Orbital Debris Detection: Techniques and Issues

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The primary data sources for analyses of the measured artificial Earth satellite population are the U.S. Space Command's Satellite File and Satellite Catalog. The accuracies, limitations, and utility of these data are not well understood by most users. The actual cataloged satellite population is found to be less than 6500 with more than 200 objects currently lost. To date, published population distribution and spatial-density calculations do not adequately account for data-base deficiencies. Another U.S. Space Command data source is the Radar Cross-section (RCS) Catalog. Radar cross-sectional data are subject to many influences that may result in size estimate errors of an order of magnitude or more. The orbital lifetime of low-Earth-orbit (LEO) satellite debris has often been overestimated as a result of ballistic coefficient assumptions and failure to model atmospheric variations with sufficient detail. Individual sensors of the U.S. Space Surveillance Network can provide substantially more information on satellite numbers and characteristics than the network as a whole.

Introduction

THE only source of comprehensive satellite tracking data in the United States is the Space Surveillance Network (SSN), which supports U.S. Space Command's Space Surveillance Center (SSC) at the Cheyenne Mountain AFB, Colorado, and the Alternate Space Surveillance Center (ASSC) at Headquarters, Naval Space Command, Dahlgren, Virginia. These data are normally distributed to the civilian community via the NASA Goddard Space Flight Center, Greenbelt, Maryland.

Processed SSN data at U.S. Space Command are available in two primary formats: the Satellite File and the Satellite Catalog. The types of data provided by each of these documents are summarized in Table 1. The Satellite File contains the most current orbital element data for each Earth satellite, while the Satellite Catalog is an historical record of all cataloged satellites since 1957 with limited orbital data. Satellite File element sets that exceed established accuracy tolerances are updated and placed in the Field File for distribution to external users.

For in-orbit satellites, the Satellite Catalog derives basic orbital parameters (apogee, perigee, anomalistic period, inclination) from the Satellite File. Satellites (payloads, rocket bodies, etc.) that have escaped Earth orbit for destinations elsewhere in the solar system are referred to as space probes in the Satellite Catalog, and their current status is provided in the form of a descriptive statement, e.g., "Selenocentric Orbit." Objects in Earth orbit that are being tracked but have not yet been identified and therefore are awaiting formal cataloging are maintained in a section of the Satellite File often referred to as the Provisional Catalog, analyst satellites, or the 8X, XXX series. The latter refers to the satellite's assignment of a temporary SSC satellite number between 80,000 and 89,999 until the cataloging process has been completed. Data transmitted to Goddard are based on Satellite File data contained in the Field File. Updates to most element sets occur automatically depending upon the accuracy of the element set when compared to current observational data. It is possible for the Goddard listings based upon the Field File to have older data than that maintained in the operational Satellite File.

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Uncorrelated Target Processing

Each sensor in the SSN maintains a portion of the current Satellite File to facilitate its tasking assignments. When an object is detected and tracked, its orbital elements are compared with the sensor's Satellite File (Fig. 1). If the sensor can correlate the track of observations with an existing satellite, that track is tagged accordingly. In the event no correlation occurs, e.g., for a maneuvered satellite or an object released from another satellite, that observation is transmitted to the SSC as an uncorrelated target (UCT). Some UCTs originate due to poor-quality observational data, outdated element sets in the sensor data base, incomplete sensor Satellite File, or special conditions where software correlation does not occur.

The SSC 427M computer system will re-examine the UCT to verify that the object is not already cataloged. Although this process is often successful, some observations will remain uncorrelated and will be forwarded to UCT observation files. Using manual techniques or special software aids, an analyst must examine the UCT observation files and create a provisional element set based on observations from one or more sensors. The resultant element set is placed in the provisional portion of the Satellite File.

If the original UCT represents an actual satellite of sufficient size, future sensor observations may correlate with the provisional element set, refining the estimated orbital parameters. When a provisional element set continues to collect correlated observations from two or more sensors, an analyst may then attempt to identify the object's launch of origin and, if successful, make a new Satellite Catalog entry.

