SATELLITE RE-ENTRY PREDICTION PRODUCTS FOR CIVIL PROTECTION APPLICATIONS

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ABSTRACT

In order to meet the specific requirements of civil protection authorities, since 2003 a set of tailored products has been developed and applied in Italy to define, a few days ahead of re-entry and in wide areas of interest, risk zones and corresponding alert time windows in the event of an uncontrolled satellite decay leading to undue debris impact hazard on the ground and in the overlying airspace. Based on the general properties of re-entries from nearly circular decaying orbits, on the results of detailed fragmentation analyses, when available, on standard re-entry prediction outputs, on specific simulations of endo-atmospheric debris dynamics, and on the basics of orbital motion with respect to the Earth, accurate re-entry tracks over the region(s) of interest are determined, with sufficiently conservative ground safety swaths, accounting for the sources of cross-track debris dispersion, and associated risk time windows, depending on debris flight time dispersion and residual trajectory along-track uncertainties. With the approaching re-entry and the consequent shrinking of the global uncertainty window, some of the risk zones and time windows identified in advance can be progressively discarded, leaving at most, until the end, one re-entry opportunity, but more often none, over a region the size of Italy. These products are easy to understand and are timely, accurate, unambiguous and remarkably stable, all qualities that render them particularly suitable for civil protection applications.

1. INTRODUCTION

Currently, approximately 70% of the re-entries 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 re-entry every week, with an average mass around 2000 kg [1]. Even though a detailed demise analysis is available only occasionally, in many cases the alert casualty expectancy threshold of 1:10,000 is probably violated.

Re-entry predictions are affected by various sources of inevitable uncertainty and, in spite of decades of efforts, residual lifetime mean relative errors around 20% should typically be expected [1] [2]. Due to the fact that re-entering satellites in nearly circular orbit complete a full revolution around the Earth in just less than 90 minutes, even a few days before orbital decay a global re-entry 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 (corresponding to one full orbital path), possibly halved during the last hour, if further tracking data are available [1] [3] [4].

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. In order to overcome these problems, since 2003 specific approaches and procedures were developed by the authors, producing output products tailored for civil protection applications by the Italian national authorities [1] [2]. The experience gained during several re-entry campaigns was very positive and it was possible to verify in real case situations the accuracy and appropriateness of the developed products [3] [4].

This paper presents in detail the work carried out so far for the Italian territory and air space. In particular, a detailed description of the followed approaches and procedures is given, with product examples taken from real re-entries occurred during the last decade. Moreover, prescriptions are provided on how our methods and strategies might be extended and applied to wider areas of the planet, possibly the entire world, in order to supply more accurate early alerts to aircraft and on the ground, in terms of reasonably slim risk time windows and re-entry tracks for any location possibly affected by the re-entering debris.

2. RE-ENTRY UNCERTAINTY WINDOWS

Predicting the re-entry time and location of an uncontrolled space object is an extremely demanding undertaking. As a matter of fact, it can re-enter anywhere on a large portion of the Earth surface, making all the places within the latitude band defined by the orbit inclination potentially at risk. The considerable uncertainty affecting the estimation of the re-entry epoch and place may be due to sparse and inaccurate tracking data, to the complicate shape and unknown attitude evolution of the re-entering object, to biases and stochastic inaccuracies in the estimation of the atmospheric density, to the magnitude, variability and prediction errors of solar and geomagnetic activity, and to the mismodeling of gas-surface interactions and drag coefficient [1].

All these uncertainty sources combine in a complex way, depending on the specific properties of the re-entering object and on the particular space environment conditions experienced during the final phase of the orbital decay. Therefore, even applying the same and best models, methods and procedures, the overall relative re-entry prediction errors may be quite different for various objects and diverse epochs. The experience accumulated worldwide shows that a relative prediction error of ±20% should be adopted to compute the uncertainty windows associated with re-entry 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 [1].

These re-entry time uncertainties are quite huge, as shown in Tab. 1. A couple of days before re-entry, the event occurrence is generally uncertain by 20 hours, corresponding to about 13 full revolutions of the object around the Earth. Around the beginning of the last day, the uncertainty window is still 10 hours wide, including more than 6 satellite revolutions. The very high orbital velocity at low altitudes translates into large along-track spatial uncertainties even a few hours before decay.

