MODELING AND MONITORING THE DECAY OF NASA SATELLITES

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ABSTRACT

In February 2002, NASA Headquarters directed that greater attention be paid to the reentry of old NASA space hardware. A process, which begins before launch and which includes cooperation with the U.S. Space Surveillance Network (SSN), has been developed to model and to monitor the orbital decay of NASA space objects. NASA's *Prop3D* orbit propagator is the principal tool used to predict orbital lifetimes in the period prior to 60 days before reentry. In the final two months before reentry, emphasis is placed on the more accurate numerical tools of the SSN. During a satellite's final four days in space, specific reentry time and location predictions are made by the SSN and distributed by the NASA Orbital Debris Program Office to relevant NASA offices. This paper explores the detailed procedure in predicting reentry dates, addresses inherent difficulties in reentry predictions, and suggests areas for improvement for future predictions.

1. NASA RESPONSIBILITY OVERVIEW

In January 2003, the NASA Policy Directive (NPD) 8710.3 (*NASA Policy for Limiting Orbital Debris Generation*, 2003) was revised in order to more specifically establish policies and procedures for limiting orbital debris generation. One of the four policies within the directive obliges NASA to "provide timely notification to, and coordination with, other appropriate government entities concerning the proposed reentry of NASA spacecraft or their rocket bodies from Earth orbit". The responsibilities for maintaining this policy are assigned to the Office of Safety and Mission Assurance, the Office of External Relations, the Office of Public Affairs, and the Director of NASA Johnson Space Center, through the Orbital Debris Program Office.

The Office of Safety and Mission Assurance (OSMA) is responsible for coordinating NASA orbital debris reentry information within the Agency.

The Office of External Relations is responsible for developing procedures in consultation with the Enterprise Associate Administrators, Office of Safety and Mission Assurance, and the Office of General Counsel for coordinating information about NASA spacecraft and other significant NASA reentries with other U.S. Government Agencies. This office is also responsible for coordinating all NASA pre-reentry press releases with the National Security Counsel and the White House Office of Science and Technology Policy.

The Office of Public Affairs is responsible for coordinating all NASA pre-reentry press releases with the U.S. Space Command [now U.S. Strategic Command] (via the Department of Defense Public Affairs) and the NASA Office of External Relations, as well as distributing timely and accurate information about NASA spacecraft reentries to the public.

The Director, Johnson Space Center, through the Orbital Debris Program Office, is given the task to maintain a list of predicted reentry dates for NASA spacecraft and their associated orbital stages and notifying the appropriate NASA personnel.

2. MODELING ORBITAL DECAY

2.1 Orbit Propagation

To fulfill the policy requirements for orbital lifetime prediction, the NASA Orbital Debris Program Office uses its own *Prop3D* orbit propagation software. Developed from 2000 to early 2003, *Prop3D* was designed for implementation into the LEO-to-GEO Environment Debris model (LEGEND), a model used to estimate the lifetimes of thousands of objects in an attempt to better understand long-term near-Earth environmental issues. Because of the large quantity of objects and in order to maintain a reasonable computation speed, *Prop3D* only models the most pertinent orbital perturbations, with the requirement that long-term integration accuracy must be maintained. The perturbations *Prop3D* accounts for are atmospheric drag, zonal harmonics (J_2, J_3, and J_4), solar and lunar gravitation, and solar radiation pressure. Other perturbations and influences are omitted, since their influence on larger objects (especially payloads and rocket bodies) is normally negligible.

Derivation of an accurate value for area-to-mass ratio (A/M) is essential to modeling the orbital lifetime of a satellite. A second software tool used for object reentry estimations is *Aomorbit*, which performs a curve-fit of

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the historic values of the semi-major axis of the object in question and estimates the A/M. By solving for A/M, the ballistic coefficient is better estimated, and, consequently, the modeling of an object's degrading orbit due to atmospheric drag is improved. *Aomorbit* models the semi-major axis curves directly, using a least-squares filter.

