Reentry Predictions of Potentially Dangerous Uncontrolled Satellites: Challenges and Civil Protection Applications

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Summary

Currently, nearly 70% of the reentries of intact orbital objects are uncontrolled, corresponding to about 50% of the returning mass, i.e. approximately 100 metric tons per year. In 2015, 79% of the mass was concentrated in 40 upper stages and the remaining 21% mostly in about ten large spacecraft. The average mass of the sizable objects was around 2 metric tons. Predicting the reentry time and location of an uncontrolled object remains a very tricky task, being affected by various sources of inevitable uncertainty. In spite of decades of efforts, mean relative errors of 20-30% often occur. This means that even predictions issued 3 hours before reentry may be affected by an along-track uncertainty of 40,000 km (corresponding to one full orbital path), possibly halved during the last hour if further tracking data are available. This kind of information is not much useful and manageable for civil protection applications, often resulting in confusion and misunderstandings regarding its precise meaning and relevance. Therefore, specific approaches and procedures have been developed to provide understandable and unambiguous information useful for civil protection planning and applications, as shown in practice for recent reentry prediction campaigns of significant satellites (UARS, ROSAT, Phobos-Grunt, GOCE, Progress-M 27M).

***Keywords**: uncontrolled reentry, reentry predictions, uncertainty windows, risk objects, sub-satellite ground track, civil protection applications.*

1 Introduction

Currently, approximately 70% of the reentries of intact orbital objects are uncontrolled, corresponding to about 50% of the returning mass, i.e. ~100 metric tons per year. On average, there is one spacecraft or rocket body uncontrolled reentry every week, with an average mass around 2000 kg.[1]

Detailed computer simulations and the analysis of retrieved spacecraft and rocket body components led to the conclusion that, also in the case of objects not specifically designed to survive the reentry mechanical and thermal loads, a mass fraction between 5% and 40% of sufficiently massive bodies is able to reach the Earth surface.[2,3] In terms of mass, number and component survivability, the uncontrolled reentries of spent upper stages generally present a higher risk on the ground compared to spacecraft and, apart from uncommon accidental cases, as the tragic loss of the Columbia Space Shuttle orbiter (2003), or the demise of Skylab (1979), the bulk of the reentry fragments recovered so far on the ground comes from rocket bodies.

However, although approximately 1650-2200 metric tons of manmade orbital debris are suspected to have survived reentry and hit the ground without control so far,[1] no case of personal injury caused by reentering debris has been confirmed. Nonetheless, due to an expanding use of space and to a consequent rise in the amount of space hardware, the number of uncontrolled reentries will remain significant in the foreseeable future. Also taking into account the concurrent increase of the population, the ground casualty risk, even if still small compared to other commonly accepted risks linked to the lifestyle or the workplace and household safety, will presumably show a tendency to grow in the coming years.

For this reason, specific guidelines to minimize the risk to human life and property on the ground have been defined. Reentries compliant with the NASA standard 8719.14 must have a casualty expectancy (i.e. the change that anybody anywhere in the world will be injured by a piece of falling debris) lower than 1:10,000. Such alert threshold is now adopted by several organizations and countries around the world, even though only for a relatively small number of spacecraft and upper stages detailed breakup studies have been carried out, or disclosed to the public, in order to estimate their casualty expectancy.[2,4] Therefore, every week or two, on the average, an uncontrolled reentry violating the alert casualty expectancy threshold of 1:10,000 probably occurs, unknown to most of the governments and safety authorities around the world.

2 Reentry statistics

Since 1957, on average, reentered in the atmosphere 54 payloads, 64 upper stages and 289 debris per year, i.e. 2-3 intact objects per week (Figure 1). During the last decade, reentered on average 42 payloads, 40 rocket bodies and 361 debris per year, i.e. 1-2 intact objects per week.[5] Considering the uncontrolled reentries of intact objects occurred in 2015, 62% (64) were payloads and 38% (40) were upper stages, but 79% of the mass (i.e. 82 metric tons) was concentrated in the latter and the remaining 21% (i.e. 22 metric tons) in the former ones, consisting of small satellites with a mass lower than 50 kg in 83% of the cases.[5]