Table 1. Amplitude of the uncertainty window and number of orbital sub-satellite tracks included in it, as a function of the re-entering object residual lifetime. A relative prediction error of ±20% and a satellite in nearly circular orbit were assumed.

Satellite residual lifetime since the last determined orbit	**Amplitude of the uncertainty window**	**Orbital sub-satellite tracks included in the uncertainty window**
10 days	± 2 days	≈ 64
5 days	± 1 day	≈ 32
3 days	± 14.4 hours	≈ 19
2 days	± 9.6 hours	≈ 13
1 day	± 4.8 hours	≈ 6.4
12 hours	± 2.4 hours	≈ 3.2
6 hours	± 1.2 hours	≈ 1.6
4 hours	± 0.8 hours	≈ 1.1
3 hours	± 0.6 hours	≈ 0.8
2 hours	± 0.4 hours	≈ 0.5
1 hour	± 0.2 hours	≈ 0.3

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 re-entry prediction, so the final forecasts issued during the last hour or minutes preceding the actual re-entry are based on a state vector with a 2-3 hours old epoch. The consequence of this is that the predictions issued around 2 hours before re-entry have a typical along-track uncertainty of approximately one orbit (i.e. ~40,000 km), while those issued immediately before re-entry present a typical along-track uncertainty of half an orbit (i.e. ~20,000 km).

3. GROUND TRACKS UNCERTAINTY

Unfortunately, the huge along-track uncertainty associated with the global re-entry time windows represents only one aspect of the problem of finding the locations on the Earth possibly affected by the uncontrolled re-entry. In fact, it should be emphasized that the sub-satellite tracks themselves may result quite inaccurate in the cross-track direction, as a direct consequence of the trajectory propagation errors and the Earth rotation. In other words, even though this important aspect is often overlooked, the error sources impacting the propagation accuracy, and leading to the relatively large re-entry epoch uncertainty, imply also a smaller, but not negligible, uncertainty in the satellite overflight times at given latitudes, for instance at ascending nodal crossings. Due to the Earth rotation, a satellite overflight delay with respect to the nominal propagated trajectory, at the ascending nodal crossing, would cause a westward shift of the sub-satellite ground track, while an earlier transit would result into an eastward shift of the trajectory with respect to the surface of the planet [2].

Table 2. Shift of the sub-satellite ground track at the equator resulting from a nodal crossing time error. An anticipated crossing causes an eastward drift of the ground track, while a delayed crossing causes a westward drift.

Nodal crossing time error (minutes)	**Shift of the sub-satellite ground track at the equator (km)**
1	≈ 28
5	≈ 140
10	≈ 279
15	≈ 419
20	≈ 558

Considering the propagation errors involved, the possible cross-track shifts of the sub-satellite ground tracks included in the re-entry time uncertainty windows may be considerable, even during the last few days before decay. Taking into account that the Earth surface at the equator moves eastward at the velocity of 0.465 km/s, a difference of just 1 minute in the equator crossing would correspond to a sub-satellite track shift of 28 km, while a difference of 15 minutes would correspond to a ground shift of approximately 419 km (Tab. 2).

Figure 1. Predicted sub-satellite ground track over Italy of a re-entering satellite in nearly circular orbit at sun-synchronous inclination

Figure 2. Eastward drift of the sub-satellite ground track over Italy caused by an ascending nodal crossing anticipated by 10 minutes.

Due to the fact that even 24 hours before re-entry the predicted overflight times included in the uncertainty window may be affected by errors as large as 10-15 minutes (or more), it is clear that the trajectory cross-track uncertainty cannot be ignored, making the plots of the ground tracks issued by many during the final days of orbital lifetime not only useless for civil protection applications, but also misleading, as shown in Fig. 1, 2 and 3. Typically, only the ground track plots propagated less than 12 hours before re-entry may be sufficiently accurate to be represented on a small scale world map, but a totally different approach should be used to produce accurate medium or large scale geo-referenced information, as explained in the following section.

