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

Carmen Pardini[1], **Luciano Anselmo**[1]

[1]Space Flight Dynamics Laboratory
ISTI-CNR, Via G. Moruzzi 1
56124 Pisa, Italy
{carmen.pardini@isti.cnr.it, luciano.anselmo@isti.cnr.it}

Abstract. 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 is 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 were 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, and Progress-M 27M).

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

1 Introduction

As of mid-January 2017, and since the decay of the Sputnik 1 launch vehicle core stage on 1 December 1957, more than 24,000 cataloged orbiting objects have reentered into the Earth's atmosphere, with a total mass of about 30,000 metric tons. Of these, approximately 71% were orbital debris, while the remaining 29% was represented by intact objects, where most of the mass (> 99%) was concentrated. 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 have suggested that, also in the case of objects not specifically designed to survive the severe mechanical and thermal loads, 5% to 40% of the mass of sufficiently massive bodies is able to reach the Earth surface [2, 3, 4]. 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.

No case of personal injury caused by reentering orbital debris has yet been confirmed. Nonetheless, uncontrolled reentries of sizable space objects are becoming of growing concern due to the increase of space activities around the Earth and population on the ground. 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.

Therefore, specific guidelines to minimize the risk to human life and property on the ground have been defined. For instance, single reentries compliant with the NASA standard 8719.14 must have a world-wide human casualty risk not exceeding 0.0001. In other words, the chance for anybody anywhere in the world of being injured by a piece of falling debris from a single uncontrolled reentering object must be lower than 1:10,000 [5]. 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 are being carried out, or disclosed to the public, in order to estimate their casualty expectancy [2, 6].

Hence, every week or two, on average, an uncontrolled reentry violating the alert human casualty risk threshold of 1:10,000 probably occurs, unknown to most of the governments and safety authorities around the world.

2 Reentry Statistics

Since 1957, reentered on average in the atmosphere 54 payloads, 63 upper stages and 272 debris per year, i.e. 2-3 intact objects per week. During the last decade [2007-2016], reentered on average 45 payloads, 40 rocket bodies and 354 debris per year, i.e. 1-2 intact objects per week (Fig. 1).

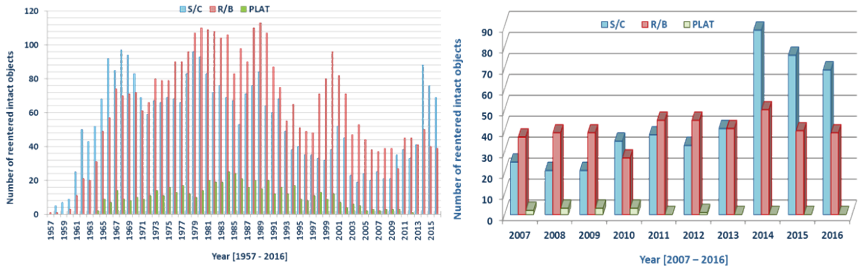

Fig. 1 Intact space objects (S/C: spacecraft; R/B: rocket bodies; PLAT: platforms) reentered since 1957 (left) and from 2007 to 2016 (right)

Considering, for instance, the uncontrolled reentries of intact objects occurred in 2015, 62% (64) were payloads and 38% (40) were upper stages. However, while the latest accounted for nearly 79% of the mass (i.e. 82 metric tons), the payloads, consisting of small satellites with a mass below 50 kg in 83% of the cases, contributed with the remaining 21% (i.e. 22 metric tons) to the uncontrolled reentered mass [7].

The decay rate of intact objects was mainly driven by the launch activity, with a lower, but not trivial, contribution linked to the solar activity cycle and the corresponding change in the magnitude of the drag perturbation. A much more strong correlation with the launch activity was highlighted in [1], by excluding from the tally all spacecraft associated with human spaceflight, i.e. manned spaceships and capsules, space stations, man-tended modules and cargo vehicles. The top decay rates, observed between the mid-1960s and the end of the 1980s, were followed by a declining trend, at the beginning of the 1990s, in consequence of the breakup of the Soviet Union. The last decade was instead characterized by an increase in the number of commercial launches, also from emerging countries, typically consisting of lightweight payloads.

