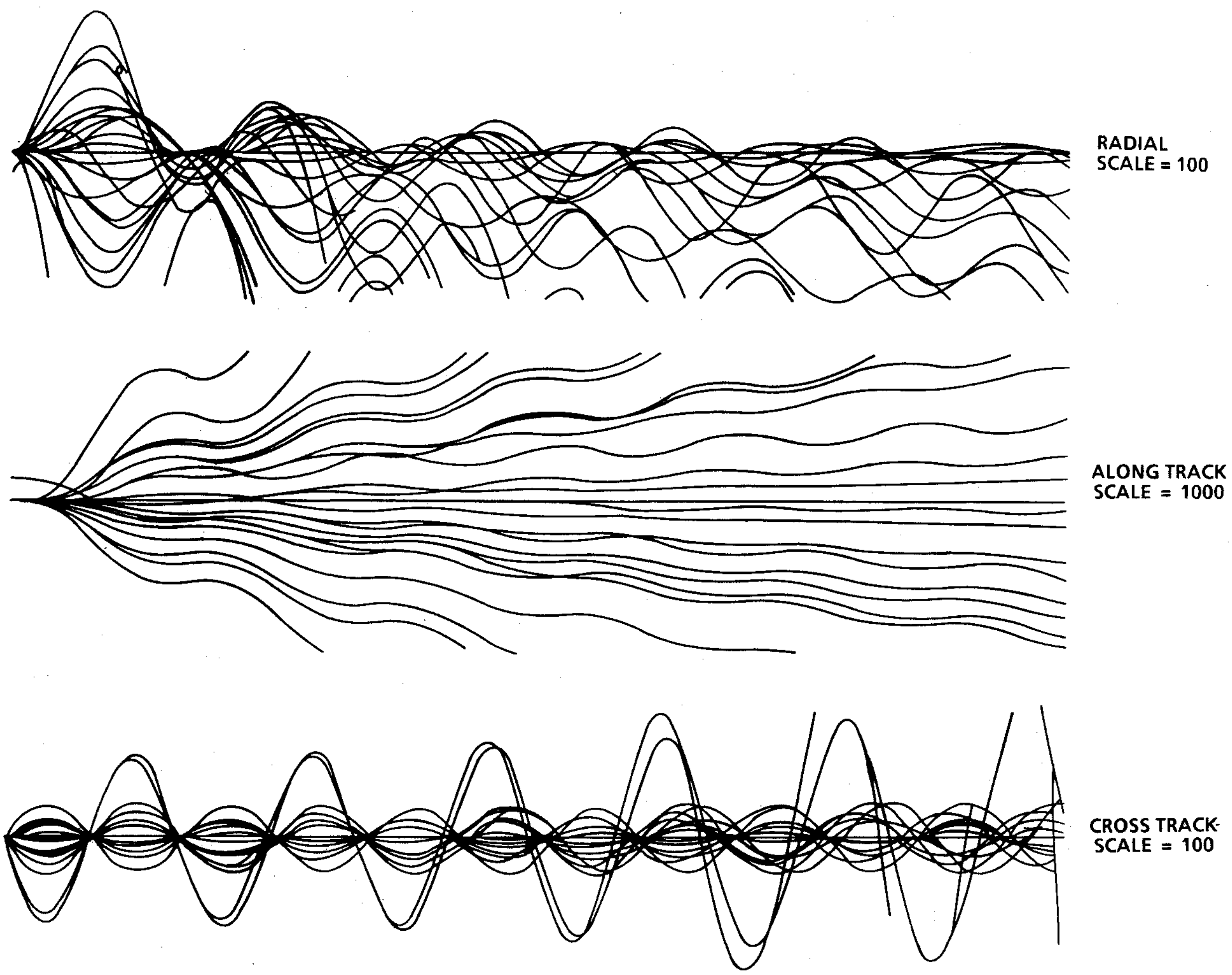

Fig. 3 Graph of orbital velocity components vs time in radial, along-track, and cross-track directions.

This corresponds to a model of "hard," or semielastic, collision, where the two bodies interact only enough to disrupt each other's structure and then continue their path, rather than a "soft," or sticky, collision, where the two bodies turn into one for kinetic energy purposes.