Figure 3. Westward drift of the sub-satellite ground track over Italy caused by an ascending nodal crossing delayed by 10 minutes.

4. CIVIL PROTECTION APPLICATIONS

For the reasons described in the previous sections, the re-entry prediction standard products for potentially risky and uncontrolled space objects, i.e. (1) the nominal decay forecast, (2) the global uncertainty time window and (3) the sub-satellite ground tracks included in the latter, are of no or very limited use for civil protection applications, as established in more than 30 years of cooperation on the subject with the Italian national authorities. The nominal decay forecast (1) is just the result of a physical mathematics modeling process, but its intrinsic large uncertainty makes it absolutely useless for civil protection planning. The global uncertainty time window (2) provides instead relevant information, identifying the time interval in which the re-entry should be expected, somewhere in the world. But this interval remains too large until re-entry (Tab. 1), so it is not possible to devise and apply practical precautionary civil protection measures based on it. Moreover, inside the global uncertainty window, the re-entry location remains quite undetermined (Tab. 1), along a varying number of orbital sub-satellite tracks (3), themselves possibly affected by a considerable cross-track error (Tab. 2). Therefore, the locations possibly at risk in a given area, for instance in Italy, cannot be identified reasonably ahead of re-entry with this information (Fig. 1, 2 and 3).

In order to overcome these problems and intrinsic limitations, a completely different approach was devised, implemented and applied in Italy to real re-entry predictions campaigns since the orbital decay of the BeppoSAX spacecraft in 2003 [1] [2] [3] [4] [5] [6] [7]. We started from the following question, relevant for any meaningful civil protection planning: «Given a certain global uncertainty time window, where and when a re-entering satellite fragment might cross the airspace and hit the ground on a specific area of the world (e.g. Italy) overflown by the falling uncontrolled object?»

First of all, it was needed to find reliable re-entry times associated with a given location and accurate ground tracks, possibly a few days in advance, in order to make possible the appropriate civil protection planning in the areas potentially affected and the reliable identification of the areas excluded from any risk. To do so, we started from the simple remark that for each overflown location included in the global uncertainty time window, re-entry or debris ground impact was possible, in principle, but not certain; however, in each place, the eventual re-entry or impact would have occurred only during a specific and quite accurate risk time window, which could have therefore been used to plan risk mitigation measures on the ground and in the overhead airspace.

The trajectory propagation uncertainty, leading to the comparatively wide global uncertainty time window, is dominated by the atmospheric drag mismodeling, i.e. by the inaccuracy of the product among drag coefficient, satellite cross-sectional drag area and atmospheric density. The possible variations of the re-entry time included in the uncertainty window are just the consequence of the possible variations of such a product. It is therefore quite straightforward to explore iteratively this product inside the expected variation range (for instance by varying either the drag coefficient or the cross-section), in order to identify all the satellite re-entry or (intact) impact opportunities on a given area during the current global uncertainty time window.

Even 3-4 days before the satellite decay from orbit, the specific re-entry times computed with the above mentioned approach, at a geodetic altitude in between 100 and 80 km, i.e. above the height were most of the breakups occur, are very accurate and nearly all the cross-track errors in the corresponding sub-satellite ground tracks, expected up to satellite decay, cancel out to less than a few tens of kilometers. These results are the direct consequence of "anchoring" the satellite dynamical evolution with the Earth rotation, in order to obtain a re-entry over a selected area of the planet. Such eventuality will probably not occur and the satellite will re-enter elsewhere, but if the decay from orbit will happen just in the region of interest, the timing and the geometry of the event will be quite exactly those computed with the described approach. Moreover, 3-4 days in advance offer a very good margin for civil protection preparations, and the further accuracy improvements possible in the following days may be used to refine and update an already clear picture of the situation and its expected evolution.