2.2 NASA Procedure for Lifetime Prediction

Every six months the NASA Orbital Debris Program Office updates a master list of reentry dates for the approximately 200 NASA objects (payloads and orbital stages) which reside in or pass through low Earth orbit (LEO). During the data gathering stage, the NASA solar flux table is updated with the most recent F10.7 historic flux data. The historic F10.7 flux data is acquired from the Space Environment Center webpage, maintained by the National Oceanic and Atmospheric Administration. The historic flux data is combined with near-term flux forecasts and a 131-month cycle repeated for up to 200 years. The 131-month cycle is calculated from the last five solar cycles (approximately 1945 to the present).

The orbital element histories for all NASA objects are extracted from two-line element (TLE) sets provided by the U.S. Space Surveillance Network (SSN), which actively maintains and updates the data from ground-based radar observations. The SSN maintains a TLE history for the entire lifetime of each observed object, with new TLEs normally generated on a daily basis for most objects in LEO. This TLE database is used to curve-fit the semi-major axis for A/M determination (by *Aomorbit*), and propagate for lifetime estimation (by *Prop3D*).

Most of the NASA objects that orbit the Earth are no longer operational satellites and, therefore, are decaying naturally without the ability to actively change their orbits. These objects usually show very little change in predicted reentry epoch over each six-month forecast. However, some objects employ active propulsion systems to maintain orbits. In these cases, reentry is predicted with the assumption that no further orbit maintenance will be performed. That is, if the satellite were to functionally expire today and fail to execute an end-of-mission maneuver, a resulting reentry epoch is calculated.

Once the TLE data are acquired for all NASA objects, *Aomorbit* is used to curve-fit the semi-major axis to estimate A/M for each object. The A/M values derived from the curve-fit are then compared with the A/M values estimated six months earlier. If a significant difference in A/M is estimated, a visual inspection of the curve-fit is performed. This inspection is especially necessary for objects that have been decommissioned and either been transferred to a disposal orbit or have assumed a new A/M value based on an attitude or mass change. Fig. 1 displays a reasonable curve fit of semi-major axis for the Mars Exploration Rover-B (MER-B) Delta 2 Rocket Body (International ID 2003-032C).

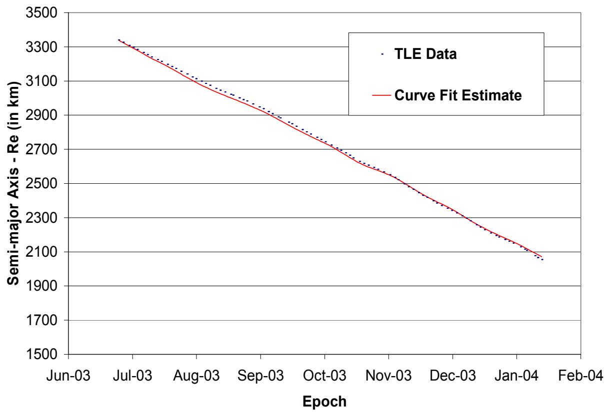

Figure 1. Good least squares curve-fit of semi-major axis for the MER-B, Delta 2 rocket body (2003-32C, estimated A/M = 9.29E-3 m^2/kg).

Some problems in the curve-fit technique cannot be overcome. The most frequent example is station-kept objects. If the altitude of a spacecraft is maintained via discrete or continuous station-keeping methods, the A/M cannot be derived via the orbit data itself. A priori knowledge of the size and weight of the object must be used to create a database A/M.

Some objects like the International Space Station are station-kept but with maneuvers that are generally months apart. In these cases, A/M estimations can be performed on sets of the TLEs between such maneuvers.

When an A/M value is determined (either via orbital decay measurement from TLE data or with a database value), this A/M is combined with a coefficient of drag and a coefficient of reflectivity to predict a reentry epoch. The C_d and C_r values are reasonable approximations that have produced accurate results over time when used in *Prop3D*. The most recent TLE set for each object is propagated forward in one day increments using *Prop3D* until perigee is shown to pass below 90 km. Fig. 2 shows an accurate propagation and subsequent reentry prediction for the MER-B Rocket Body.