A systematic decreasing trend in the decay rate of intact objects was observed during the last four decades. Fig. 2, based on the reentry statistics carried out in [1], between December 1957 and April 2013, shows the yearly (in the top) and the weekly (in the bottom) decay rate of intact objects over the last 5, 10, 20, 30, 40, 50 and 55 years with respect to the end of 2012, by excluding all spacecraft associated with human spaceflight (typically performing controlled reentries) from the tally. The decay rate passed from a maximum of about 130 reentries per year, corresponding to nearly 2-3 reentries per week, over 50 years [1963-2012], to a minimum of approximately 57 reentries per year, i.e. just a reentry per week, during the 2008-2012 five years period.

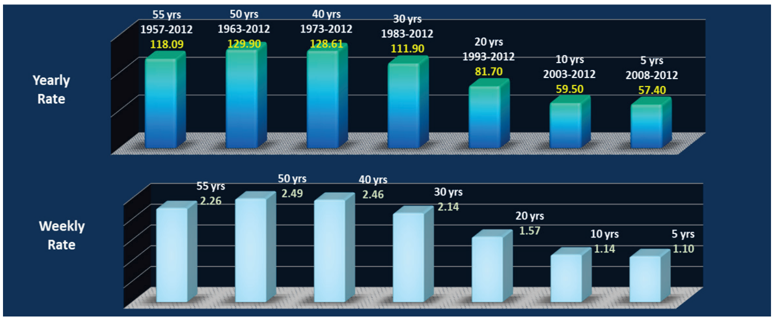

Fig. 2 Average decay rate (yearly in the top, weekly in the bottom) of intact objects, excluding the spacecraft associated with human spaceflight programs (statistics based on reentries in between 1957 and 2013 [1])

Such a progressive decline of the average decay rate of intact objects might most likely reflect changes in the number of launches, as well as in the mission profiles, for which a considerable number of payloads and upper stages would have been placed in high Earth orbits. Moreover, a notably long and deep minimum characterizing the solar activity cycle 24 (the smallest sunspot cycle in over a century) undoubtedly could have played a significant role.

While the decay rate of all cataloged intact objects can be directly inferred from the information included in the US Strategic Command (USSTRATCOM) catalog, made available to registered users through the Space-Track Organization (www.space-track.org), the actual number (and mass) of spacecraft and upper stages reentered so far into the Earth's atmosphere without control cannot be easily attained. As a matter of fact, in addition to vehicles associated with manned space programs and controlled reentries carried out for safety reasons, there have been several classified military reconnaissance satellites, which have systematically performed a controlled reentry to recover and/or to prevent the retrieval of secret spacecraft components. Moreover, also for a small number of upper stages, a controlled reentry has been accomplished during the last few years.

Notwithstanding, thanks to a detailed and massive research based on the information available in the open literature, it was possible to identify, with an adequate level of confidence, all spacecraft performing controlled reentries [1]. It was found that during the Space Age, on average, one out of five reentries of intact objects was controlled in some way. The total mass associated with the uncontrolled reentered objects was assessed to be around 11,000 metric tons, mainly concentrated (> 98%) in almost 5700 intact objects, as of April 2013. Currently, more than 11,300 metric tons of man-made materials are expected to have reentered into the Earth's atmosphere without control. On average, there is one sizable spacecraft or rocket body uncontrolled reentry every week, with an average mass around 2000 kg.

An uncontrolled satellite can reenter anywhere on a large portion of the Earth surface, putting all locations within the latitude band defined by the orbit inclination into the area potentially affected by the surviving debris fall. The knowledge of the approximate reentry points for a representative sample of decayed objects might be of value to investigate the potential impact of some factors related to the launch pattern, the mission profile and the lifetime in orbit on the distribution of reentries over the Earth.

A distribution of the reentry locations was obtained [7] by analyzing the uncontrolled reentries of intact objects occurred from 2004 to 2015 and for which a USSTRATCOM post-reentry time assessment with a claimed error of ±1 minute was available (for 287 rocket bodies and 59 payloads/platforms). For this sample of objects, and in the interval of time considered, it was found a slight prevalence (53.5% vs. 46.5%) of reentries in the Southern Hemisphere. Moreover, the Southern Hemisphere bias was smaller for upper stages (51.6% vs. 48.4%) and higher for payloads (62.7% vs. 37.3%).

In a previous study carried out by Nicholas Johnson in 1997 [8], by analyzing the uncontrolled reentries of 331 objects occurred from September 1992 to December 1996, it was instead found a prevalence of reentries in the Northern Hemisphere (56.5% vs. 43.5%). Moreover, while objects staying in orbit less than 1 month showed a more marked bias (62% North vs. 38% South), those with a longer orbital lifetime displayed a nearly symmetrical distribution (51% North vs. 49% South).