The experience gained in several re-entry prediction campaigns has shown that, in alternative to the re-entry times, the simulated ground impact times of the intact decaying object can be used as well. In other words, the procedure just outlined can be used to find the possible "fictitious" ground impact times of the intact satellite inside the current global uncertainty time window. As previously remarked, it is well known that re-entering spacecraft and upper stages are generally prone to catastrophic breakup below the altitude of 80 km, so it should make nonsense to talk about intact objects reaching the ground. However, if we model the "fictitious" intact satellite, i.e. a mere mathematical idealization, down to the ground, we found that the dynamic parameters, the flight times and the down range are typically in between those corresponding to the generated fragments, just because the area-to-mass ratio of the intact body is generally in between those of its components and resulting surviving debris. Therefore, from a practical point of view, the simulated ground impact times of the "fictitious" intact satellite and the associated ground tracks over the selected area of the world are easier to use for accurately defining in advance the times and locations potentially affected by a debris fall.

5. REGIONAL RISK TIME WINDOWS

A re-entering satellite in nearly circular orbit overflies more than 455 km in only 1 minute, so if we determine, with the approach outlined in the previous section, the re-entry time or, alternatively, the ground impact time of the intact object on a given location, just moving along the correct ground track 910 km forward or backward, the computed event times should be shifted by 2 minutes, respectively forward or backward. This means that if we subdivide the basically error free re-entry ground tracks included in the global uncertainty time window in arcs 1820 km long, considering just the event time computed in the middle would entail a maximum time error over the full arc of ±2 minutes.

Of course, nothing prevents in principle the computation of much closer, up to nearly continuous, re-entry or impact times, but in practice this is not necessary, because the re-entry simulations already intrinsically guarantee the almost exact synchronization of satellite dynamics and Earth rotation, canceling out nearly all the cross-track errors, by targeting re-entry points a few thousand kilometers apart. And a ±2 minutes (deterministic and computable) difference in the event timing inside the chosen arc is in any case small compared to the flight time dispersion of the fragments produced by the breakup of the re-entering object, so it can be tolerated and incorporated in the other timing uncertainties, in order to maintain reasonably small the number of fictitious re-entries to be simulated.

Therefore, for Earth surface regions sufficiently wide to include Italy and a significant portion of the surrounding lands and seas, each possible re-entry track may be accurately modeled by simulating only one re-entry, or ground impact, inside the area of interest. Considering wider regions of the planet overflown by the satellite, the exercise must be repeated for the applicable number of arcs, about 22 per orbit if a maximum timing error of ±2 minutes is deemed acceptable.

The further step in the definition of a regional risk time window must take into account the different flight times of the satellite fragments able to survive the harsh conditions of the re-entry, crossing the airspace below the altitude of, for instance, 15 km and impacting the ground. They are characterized by distinct ballistic properties, fragmentation altitudes and ablation histories, and obviously vary as a function of the nature of the parent object. However, their timing dispersion, in terms of airspace crossing and ground impact, 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.

Around any sub-satellite location included in the global uncertainty time window, it is therefore possible to define a quite accurate regional risk time window, accounting for the dispersion of the fragments (a few tens of minutes), the finite size of the considered area (±2 minutes in our example), and a further rather conservative time dispersion (a few minutes), to include the unaccounted for effects of initial conditions and trajectory propagation errors. Even though the re-entry probability on a given area will remain small until the end (of the order of a few percent or less), the eventual debris fall and impact may occur only during a specific risk time window, which can be therefore used to plan risk mitigation measures on the ground and in the overhead airspace. For a region sufficiently wide to include Italy, it was shown that, depending on the specific cases analyzed, risk time windows 30-40 minutes wide were appropriate and could be accurately identified already 3-4 days ahead of the foreseen re-entry, resulting very easy to understand for people not involved in the re-entry prediction activity and extremely useful for civil protection planning and applications [2] [3] [4].

Concerning the volume of airspace and the surface on the ground associated with the regional risk time window, they can be obtained, starting from the accurate re-entry ground track found for the area of interest, by defining a cross-track safety margin, taking into account the expected dispersion of the fragments perpendicularly to the satellite trajectory, based on previous observations or specific fragmentation analyses. It depends on the breakup nature and the debris endo-atmospheric dynamics (lift components in the cross-track direction), amounting to as much as several tens of kilometers. A further cross-track safety margin will account for the residual cross-track trajectory uncertainty due to the mismodeled part of the actual decay evolution during the last days of residual lifetime, amounting to a few tens of kilometers 3-4 days ahead of orbital decay, but progressively decreasing with the approach of the re-entry epoch.