Not all provisional element sets represent trackable satellites. Some element sets are fictitious and are used for training or other operational purposes. Some objects, due to their altitude or size, cannot be tracked regularly and may repeatedly be "lost" and "found" again. These objects are known as transient satellites. Some element sets never collect observations and may have never represented a real object. Other objects may be well tracked but not cataloged for months or even years because identification with a known space launch is not made. After a low-altitude fragmentation, some debris may decay before the tracking, identification, and cataloging process can be accomplished.

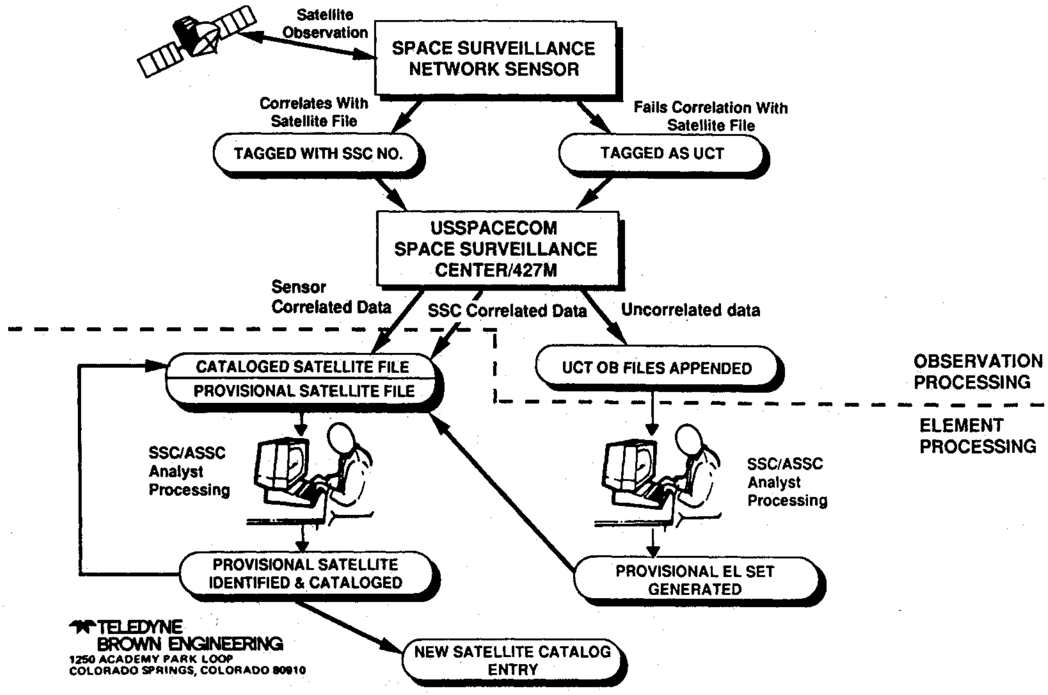

Fig. 1 Uncorrelated target processing.

Table 1 U.S. Space Command satellite data sources

Extent of information available		U.S. Space Command Satellite file	U.S. Space Command Satellite catalog
Satellite type	Earth satellites	X	X
	Space probes		X
Catalog status	Cataloged	X	X
	Provisional (8X,XXX)	X	
Orbital status	In-orbit	X	X
	Decayed		X
Nomenclature	Satellite number	X	X
	International designator	X	X
	Common name		X
Orbital data	Complete element Set	X	
	Apogee, perigee, period, inclination only		X (No epoch information)
Satellite information	Payload, R/B, debris		X
	Country of origin		X
Radar cross-sectional data			X

Discerning the Tracked Satellite Population

Historically, the magnitude of the tracked Earth satellite population has been monitored through a statistical summary of the Satellite Catalog called the Box Score. Box Scores are compiled by U.S. Space Command and NASA Goddard Space Flight Center in a variety of formats. A full Box Score provides a numerical tally of all payloads (Earth satellites and probes) and all "debris" (rocket bodies and debris) by the owning country whether in orbit or decayed.

The "in orbit" values presented in the Box Score are often mistaken for the tracked Earth satellite population. For example, a Box Score derived from the January 1, 1990 Satellite Catalog indicates that of the 20,400 satellites cataloged since 1957, only 6685 remain "in-orbit." However, of this number 134 objects have escaped Earth orbit for deep space missions. Of the remaining 6551 satellites, element sets for 166 in the Satellite File are more than 30 days old with some lost for several years. A closer examination suggests about 50 of these satellites have already decayed. Another 131 satellites are technically "in-orbit" without any element sets in the Satellite File. About 31 of these satellites have probably decayed. Hence, the true cataloged Earth satellite population is approximately 6470, which includes 216 lost satellites.