From the results of both analyses, it can be reasonably concluded that the varying north-south asymmetry observed in the two cases was mainly driven by the different launch pattern, mission profile and residual lifetime of the objects put in orbit in different historical periods.

Considering all the uncontrolled reentries of intact objects (i.e. not only those characterized by a post-event assessment claimed error of ±1 minute) occurred from 2004 to 2015 (a total of 722 uncontrolled reentries, including 447 rocket bodies and 275 payloads/platforms), it was found that the mean flux of decaying intact objects over the Earth was approximately 1.05×10^{-7} km^{-2} per year [7]. This would imply, on average, an uncontrolled reentry over Italy every 28 years and over Europe every 10 months.

3 Reentry Risk Evaluation

If an average surviving fraction of 15-20% is applied to the total amount of mass suspected to have reentered the Earth's atmosphere without control so far (i.e.

about 11,300 kg), around 1695-2260 metric tons of manmade debris would have likely survived reentry and hit the ground, with no case of personal injury confirmed heretofore.

Nonetheless, due to an expanding use of space and to a consequent rise in the amount of space hardware, the number of uncontrolled reentries is doomed to remain significant in the foreseeable future. Moreover, if the concurrent increase of the population is taken into account, the ground casualty risk, even if still relatively small, will probably raise in the coming years.

This is the reason why specific guidelines to minimize the risk to human life and property on the ground have been defined and are now adopted by several organizations and countries around the world. The case of NASA has been already mentioned in the introduction [5], but also for the European Space Agency the human casualty risk should not exceed 1 in 10,000 for any reentry event, either controlled or uncontrolled (ECSS-U-AS-10C/ISO 24113) [9, 10].

The main factors affecting the estimation of the risk of human casualty from uncontrolled reentries include the number of debris expected to reach the surface of the Earth, the kinetic energy of each surviving fragment and the amount of the world population potentially at risk. A kinetic energy threshold of 15 J is typically accepted as the minimum level for potential injury to an unprotected person [5], while a probability of fatality of 50% corresponds to a kinetic energy of 103 J [11].

A crucial metric used by NASA [5] to represent and to evaluate the potential risk from reentering debris is the so-called total debris casualty area (A_C), which for a reentry event is the sum of the debris casualty areas of all debris pieces able to survive reentry. It is computed as follows:

$$A_C = \sum_{i=1}^{n} \left(\sqrt{A_h} + \sqrt{A_i} \right)^2 \tag{1}$$

where $A_h = 0.36\ \mathrm{m}^2$ is the projected cross-sectional area of a standing human and A_i is the cross-section of each individual fragment reaching the ground. A_C is de facto a simple and effective method to combine in a single figure all information on the breakup process of a reentering space object.

The casualty area (Eq. 1) and the impact location of the surviving fragments for a reentry event are usually computed by means of specific reentry analysis tools, which can be grouped in two main families, named the object-oriented tools, e.g. the NASA's Debris Assessment Software (DAS) and the Object Re-entry Survival Analysis Tool ORSAT (orbitaldebris.jsc.nasa.gov/reentry/orsat.html), and the spacecraft-oriented tools, like the ESA's SpaceCraft Atmospheric Re-entry and Aerothermal Break-up software tool SCARAB (www.htg-hst.de/1/htg-gmbh/software/scarab).

The total human casualty expectation, better known as the casualty expectancy (E_C), is obtained as the product of the total debris casualty area and the total average population density (P_D) in the area overflown by the reentering object, i.e.: $E_C = A_C \times P_D$. For instance, for mid-inclination orbits, it can be shown that a world-wide casualty expectancy of 1:10,000 can be currently exceeded in a single uncontrolled reentry event if the total casualty area of the surviving debris is greater than approximately 8 m^2.

The reentry casualty risk can be determined through the probability to cause serious injury or death. For a reentry event with surviving fragments, and inside a given latitude belt, the probability of debris fall is one, but the expected consequences, at least for people in the open, are not particularly adverse with respect to the common risks accepted in the everyday life. As an example, the risk of being hit by falling orbital debris amounts to about one part per trillion per human per lifetime, i.e. it is of the order of 10^{-12} [12]. Instead, the risks in our daily life are comparatively huge: the risk of being killed in a car accident amounts to about 1/100 in industrialized countries, of death by fire is about 1/1000, of being hit by a lightning is approximately 1/1,500,000 [12].