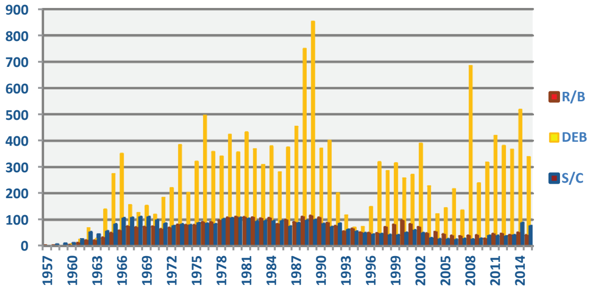

Figure 1. *Space objects reentered since 1957.*

3 Prediction uncertainties

After nearly six decades of space activity, predicting the reentry time and location of an uncontrolled satellite remains a very tricky task. There is considerable uncertainty in the estimation of the reentry epoch due to sometimes sparse and inaccurate tracking data, complicate shape and unknown attitude evolution of the reentering object, biases and stochastic inaccuracies affecting the computation of the atmospheric density at the altitudes of interest, magnitude, variability and prediction errors of solar and geomagnetic activity, and mismodeling of gas-surface interactions and drag coefficient.

All these uncertainty sources combine in a complex way, depending on the specific properties of the reentering object considered and on the particular space environment conditions experienced during the final phase of the orbital decay. Therefore, even applying the same (best) models, methods and procedures, the overall relative reentry prediction errors may be quite different for various objects and in diverse epochs.

The experience accumulated worldwide shows that a relative prediction error of ±20% should be adopted to compute the uncertainty windows associated with reentry epoch predictions, in order to reasonably cover all possible error sources. However, in specific cases, more conservative prediction errors, up to ±30%, should be considered, in particular during the last 2-3 days of residual lifetime. As a consequence of this, the very high orbital velocity at low altitudes (~28,000 km/h) translates into large along-track spatial uncertainties even a few hours before decay.

Moreover, also when the flux of orbit determinations is steady and optimal, there is an unavoidable processing and communication delay of at least 2-3 hours between the orbit determination epoch and the release of the corresponding reentry prediction, so the final forecasts issued during the last hour or minutes preceding the actual reentry are based on a state vector with a 2-3 hours old epoch. Therefore, even predictions issued around 3 hours before reentry have a typical along-track uncertainty of approximately one orbit (i.e. ~40,000 km), while those issued immediately before reentry present a typical along-track uncertainty of half an orbit (i.e. ~20,000 km).

4 Reentry predictions

Following the accidental reentry of the nuclear-powered satellite Cosmos 954, in 1978, independent reentry prediction capabilities were established and maintained at the facilities of the Italian National Research Council (CNR) in Pisa (formerly CNUCE-CNR, now ISTI-CNR), to provide support to the Italian civil protection authorities in case of new emergencies. The criterion for the activation of a reentry prediction campaign of national concern is in theory met whether an uncontrolled reentering satellite, apparently exceeding the casualty expectancy alert threshold (1:10,000), overflies the Italian territory. If this is the case, the goals of the appointed ISTI-CNR team are those to monitor the orbital decay, to provide reentry predictions and to predict possible passes over Italy, together with the related sub-satellite tracks during the last phases of the flight.

The purpose of a reentry prediction process is to determine the time interval (or reentry window) in which the natural reentry of a satellite can be foreseen, taking into account all the uncertainties affecting the reentry predictions. The definition of appropriate reentry uncertainty windows is obviously a critical aspect of the prediction process and is typically based on past experience. Reentry windows amplitudes in between ±15% and ±25% of the residual lifetime may be adequate in 90% of the cases,[2] depending on satellite characteristics, decay phase, solar activity level and atmospheric model. However, residual lifetime errors well in excess of 30% cannot be completely excluded due to unpredicted geomagnetic storms in the last few days of flight or to ballistic parameter and atmospheric density mismodeling in the hours preceding the reentry.