On the other hand, the provisional portion of the Satellite File contains nearly 500 entries of which approximately 300 are assessed to be potentially real satellites. A comparison of the 216 lost cataloged satellites with these 300 element sets to determine possible matches was beyond the scope of this study. These objects are normally maintainable by the SSN and SSC. Some objects are not in the catalog because they cannot be maintained on a regular basis. These objects are generally small, light objects that are difficult to track with radar or optical sensors and are greatly affected by atmospheric effects.

Determining Population Distributions and Spatial Densities

Analysts performing satellite collision hazard computations and evaluating population-growth trends need not only the number of objects in Earth orbit, but also their respective orbits. Depending upon the type and fidelity of information desired, either the Satellite File or the Satellite Catalog may be employed. However, corrections to both data bases must be made to permit accurate results.

If the Satellite File is used to determine population distributions and spatial densities, adjustments must be made for in-orbit satellites with no element set entries, noncurrent entries, and for entries in the provisional portion of the Satellite File. In the January 1, 1990 Satellite File, 331 satellites purported to be in-orbit (from the Satellite Catalog) have no entries at all. As noted above, 31 of these have probably decayed. The remaining 300 fall into three categories in the Satellite Catalog: 1) "No Current Elements," 2)"Element Code 1," and 3) "No Elements Available." The first category represents acknowledged lost satellites. The last category, which contains 200 satellites, represents in-orbit satellites for which orbital data are not releasable. Some recent cataloging actions have violated this convention.

Although 300 in-orbit satellites without element sets represent a small percentage of the 6470 total cataloged population, the omissions can have significant effects on certain orbital regime calculations. For example, of the approximately 315 payloads known to have been placed in roughly geosynchronous orbits, 40 are lost and elements are not available for an additional 30. This represents more than 20% of the payload population in the geostationary belt. Similar data deficiencies exist for the associated geosynchronous rocket bodies. Some rocket bodies and debris are not cataloged in this regime because they cannot be consistently tracked and maintained by the present SSN.

Users of the Satellite File must also decide how to account for the 166 cataloged satellite element sets that are more than 30 days old. As previously indicated, approximately 50 of these objects have probably decayed. For the other satellites, an estimate of the current orbits must be made. If analyst satellite data are also to be used, each element set must be examined individually. Only about 60% of the analyst satellites in the January 1, 1990 Satellite File probably represent in-orbit satellites.

Finally, the Satellite File gives the analyst the opportunity to evaluate the satellite population at a single epoch by propagating the element sets to the desired time. Such propagations should only be performed with software compatible with the SSC theories and techniques that generated the element sets. Serious propagation errors may otherwise arise. For element sets with epochs more than 30 days old, individual attention is required because mean orbit propagators potentially suffer extreme inaccuracies beyond 30 days.

Lower fidelity estimates of population distributions and spatial densities can be performed using only the Satellite Catalog. However, no current information is available on the 230 satellites with no elements ("No Current Elements" and "No Elements Available") or on the 101 satellites designated with "Element Code 1." In addition, the analyst has no way to determine the number of other satellites with elements older than 30 days (166), to identify unreported decays (81), to account for uncataloged satellites, or to define a common epoch.

Estimating the Size of Satellites

The common method of estimating the size of Earth satellites, particularly fragmentation debris, is by examining the strength of the reflected signal received by SSN radar sites. Unfortunately, these size estimates are strongly affected not only by satellite size but also satellite configuration, satellite stability and orientation, pass geometry with respect to the radar, radar calibration techniques, radar frequency, signal-return averaging techniques, pass-to-pass averaging techniques, conversion of dBsm values to m^2, simplified physical interpretation of m^2 values, discrete errors, and Rayleigh effects for very small objects.

A full description of these effects is beyond the scope of the present paper, but some illustrative examples are offered. Figure 2 depicts the January 1, 1990 SATCAT radar cross-sectional (RCS) values for 30 identical, unstabilized rocket bodies in nearly circular orbits at altitudes of about 1500 km. The values range over a full magnitude. Moreover, the majority of the values exceed the actual maximum physical cross-sectional area, i.e., side view of the rocket body. Published RCS values for a single satellite over a 14-year period are shown in Fig. 3. Again the variation spans more than an order of magnitude with many values exceeding the maximum physical cross-sectional area of the satellite.