4 Reentry Prediction Uncertainty

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 nominal 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. In support of this, it was found that for the recent USSTRATCOM last reentry predictions before decay, from December 2014 to January 2016, a reentry time uncertainty of ±30% was able to include nearly 90% of the events [7]. Moreover, these predictions were based on orbit data with a mean epoch at nearly five hours before decay (only in 2% of the cases the last available orbit was at less than 1 hour before reentry, in 20% of the cases at less than 2 hours, in 33% of the cases at less than 3 hours).

Therefore, if an uncertainty of ±30% is applied, for instance, to a residual lifetime of 5 hours, the reentry time prediction error is ±1.5 hours, corresponding to a couple of orbit tracks around the Earth for a reentering satellite in near-circular orbit. Anyway, 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).

As a consequence, for uncontrolled reentries driven by thermospheric drag, it is not possible to predict a reentry location, which remains quite undetermined until the end, along the satellite trajectory, but it is only possible to identify the areas of the planet where the reentry may no longer occur, with a given confidence level.

5 Reentry Prediction Process

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 of 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 with uncertainty time windows 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.

Among the main ISTI-CNR activities carried out during the uncontrolled reentry of a potentially dangerous space object there are the following: 1) Acquisition of the orbital elements of the reentering object; 2) Updating of data files including the environmental conditions, i.e. the observed and forecasted solar and geomagnetic activity indices; 3) Determination of the object's ballistic parameter; 4) Propagation of the last available orbital state up to the final plunge down to the altitude of 80 km (nominal reentry epoch); 5) Evaluation of the global uncertainty time window around the nominal reentry epoch; 6) Representation of the sub-satellite ground track corresponding to the current global uncertainty time window, during the last 2-3 days preceding the final decay (Fig. 3).

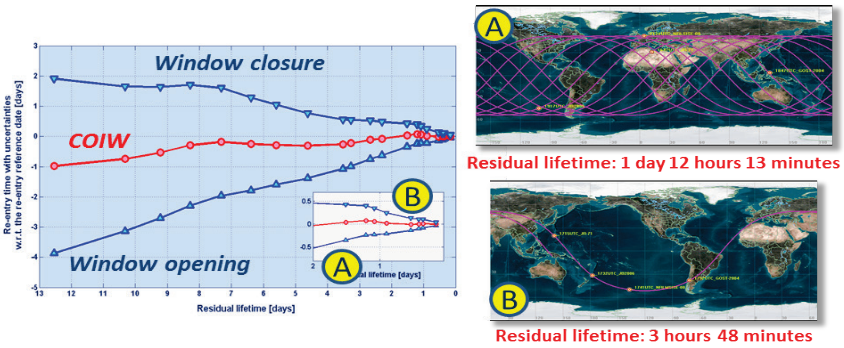

Fig. 3 Example of the representation of the sub-satellite ground track corresponding to two global uncertainty time windows computed 1^d 12^h 13^m (case A) and 3^h 48^m (case B) before reentry (the uncertainty window evolution is shown on the left)

5.1 Civil Protection Applications

However, typical reentry prediction standard products, such as those of points 4 to 6, are of no, or very limited, use for civil protection applications. As a matter of fact, the nominal decay forecast is absolutely useless for civil protection planning, due to its intrinsic large uncertainty. The global uncertainty window provides relevant information, identifying the time interval in which the reentry should be expected somewhere in the world. However, this interval remains too large until reentry, so it is not possible to devise and apply practical precautionary civil protection measures based on it. Finally, the reentry location inside the global uncertainty window remains quite undetermined, along a varying number of orbital sub-satellite tracks, themselves possibly affected by a considerable cross-track error.

Therefore, the locations possibly at risk in a given area, for instance in Italy, cannot be identified reasonably ahead of reentry using the information from points 4 to 6. For these reasons, a new approach was devised and applied in Italy to real reentry prediction campaigns since the orbital decay of the BeppoSAX spacecraft in 2003 [13]. It was firstly based on the attempt to answer the question: «Given a certain global uncertainty time window, where and when a reentering satellite fragment might cross the airspace and hit the ground on a specific area of the world overflown by the falling uncontrolled object?», and then on the following reasoning: «For each location inside the global uncertainty time window, the reentry and debris ground impact is possible but not certain. However, the eventual reentry or impact may occur in each place only during a specific and quite accurate risk time window, which can be used to plan risk mitigation measures on the ground and in the overhead airspace».