The predicted reentry date for each object is then compared with the previous reentry prediction. Unexpected changes in the predicted reentry date are scrutinized for potential explanations. For example, the semi-major axis of an object may have been lowered via an orbit maneuver. In this case, a change in the prediction of a reentry epoch and A/M should be expected. Fig. 3 shows how, in accordance with NASA guidelines for limiting post-mission orbital lifetimes, apogee and perigee were lowered for the Earth Radiation Budget Satellite (ERBS, International ID 1984-108B).

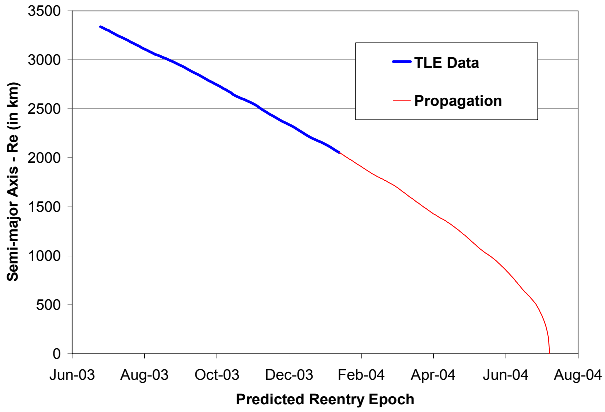

Figure 2. Propagation of semi-major axis for MER-B, Delta 2 rocket body (2003-32C). Predicted reentry: July 28, 2004, Actual reentry: July 26, 2004.

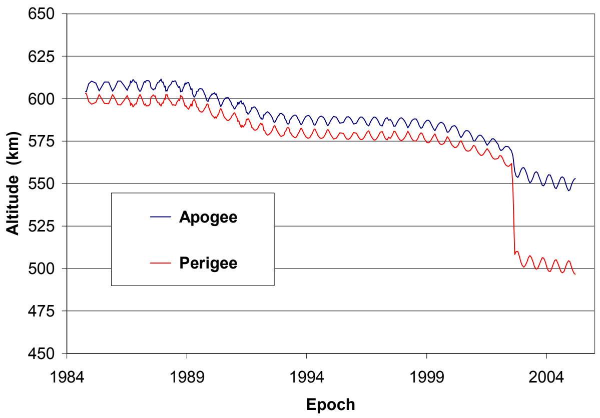

Figure 3. ERBS (1984-108B) orbit history.

The lowering of apogee and perigee changes the predicted reentry date since the object experiences more atmospheric drag on each revolution. Also, the mass of the object may change noticeably, since onboard propellants are expended for such a maneuver. The object's effective cross-sectional area might also change, for instance if the attitude is no longer maintained at end-of-life. The effect of atmospheric drag changes as the object's A/M changes.

Prop3D is also used before launch to estimate likely orbital lifetimes of spacecraft and rocket bodies, in conjunction with NASA Safety Standard 1740.14, which limits post-mission LEO longevity to 25 years (*Guidelines and Assessment Procedures for Limiting Orbital Debris*, 1995). Specifically, this software is used to verify the minimum maneuver requirements for disposal orbits. For high altitude missions which leave stages in eccentric transfer orbits, Prop3D can also assist mission planners in the selection of launch times to take advantage of solar-lunar gravitational perturbations to limit orbital lifetimes.

2.3 Major Error Sources

There are a few error sources that can cause reentry predictions to become inaccurate or inconsistent. The semi-major axis of an object passing through LEO can be a factor for reentry prediction error, particularly for objects in highly elliptical orbits. Objects with apogees above LEO can become sensitive to perturbations other than the atmosphere, and, therefore, estimating an A/M value becomes more difficult. Although A/M becomes a secondary factor in reentry estimation (to perturbations like solar and lunar phase), error in A/M for these higher eccentricity objects can lead to significant orbit element prediction errors when the object is near perigee and experiences denser atmospheric drag conditions.