Although the initial differential velocities may be close to random, orbital dynamics dictates that the behavior of the piece orbits will be significantly different over the few days after blast in the along-track, radial, and cross-track directions. This is illustrated well by Fig. 3, which shows the change from nominal position in the few orbits after blast for a typical breakup. The distribution in the cross-track direction is fairly strictly periodic, with the plane change of the pieces resulting in all pieces returning to the same point in the cross-plane coordinate at each half-revolution. This fact could be used as an additional clue in identifying debris pieces, although NAVSPASUR has not done so. In the along-track direction, the trend is clearly secular, or constantly diverging. This is caused by two effects. Any velocity change in the along-track direction causes a direct change in the orbital energy and, thus, its period. Also, any variation in the area-to-mass ratio, or coefficient of drag, in the resultant debris will also cause a secular change in along-track position. The radial picture is somewhat mixed, with an initial recycling but then divergence. At least in this case, the majority of pieces exhibited higher drag than the parent. This would be expected, since surface-to-mass ratio increases with decreasing size. Clearly, the initial spreading out of debris is primarily in an along-track direction. There exist models[5] that represent the behavior of debris after a collision. However, information can clearly be gained from the analysis of specific events, as just described.

After a few days, other orbital effects not illustrated in Fig. 3 become important. The primary one is that the difference in orbits causes a difference in the rate of precession of the nodes, and the debris spreads out to form a shell, or torus, with the orbital inclination and approximate semimajor axis of the parent.

General Considerations

In conjunction with the problem of identifying debris, it should be noted that objects must meet certain definite "bureaucratic" criteria for inclusion in the U.S. Space Command official satellite catalog. These criteria include the ability to be seen regularly enough by the surveillance network (SSN) to be tracked well, the probability of remaining on orbit for a fairly extended time, and, for international treaty reasons, the association with a definite launch by an identifiable country. Upon acceptance for cataloging, each object is assigned a five-digit sequential identifying number; these sequence numbers have now reached the low 20,000s. The U.S. Space Command catalog contains approximately 7000 objects; the remainder of the cataloged objects have decayed or become lost. A logical outcome of the cataloging process has been the creation of an "underclass" of satellites not quite worthy of inclusion in the official catalog. These objects are known as analyst satellites, and are given satellite numbers in the 80,000 series. Unlike officially cataloged objects, analyst numbers are recycled when the original object decays, disappears, or is cataloged. This subject is important, because as a debris catalog expands it can be expected to include a number of such objects. One possibility is to start a separate cataloging/numbering system for debris. In recent years, NAVSPASUR has devoted attention, in its role as ASSC, to ensuring that as many analyst satellites as possible are included in the official catalog. Since 1986, NAVSPASUR has transferred a total of 1009 analyst satellites to the U.S. Space Command catalog. There are currently 354 analyst satellites in the NAVSPASUR data base.

The accuracy with which NAVSPASUR tracks a piece of debris is approximately that of the standard U.S. Space Command orbit. Such an orbit has a precision of a few kilometers for predictions within a few days of the observation time. Using predictions of this accuracy to forecast actual collisions with a few square meter satellite will result in gross overalerting, and is, thus, likely to be ignored. If we take as an example a ± 5 km orbital accuracy with a 10 m^2 satellite, the owner will be alerted 2.5 million times for every genuine collision. This is obviously unsatisfactory for operational warning purposes. Can this situation be improved? Certainly under favorable conditions the orbits of selected satellites can be determined with an accuracy of a few meters, rather than a few kilometers. There are several limitations that prevent this accuracy in the space surveillance network orbits. Most SSN active radars are not designed to have the degree of metric accuracy that is available from, for example, coherent cooperative Doppler tracking. However, accuracy of a few meters is available from properly designed tracking radars. The possible predictive accuracy degrades severely for very low orbits because of the unpredictability of atmospheric drag. An important limitation is that the SSC/ASSC use general perturbations, or analytical, orbital theories instead of special perturbations, or numerical integration, theories in order to save on computer resources. These theories, as presently implemented, have an accuracy of about 300 m. To summarize, significant improvement in accuracy of the present space catalog is possible, but a careful study is necessary in order to recommend a cost effective improvement mix.

Another important factor in determining discrete orbits for debris is the total object load. Keeping discrete orbits for all debris pieces can be expected to multiply by several fold the computer resources required, a burden that the system, as presently constituted, cannot support. This is true both for the "static" load of maintaining orbits of cataloged objects and for the "dynamic" task of analyzing breakups. Unlike most astronomical catalogs, a near-Earth space object catalog requires observations several times a day and daily orbit redeterminations. This is because the exoatmospheric drag has a major orbit-perturbing effect on near-Earth orbits, and cannot be predicted accurately a priori at this time. Because of this observation requirement, the observation throughput of the various sensors is also a limitation. It should be noted that even a statistical debris catalog cannot claim to be a time-invariant representation, due to the dual uncertainties of variable man-made debris input rate and variable solar "cleanout" rate.

In summary, the techniques for analyzing breakups and for keeping track of debris exist, but are at this moment implemented in semimanual fashion with limited resources. A comprehensive approach, with significant resource allocation, is needed to assure comprehensive, complete tracking of debris down to a nondamaging size level.

Acknowledgment

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