Hence, the solution of the problem should consist, in general, in identifying the risk time window for each overflown location of the planet inside the global uncertainty window, and in computing, in particular, the "regional risk time window" corresponding to each pass over an area of interest, e.g. Italy [14]. The procedure adopted at ISTI-CNR to assess the regional risk time windows for a finite area embracing Italy starts 3-4 days before the final decay (this is to focus the attention on a relatively low number of sub-satellite tracks overflying the target area), by simulating a reentry opportunity for each pass over the area of interest (that is obtained by slightly modifying the nominal predicted trajectory through small changes of the reentering object's ballistic parameter, in order to obtain simulated reentries over the target area in the time interval corresponding to the current global uncertainty window).

Then, for each reentry opportunity, a regional risk time window is defined by accounting for: 1) The different flight times of the fragments generated by the satellite breakup (their timing dispersion is typically a few tens of minutes wide and includes the time of flight of the "fictitious" intact parent object, taken as reference to set the absolute scale of time, and also small particles not representing a hazard on the ground, but possibly dangerous for aircraft crossing the airspace during the reentry); 2) The variation of the initial conditions leading to nominal reentries in different parts of the country along the trajectory, as well as the trajectory propagation errors (a few minutes); 3) The finite size of the area of interest around the simulated reentry opportunity (±2 minutes for areas of about 2000×2000 km^2, i.e. ten times those of a country like Italy). Considering the reentries of typical spacecraft or upper stages, the amplitude of the risk time window for such areas should be around 30-40 minutes, including the airspace up to an altitude of 10-20 km.

It is worth mentioning that the ground tracks crossing the area of interest are much more stable and less affected by uncertainties, being computed with the "right" times (in fact, as a direct consequence of the almost exact synchronization between the satellite dynamical evolution and the Earth's rotation, the potential reentry time over specific locations of the planet can be estimated with a reasonable accuracy already a few days before the final decay) and approximately including the reentry dynamics down to ground impact.

Finally, a cross-track safety margin, with respect to each reentry ground track for the area of interest, should be defined to obtain the volume of airspace and the surface on the ground associated with the regional risk time window. Its definition depends on: 1) The expected dispersion of the fragments perpendicularly to the satellite trajectory (this is a function of the breakup nature and of the endo-atmospheric dynamics of the fragments, amounting to as much as several tens of km); 2) The cross-track trajectory uncertainty due to the mismodeled evolution of the orbital decay (it might amount to a few tens of km 3-4 days before decay, progressively decreasing as the reentry is approaching); 3) The effects of the prevailing or predicted winds in the stratosphere and troposphere (the cross-track drift of macroscopic fragments exposed to winds during the final phase of nearly vertical fall is less than a few tens of km).

Limiting the attention to the relevant fragments and depending on the specific nature of the reentering parent object, the cross-track safety margin may be ±90-200 km around 3-4 days before reentry, and ±80-120 km during the last 24-48 hours. In conclusion, the volume of airspace which could be potentially affected by the debris fall is the region of space extended up to the relevant geodetic altitude (e.g. 15 km), centered on the reentry ground track and with a cross-track swath of ±100-200 km, which might progressively drop to ±100 km, or less, as the reentry is approaching.

6 Recent Significant Reentries

During five months, from September 2011 to January 2012, three massive satellites reentered without control in the atmosphere: UARS, ROSAT and Phobos-Grunt [6].

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.

Another engrossing and uncommon reentry was that of the ESA’s GOCE satellite, having 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. Following the automatic shutdown of its depleted propulsion system, on 21 October 2013, the satellite reentered on 11 November 2013 [15].

Finally, after encountering severe problems immediately after launch, the cargo ship Progress-M 27M was declared officially lost on 29 April 2015 and reentered uncontrolled nine days later, on 8 May 2015. It had a launch mass of

7289 kg, a dry mass in excess of 5 metric tons and carried on board 1373 kg of highly toxic propellants [7].

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. The 5 mentioned satellites are shown in Fig. 4.

Fig. 4 Artistic representation of five significant objects recently reentered without control in the Earth's atmosphere

6.1 UARS – Upper Atmosphere Research Satellite

The NASA's satellite UARS was deployed into a 580 km circular orbit by the space shuttle Discovery, on 15 September 1991. After 14 years of mission, the residual propellant was used to lower the satellite orbit with a series of eight maneuvers, for the purpose of reducing its residual lifetime, according to the space debris mitigation guidelines. UARS was decommissioned by NASA in December 2005, leaving the tanks completely empty in order to complete the satellite passivation. Since then, the orbit of UARS continued to decay up to the final reentry into the Earth's atmosphere, on 24 September 2011.