Solar flux forecasts are another source for reentry prediction error. The prediction of solar flux is especially important for objects in orbit longer than one solar cycle. Inaccuracies in the model of solar activity, like the unpredictable high activity seen in the final months of 2003, can have a significant effect on the orbits of all satellites.

For station-kept objects, the physical assumptions of mass and size of an object, can lead to A/M database values that may not be accurate, especially for objects that have a mass that is varying over time, e.g., in the case of propellant expenditure. Any significant errors in A/M can lead to reentry prediction errors, especially over the long term. A/M inaccuracies may also be realized when a derelict space object undergoes a change in its tumble mode.

2.4 Areas for Improvement

The NASA Orbital Debris Program office is continuously exploring areas in which the reentry prediction procedure can be improved. A difficult, yet most promising improvement could be to curve-fit eccentricity along with semi-major axis when determining A/M with *Aomorbit*. This could be effective for objects with eccentricity greater than 0.1. Since eccentricity degrades like semi-major axis, a better A/M determination could be derived by curve-fitting eccentricity as well. Also, varying coefficient of drag as a function of altitude and solar activity, i.e., atmospheric density and composition, can improve reentry prediction accuracy.

3. MONITORING THE DECAY OF NASA OBJECTS

After the semiannual NASA object report is updated, objects predicted to reenter in less than a year will require auxiliary reentry estimations in the following months. These estimations are typically performed every few weeks in order to ensure that the reentry prediction has not changed unexpectedly. Also, because many rocket bodies reenter less than a year after launch (some in less than two months), reentry calculations for newly launched objects must be performed as soon as TLE data becomes available.

Once an object nears two months from predicted reentry, coordination and communication with the SSN is increased. Sixty days prior to reentry, the NASA Orbital Debris Program Office notifies NASA Headquarters and other relevant organizations of the predicted reentry, with information about potential debris survival. From this point forward, details with respect to the reentry are updated as needed, as the SSN continues to monitor the orbital decay of the object, using their own models and software tools, to best estimate reentry epoch and location. However, *Prop3D* is still used as a check to other reentry estimation techniques.

At 96 hours prior to expected reentry, the SSN issues an official reentry prediction report called a TIP (Tracking and Impact Prediction), also known as an RA (Reentry Assessment). This report is then forwarded to NASA Headquarters and other interested parties within NASA and the community. The TIP/RA report includes the latest prediction for reentry epoch and location given the most recent observational data from the SSN. Subsequent TIP/RA reports are issued at 72, 48, 24, 12, 6, and 2 hours before reentry, each with updated tracking information. After the object has reentered, the SSN forwards its best assessment of the actual reentry epoch and location to all interested parties.

Reentry time and location predictions are combined with estimates of the risk of human casualties from debris which survives to reach the surface of the Earth. Using a detailed technical characterization of the reentering vehicle, NASA's Object Reentry Survival Assessment Tool (ORSAT) determines which components are likely to survive along with the associated impacting kinetic energy. Objects with impacting kinetic energy less than 15 Joules may be excluded from human casualty risk assessments.

During 2004, five Delta 2 second stages used for NASA space missions (AURA, Gravity Probe B, Mars Exploration Rovers A and B, and SWIFT) fell back to Earth following natural orbital decays. The reentry prediction and notification process described above was employed for each reentry with success.

4. SUMMARY

The Orbital Debris Program Office at the NASA Johnson Space Center can predict most object reentry epochs with an accuracy better than 20%. The NASA technique for reentry prediction has proven to be an effective way to monitor object reentry until the final two months, when tools of the SSN prove more accurate. The NASA Orbital Debris Program Office continues to explore ways to improve this overall process. Since the revision of NPD 8710.3 in 2003, there has been improved communication between NASA and other government agencies in order to provide the most accurate reentry information to all interested government organizations and the public.

5. REFERENCES

Guidelines and Assessment Procedures for Limiting Orbital Debris, NASA Safety Standard 1740.14, Aug 1995.

NASA Policy for Limiting Orbital Debris Generation, NASA Program Directive 8710.3A, 27 Jan 2003; revalidated as NPS 8710.3B on 28 Apr 2004.