From the point of view of the risk evaluation, an uncontrolled satellite can reenter anywhere on a large portion of the Earth surface, putting all the locations within the latitude band defined by the orbit inclination into the risk zone. Considering that a reentering satellite in nearly circular orbit completes a full revolution around the Earth in just less than 90 minutes, even a few days before orbital decay a reentry uncertainty window still includes many revolutions, overflying most of the planet. This also means that even predictions issued just 3 hours before re-entry may be affected by an along-track uncertainty of 40,000 km. However, around any sub-satellite location included in the “global” uncertainty reentry window, it is possible to define a quite accurate “regional” risk time window, which can be used to plan risk mitigation measures on the ground and in the overhead space. For a region sufficiently wide to include Italy, risk time windows 30-40 minutes wide were found to be appropriate and could be identified already 3-4 days ahead of the foreseen reentry.

5 Recent significant uncontrolled reentries

During five months, from September 2011 to January 2012, three massive satellites reentered without control in the atmosphere: UARS, ROSAT and Phobos-Grunt.[4]

UARS had a dry mass of 5668 kg, a diameter of 4.6 m, a length of 9.7 m and a quite complex shape, with booms, appendages, protruding structures and a big solar array.

ROSAT had a dry mass of 2426 kg, dimensions of 2.2 m × 4.7 m × 8.9 m, a quite compact shape and solar array configuration and just one boom aligned with the longitudinal axis.

The Phobos-Grunt vehicle, trapped by a failure in orbit around the Earth, was a complex spacecraft whose main mission was a soil sample return from the major moon of Mars, i.e. Phobos. The failed probe had a total mass at launch of 13,525 kg and dimensions of 3.76 m × 3.76 m (7.97 m with the solar arrays deployed) × 6.32 m. Historically, it was the 12th most massive space object reentering the atmosphere uncontrolled, but more than 82% of the total mass, i.e. about 11,150 kg, consisted of very toxic liquid hypergolic propellants. The dry mass was therefore around 2350 kg, a value not uncommon among spacecraft and upper stages usually reentering without control.

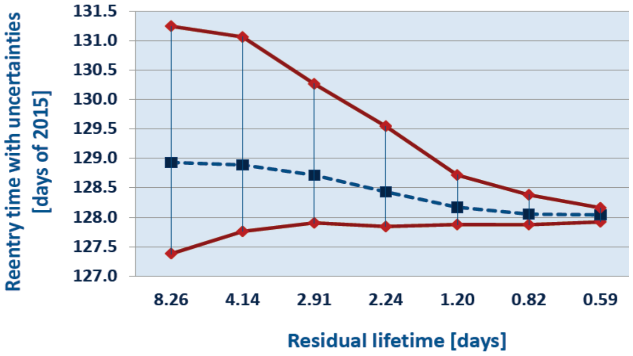

Figure 2. *Progress-M 27M reentry: evolution of the uncertainty window.*

The ESA’s GOCE satellite had a dry mass of 1002 kg and a roughly cylindrical shape of 1 m diameter and 5.3 m length, with wing-shaped fins spanning 2 m. After mapping the geopotential with unrivalled accuracy and detail for four years from an extremely low circular polar orbit, on 21 October 2013 the low thrust ion propulsion motor, used to contrast the atmospheric drag, was automatically shut down and the satellite reentered on 11 November 2013.[6]

Encountering severe problems immediately after launch, the cargo ship Progress-M 27M was declared officially lost on 29 April 2015 and reentered nine days later (Figures 2-3). It had a launch mass of 7289 kg, a dry mass in excess of 5 metric tons and 1373 kg of highly toxic propellants present on board.[5]

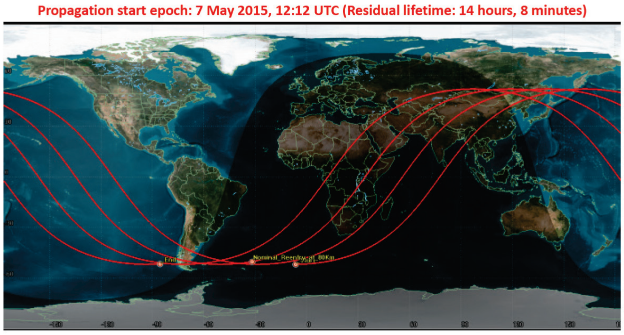

Figure 3. *Progress-M 27M reentry: sub-satellite ground track corresponding to the uncertainty window at approximately 14 hours before reentry.*

As in previous similar occurrences, the Space Flight Dynamics Laboratory of ISTI-CNR was in charge of the reentry predictions for the Italian civil protection authorities and space agency.

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