A reentry survivability analysis of UARS had been performed by NASA in 2002, using the software tool ORSAT and assuming a breakup altitude of 78 km. 26 fragments with a total mass of 532 kg were expected to survive reentry and distribute along a debris footprint 788 km long. According to NASA, the total debris casualty area was assessed to be 22.4 m^2 and the risk of human casualty was about 1:3200 in the latitude belt between ±57°.

The prediction activity was carried out at ISTI-CNR during the last 12 days of residual lifetime, marked by the solar flux on the rise and a couple of geomagnetic storms in the first half. The reentry uncertainties windows for UARS were obtained by varying its ballistic parameter by ±20%. The mean relative residual lifetime error was close to 15% over the reentry campaign and about 20% during the last 2 days. The maximum absolute errors were instead close to 28% around one day before reentry.

Information concerning the possible cross-track dispersion of the fragments was not available. Therefore, on the basis of the experience of past reentries and on the expected trajectory inaccuracies, a ground swath of ±100 km around the nominal track was assumed. The risk zones and time windows for Italy were issued about 64 hours ahead of reentry. At that time, the satellite reentry tracks possibly affecting the Italian territory were 2 in a global uncertainty window 30 hours wide. The risk time window associated with each possible reentry track was 38 minutes wide, including the airspace up to a geodetic altitude of 10 km. The last remaining risk zone over Italy fell out of the global uncertainty window 5 hours before reentry [6]. After the event, the US Joint Space Operation Center (JSpOC) assessed that the reentry at the altitude of 80 km had occurred at 04:00 UTC ±1 minute, on 24 September 2011.

6.2 ROSAT – ROentgen SATellite

The satellite ROSAT of the German aerospace center (DLR) was launched from Cape Canaveral with a Delta II rocket on 1 June 1990, and placed into a 575 km circular orbit to study astronomical sources in the extreme ultraviolet and X-ray bands of the spectrum. After 8 years of data collection, the orbit of the abandoned satellite was left to progressively decay due to the action of air drag.

A reentry survivability analysis of the satellite had been performed by DLR using SCARAB. 18 fragments with a total mass of 1700 kg were expected to survive reentry and distribute along a debris footprint 1200 km long. The largest fragment would have had a mass of 1500 kg and the total debris casualty area was estimated to be around 20 m^2. The risk of human casualty from surviving debris was about 1:3000 (DLR) in the latitude belt between ±53°.

Reentry predictions were carried out at ISTI-CNR during the last 11 days of satellite lifetime, marked by solar activity on the rise and relatively quiet geomagnetic conditions. The reentry uncertainties windows for ROSAT were obtained by varying its ballistic parameter by ±25%. The maximum relative absolute error was about 8% and occurred 19 hours before decay. The mean prediction errors were about 3% over the reentry campaign and 5% during the last 2 days.

Based on the information issued by DLR, implying a maximum cross-track dispersion of the fragments of ±40 km, and on the estimated reentry trajectory error, an initial and very conservative ground swath of ±90 km around the nominal track was assumed, successively reduced to ±85 km to account for the decreasing trajectory propagation uncertainties. The risk zones and time windows for Italy were issued about 88 hours ahead of reentry. At that time, the uncertainty window was still wide (51 hours), but the satellite reentry tracks possibly affecting the Italian territory were 5. The risk time window associated with each track was 30 minutes wide, including the airspace up to a geodetic altitude of 10 km. The last "surviving" risk zone fell finally out of the global uncertainty window about 18.5 hours before reentry [6]. According to JSpOC, the reentry of ROSAT at 80 km occurred at 01:50 UTC ±7 minutes, on 23 October 2011.

6.3 Phobos-Grunt

The Roscomos planetary probe Phobos-Grunt was launched on 8 November 2011 from the Baikonour cosmodrome with a Zenit-2 rocket. Initially placed into a 208×344 km orbit, the spacecraft, directed towards the main moon of Mars, remained unfortunately trapped in orbit around the Earth, probably due to a malfunction of the on-board computer. Any attempt to regain control from the ground was unsuccessful and, since 22 November 2011, its orbital decay was essentially compatible with natural perturbations alone.

According to various estimates carried out in Russia and in Germany, from 8 to 30 fragments, with a total mass of 200-1000 kg, were expected to survive reentry and distribute along a debris footprint 800-1300 km long. The risk of human casualty on the ground due to debris impact was assessed to be about 1:5000-1:3000 in the latitude belt between ±51.5°.