Data for Figs. 2 and 3 were provided by the FPS-85 phased-array radar at Eglin AFB, Florida. This is the primary source of RCS information published by U.S. Space Command in the Satellite Catalog and in the RCS Catalog. The RCS Catalog

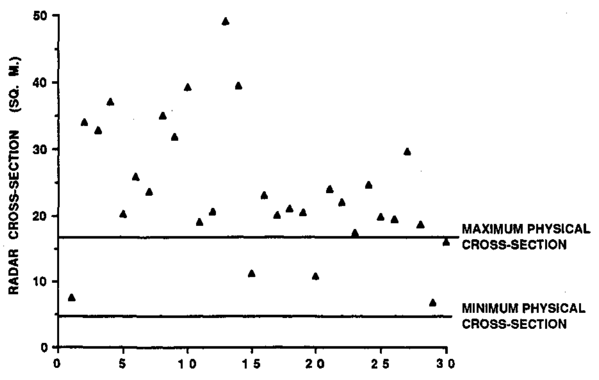

Fig. 2 RCS variations for multiple satellites of the same class.

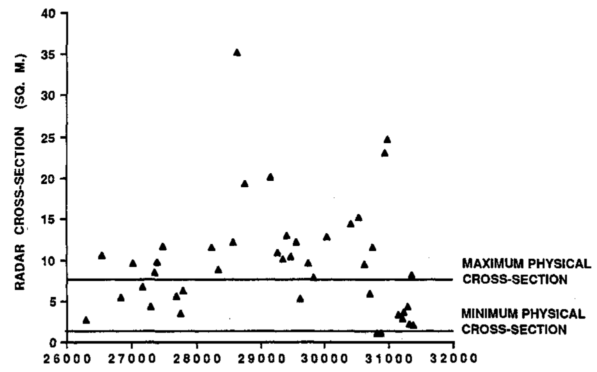

Fig. 3 RCS variations of a single satellite.

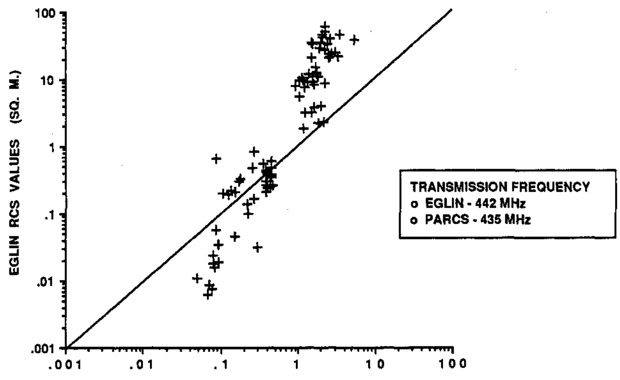

Fig. 4 Eglin and PARCS RCS discrepancy.

contains the complete Eglin RCS data base while the Satellite Catalog contains selected RCS values from a variety of SSN radars. Teledyne Brown Engineering has previously noted in special reports that the Eglin RCS data for cataloged satellites differ noticeably from similar data produced by the PARCS (Perimeter Acquistion Radar Attack Characterization System) radar in North Dakota which operates at nearly the same frequency.[1,2] Since these comparisons were done under nonstandard operational or environmental conditions, a new analysis was conducted using more routine data. Figure 4 depicts an apparent systematic bias between the two radars on identical objects under routine operations. A small radar bias recently noted and acknowledged by Air Force Space Command personnel may correct a portion of this error at the Eglin radar by the end of the year.

Calibration of SSN radars is normally performed in the 0.5-1 m^2 region which shows the best correlation in Fig. 4. What remains unclear is whether either radar provides a reasonably accurate portrayal of actual cross section. The possibility that Eglin exaggerates the size of objects greater than 1 m^2 is supported by the data plotted in Figs. 2 and 3. However, satellites of this size are normally payloads and rocket bodies that often possess appendages, such as antennas or solar panels, which in turn could cause a stronger reflected radar signal. The implied bias in the other direction for smaller objects has never been confirmed or validated. Small-object RCS data must therefore be utilized with extreme care.