The reentry campaign was carried out at ISTI-CNR during the last 13 days of residual lifetime, characterized by a declining solar activity and relatively quiet geomagnetic conditions. The reentry uncertainties windows for Phobos-Grunt were obtained by varying its nominal residual lifetime by ±25%. Overall, the maximum absolute error was about 8%, and 6% during the last two days.

Conservatively assuming a quite improbable propellant tank explosion at high altitude during reentry, and taking into account the estimated trajectory error, a ground swath of ±120 km around the nominal track was considered. The risk zones and time windows for Italy were issued about 57 hours ahead of reentry. At that time, the satellite reentry tracks possibly affecting the Italian territory were 3 in a global uncertainty window 28 hours wide. The risk time window associated with each track was 30 minutes wide, including the airspace up to a geodetic altitude of 10 km. The last "surviving" risk zone remained in play until the end. Later on it was assessed that the probe had reentered before crossing the Atlantic Ocean and then Europe. According to JSpOC, the reentry at 80 km had occurred at 17:46 UTC ±1 minutes, on 15 January 2012.

6.4 GOCE – Gravity field and steady-state Ocean Circulation Explorer

The ESA's satellite GOCE was launched on 17 March 2009 from the Plesetsk cosmodrome on a Rokot launcher. After mapping the geopotential for four years from an extremely low circular orbit, on 21 October 2013 the low thrust ion propulsion motor, used to contrast the atmospheric drag, was automatically shut down. Then the satellite entered in a Fine Pointing Mode (FPM), with an attitude control minimizing the aerodynamic drag effect. According to pre-launch specifications, the FPM state would have been maintained up to the reaching of an average drag force along the orbit of 20 mN. But contrarily to any expectation, the attitude control system remained operational until reentry, with drag forces perhaps exceeding 2000 mN. Therefore, even if the casualty expectancy for this reentry was estimated to be slightly above the alert threshold, i.e. 1:5000, it presented a number of challenges and opportunities, from the prediction and risk evaluation point of view, by reason of its peculiar nature.

A pre-launch destructive analysis of GOCE had been carried out for ESA by HTG (Hyperschall Technologie Göttingen) using SCARAB. Overall, 43 macroscopic fragments, totaling approximately 270 kg, were expected to survive reentry and hit the ground along a 900 km footprint, with a time dispersion of 17 minutes.

No.	Day	Opening	Closure
1	9 Nov. (descending)	06:37 UTC	07:17 UTC
2	9 Nov. (ascending)	17:55 UTC	18:35 UTC
3	10 Nov. (descending)	07:26 UTC	08:06 UTC
4	10 Nov. (ascending)	18:44 UTC	19:24 UTC
5	11 Nov. (descending)	06:48 UTC	07:28 UTC
6	11 Nov. (ascending)	18:10 UTC	18:50 UTC

Exclusion of the last surviving risk zone at ~14^h before reentry, thanks to the contraction of the ground safety swath

Fig. 5 Risk time windows (table on the right) and satellite reentry ground tracks possibly affecting the Italian territory for cases 2-4 associated with the GOCE reentry
The last surviving risk zone (No. 4), no longer interesting Italy due to a contraction of the ground safety swath, is shown on the bottom right

The orbital evolution of GOCE was monitored at ISTI-CNR since 23 October 2013. Following an initial period of test and analysis, in which only the opening of the reentry uncertainty window was of importance to exclude the reentry before a given epoch, reasonably and conservative criteria, mainly based on the uncertainty affecting the duration of the FPM phase, were elaborated and applied, with good and consistent results through the end of the campaign [15].

The possible cross-track dispersion of the fragments was assumed to be ±200 km around the nominal track. The risk zones and time windows for Italy were issued about 61 hours ahead of reentry. At that time, the satellite reentry tracks possibly affecting the Italian territory were 6 in a global uncertainty window 67 hours wide. The risk time window associated with each track was 40 minutes wide, including the airspace up to a geodetic altitude of 12 km. The last "surviving" risk zone fell out of the global uncertainty window about 14 hours before reentry, thanks to a significant contraction (to ±120 km) of the ground safety swath (Fig. 5). The reentry at 80 km occurred at 00:16 UTC ±1 minute, on 11 November 2013 (JSoPC). The GOCE fragments eventually plunged into the Southern Atlantic Ocean between 00:24 and 00:40 UTC.

6.5 Progress-M 27 M

The Russian cargo ship Progress-M 27 was launched on 28 April 2015 from the Baikonour cosmodrome aboard a Soyuz 2-1A rocket. After nearly nine minutes of powered flight, the cargo was separated in orbit. Shortly afterwards, during the crucial phase of the Soyuz third stage shutdown and the separation of the Progress spacecraft, there was, unfortunately, a loss of telemetry from the upper stage and the spacecraft. After vain attempts to regain control of the vehicle, the mission was declared lost by the Russian space agency on 29 April 2015. The third stage, with a mass of 2300 kg, reentered the same day. With no ability to command Progress for a safe return, the out of control supply vessel was irremediably doomed to an uncontrolled reentry.

No detailed fragmentation and demise analysis was available. However, considering the Progress launch mass of 7289 kg, and the presence on board of 1373 kg of highly toxic propellants, this uncontrolled reentry was expected to violate the alert casualty expectancy threshold of 1:10,000. A number of parts were presumed to survive reentry, like the docking mechanism and the spherical pressurant tanks. An additional unknown was represented by the tanks holding the very toxic propellants. However, due to the very short permanence in orbit of the vehicle, it was unlikely that propellants had time to completely freeze. Their dispersion at high altitude during reentry was instead considered the most probable scenario.

The first ISTI-CNR reentry prediction was issued on 30 April. In the morning of 7 May, the only potentially risky reentry trajectory over central Italy was identified and in the afternoon of the same day, about 12 hours before the actual reentry, any residual risk for Europe and Italy was finally excluded. According to JSoPC, the reentry of Progress at 80 km occurred on 8 May 2015, at 02:20 UTC ±1 minute, over the Southern Pacific Ocean.

References

1. Pardini C, Anselmo L (2013) Re-entry predictions for uncontrolled satellites: results and challenges. In: Ouwehand L (ed) Proc. 6th IAASS Conference "Safety is Not an Option", ESA SP-715 (CD-ROM), European Space Agency, Noordwijk
2. Anselmo L, Pardini C (2005) Computational methods for reentry trajectories and risk assessment, Adv Space Res 35(7):1343−1352
3. Ailor W, Hallman W, Steckel G et al (2005) Analysis of reentered debris and implications for survivability modeling. In: Danesy D (ed) Proc. of the 4th European Conference on Space Debris, ESA SP-587, ESA Publication Division, European Space Agency, Noordwijk, pp. 539−544
4. Klinkrad H, Fritsche B, Lips T et al (2006) Re-entry prediction and on-ground risk estimation. In: Klinkrad H (ed) Space Debris – Models and Risk Analysis, Chapter 9, Springer Praxis Publishing, Chichester, pp. 241−288
5. NASA (2012) Process for limiting orbital debris. NASA-STD-8719.14, Revision A with Change 1, NASA Technical Standard, National Aeronautics and Space Administration, Washington (DC), p. 44
6. Anselmo L, Pardini C (2013) Satellite reentry predictions for the Italian civil protection authorities, Acta Astronaut 87(1):163−181
7. Pardini C, Anselmo L (2016) The uncontrolled reentry of Progress-M 27M, Journal of Space Safety Engineering 3(3):117−126
8. Johnson N (1997) The re-entry of large orbital debris. In: Heath GW (ed) Space Safety and Rescue 1997, Vol. 96, Science and Technology series, Univelt Inc, San Diego (CA), pp. 285−293
9. European Space Debris Safety and Mitigation Standard Working Group (2004) European code of conduct for space debris mitigation. Issue 1.0, p. 7
10. ESA Space Debris Mitigation Working Group (2015) ESA space debris mitigation compliance verification guidelines. Issue 1, European Space Agency, p. 28
11. Cole JK, Young LW, Jordan-Culler T (1997) Hazards of falling debris to people, aircraft, and watercraft. Sandia Report, SAND97-0805-UC-706, Sandia National Laboratories, Albuquerque (NM)
12. Nicollier C, Gass V (eds) (2015) Our space environment, opportunities, stakes and dangers. EPFL Press, Lausanne
13. Anselmo L (2003) Risk analysis and management of the BeppoSAX reentry. ISTI Technical Report 2003-TR-23, Pisa
14. Pardini C, Anselmo L (2015) Satellite re-entry prediction products for civil protection applications. In: Sgobba T, Rongier I (eds) Proc. of the 7th IAASS Conference "Space Safety is No Accident", Springer International Publishing, Switzerland, pp. 453−462
15. Pardini C, Anselmo L (2015) GOCE reentry predictions for the Italian civil protection authorities. In: Ouwehand L (ed) Proc. of the 5th International GOCE User Workshop, ESA SP-728 (DVD), European Space Agency, Noordwijk