Debris Orbital Lifetimes

Analyses of major satellite fragmentations during the past five years indicate that methods for estimating the lifetimes of debris at moderate altitudes, i.e., 400-1000 km, must be reexamined and improved. Lifetime predictions performed by a variety of analysts in the military and civilian sectors have historically been exaggerated due to errors in assigning ballistic coefficients and in underestimating the changes in atmospheric density during periods of high solar activity.

The breakups of two satellites—Satellite 11278 in 1985 at an altitude of 525 km and Satellite 16615 in 1986 at an altitude of 805 km—are two prime examples. Of the 285 pieces of debris cataloged from the 11278 breakup, only 23 remained in orbit a little more than four years later. The higher-altitude 16615 breakup produced 488 cataloged debris with only 134 still in orbit just over three years later. These exhibited decay rates were significantly underestimated by many who were predicting lifetimes for these objects measured in decades or more. Figure 5 depicts the initial orbits of debris that were cataloged within three months of the 16615 breakup event and which decayed prior to January 1, 1990. Many fragments with perigees and apogees above 800 km decayed during this period. These and other data suggest that on the average small fragmentation debris have significantly shorter lifetimes than typical payloads or rocket bodies at the same altitude. Smaller debris, untrackable by the SSM, may have even shorter lifetimes than the larger, trackable debris. This is a very important consideration that should be taken into account in any software that statistically models the untrackable population.

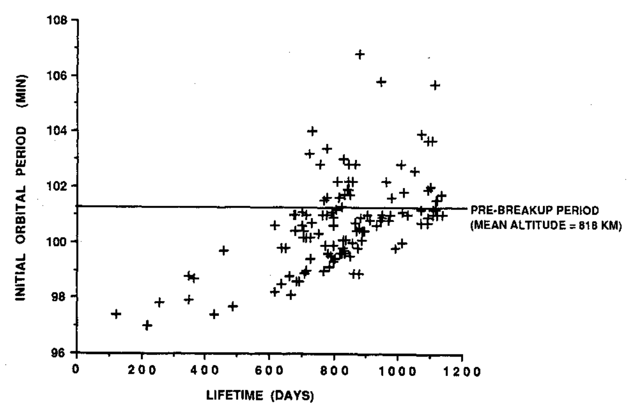

Fig. 5 Decay of debris from the breakup of satellite 16615.

Special Space Surveillance Network Detection Capabilities

Thus far, normal operational capabilities of the SSN as a whole have been addressed. Individual sensors may be employed to provide data of greater sensitivity and volume. In some cases, the results may lead to improvements in SSN operations. In 1984, a series of tests with the PARCS radar, conducted under the auspices of Teledyne Brown Engineering, led to the lowering of its SSC reporting threshold from -16 dBsm to -26 dBsm. Consequently, the SSC began to catalog smaller objects by combining the PARCS observations with those from Eglin and Cobra Dane. This procedural change and improved overall sensitivity in the SSN have sometimes been mistaken for a real change in the satellite population growth rate.

Two projects involving the PARCS radar were specifically aimed at detecting very small satellites with the intention of better defining the near-Earth environment. In 1976, 1978, and 1984 the PARCS Small Satellite Tests were conducted.[3-5] Special software was installed to increase apparent PARCS radar sensitivity below -50 dBsm. Analyses of recording tapes collected at selected intervals over several days revealed UCTs between 4 and 21% of the known population (Cataloged and 8X,XXX). No off-site correlation was attempted. A 1989 study by the Naval Space Surveillance Center suggests that a large percentage of the PARCS UCT tracks may represent known satellites.[6]

During the period 1984-1986, five editions of the *Sample Catalog of Small Objects* were produced using PARCS data with an apparent sensitivity of -30 dBsm. The number of UCT tracks ranged from 6 to 12% in normal environments.

Of particular utility is the reduction of sensor data tapes soon after a satellite breakup. Although element set data is based on short-arc tracks, the quality of the data is sufficient for many analyses, some of which are not possible with routine SSN data. Table 2 reflects the benefits of single sensor data following five recent satellite breakups. The first two breakups occurred at moderate altitudes, resulting in debris lifetimes sufficient for SSN cataloging to account for the major fragments. However, many months were required for the Satellite Catalog to reflect the numbers detected in the single pass. At lower breakup altitudes, debris often decay before cataloging can be accomplished. Hence, the official record of the event—the Satellite Catalog—may significantly underrepresent the known debris cloud.

Several SSN sensors are capable of providing debris characterization information that is often lost at the network level. The PARCS, Eglin, and Cobra Dane systems and the Naval Space Surveillance System (NAVSPASUR) are among the best in this regard. NAVSPASUR personnel have considerable expertise in processing satellite fragmentations, and in NAVSPASUR's role as the ASSC this experience can contribute to more comprehensive data collection.

Multifrequency RCS data are also available. In 1986, the Satellite Catalog was upgraded to include not only the previously available UHF RCS data from Eglin but also UHF, L-Band, and C-Band data from other sensors. In the future, X-

Table 2 Cataloged vs single sensor debris counts

Breakup satellite	Breakup altitude, km	Cataloged debris	Detected debris
11278	525	285	281
16615	805	488	465
16937	220	13	191
16938	220	5	190
17297	390	194	846

Band data may be provided on an expanded basis when the U.S. Space Command-NASA Haystack Auxilliary radar becomes operational. By examining multifrequency RCS data, a better estimate of debris size is possible. Special narrow- and wide-band processed data can even provide satellite-characterization information.

The SSN includes advanced GEODSS (Ground-Based Electro-Optical Deep Space Surveillance) facilities, which are primarily used for high-altitude "deep space" surveillance. Limited surveillance in low Earth orbit is possible in either a staring or a tracking mode. The former technique has been used to make short, statistical surveys of the near-Earth environment. However, such data provide incomplete and imprecise orbital elements. In general, GEODSS data of this type are difficult to calibrate and to compare with radar data. A concerted program of coordinated radar and electro-optical observations has not yet been undertaken.

Conclusions

Satellite tracking data from the U.S. SSN can provide significant insight into the evolution of the Earth's artificial satellite population. However, the two primary sources of official data—the Satellite File and the Satellite Catalog—are incomplete and do not accurately reflect the current status of many objects. The warning at the front of every Satellite Catalog, that "Information furnished in this catalog should not be used for precise analysis," is too often ignored by environmental analysts.

Radar cross-sectional data provided by the SSN is not calibrated across a wide range, leading to systematic biases. Moreover, pass-to-pass variations in calculated RCS at a single sensor can vary over a full magnitude due to geometry and radar characteristics. Consequently, simple relationships used to convert RCS measurements to estimated mass can be applied in only limited, statistical cases. The SSN is capable of providing data on the very small satellite population which are not reflected in the periodic SSN catalogs.

Ballistic coefficients of trackable debris created in a satellite fragmentation normally appear to be markedly different than ballistic coefficients for routine payloads and rocket bodies, often resulting in significantly shorter orbital lifetimes. Debris clouds simulated by satellite breakup models should be validated against actual, well-defined satellite fragmentation events not only in the debris number and ejection vectors, but also in the debris cloud dispersal and longevity.

References

[1]Kling, R., "Postmortem of a Hypervelocity Impact," Teledyne Brown Engineering, Colorado Springs, CO, CS86-LKD-001, Sept. 1986.

[2]Kling, R. L., and Dowdy, J. S., "The Fragmentation of Kosmos 1813," Teledyne Brown Engineering, Colorado Springs, CO, CS87-LKD-004, May 1978.

[3]Morgan, J. L. T., "SPACETRACK System—PARCS Small Satellite Test—Preliminary Analysis—Case 28758-500," Bell Lab., Oct. 1978.

[4]DeVere, G. T., "PARCS Small Satellite Test," Teledyne Brown Engineering, Colorado Springs, CO, CS85-BMDSC-0004, Oct. 1984.

[5]DeVere, G. T., "Comparison of the 1978 and 1984 PARCS Small Satellite Tests," Teledyne Brown Engineering, Colorado Springs, CO, CS85-SPACEMD-103, Sept. 1985.

[6]Jenkins, E., Reynolds, H., Farmer, R., and Litchfield, D., "An Analysis of Sensor Acquistion of Uncorrelated Targets," Naval Space Surveillance Center, Dahlgren, VA, Sept. 1989.

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