Even the effects of the prevailing or predicted winds in the stratosphere and in the troposphere might be in principle evaluated and taken into account. They can be extremely relevant for relatively fine particulate, as in the case of the radioactive contamination occurred over a vast area of Canada in 1978, following the uncontrolled re-entry of the nuclear powered Cosmos 954 spacecraft. In such event, 4000 radioactive particles in between 0.2 and 1 mm were recovered in a 100,000 km^2 area, and the smallest were found 200 km on the right of the re-entry trajectory. However, the millimeter sized ones were basically distributed along the re-entry ground track [8]. More generally, 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 kilometers [9].

From a safety point of view, disregarding a specific case like the Cosmos 954 accident, where the small particulate was important because represented a radioactive contaminant, the relevant fragments in typical uncontrolled re-entries are those with a ground impact energy ≥ 15 J, able to injure a human body in the open [10], those with a terminal kinetic energy ≥ 103 J, associated with a 50% probability of human fatality [10], and those potentially leading to a catastrophic impact with a passenger aircraft in flight. It was estimated that a 1 g compact piece of steel may pose a significant hazard to certain types of aircraft [10]. However, more recent results and evaluations indicate that, for commercial passenger aircraft with aluminum skin, penetration in flight requires the impact with debris of more than 100 g, and fragments in excess of 300 g are probably needed to induce catastrophic consequences, irrespective of the impact location [11] [12].

Limiting the attention to the relevant fragments and depending on the specific nature of the re-entering parent object, 3-4 days before orbital decay a safety margin swath of ±90-200 km around the computed re-entry trajectory may be assumed, progressively reducing it to ±80-120 km during the last 24-48 hours [2] [3] [4]. Having so defined, for the selected region of interest and at least 3-4 days in advance, a ground hazard footprint with an overlying volume of airspace, associated with a reasonably compact risk time window of 30-40 minutes, all the information needed for an effective civil protection evaluation and planning is available, being sufficiently accurate, reliable, unambiguous, relatively stable and very easy to explain, understand and manage also for personnel not expert in orbital dynamics.

For a region embracing Italy, only a few re-entry opportunities are typically included in the global uncertainty time window 3-4 days before re-entry, and for each of them a corresponding re-entry ground track, risk zone (up to a given altitude) and risk time window can be computed with the approach previously described. Often already at this stage, for some areas of the country lying outside the conservatively defined risk zones, any residual re-entry hazard can be definitely excluded. Moreover, the computed products are sufficiently accurate, conservative and stable to maintain their intrinsic validity until the end, even though improvements are possible in the ensuing days, in particular further reducing the cross-track safety margin and slightly adjusting the re-entry ground track, with the consequence of obtaining a contraction of the risk zones, but not an appreciable reduction and/or shift of the associated risk time windows (< 1-2 minutes).

The most significant event occurring in the last few days, from the prediction point of view, is the progressive contraction of the global uncertainty time window as the orbital decay approaches. When a re-entry opportunity previously identified over the region of interest is left out of the shrinking global uncertainty window, such a possibility, and the corresponding risk zone and time window, can be finally dropped from the original alert list, and this happens again and again during the last 3 days of satellite lifetime. In most cases, the last surviving re-entry opportunity may be excluded from the shrinking global uncertainty time window several hours, but less than one day, before the fall of the satellite fragments, but sometimes it is not possible to exclude any risk for an area of interest until the re-entry actually occurs [2] [3] [4].

6. RE-ENTRY DEBRIS DISTRIBUTION

A satellite in nearly circular orbit approaching re-entry has a specific mechanical energy of 3.2×10^7 J/kg. If all this energy were converted into heat entirely absorbed by the object, most materials would be totally vaporized [13]. However, only a small fraction of this energy is usually absorbed by the re-entering body, so the chance of having surviving components hitting the ground is far from negligible, in particular when sizable spacecraft and rocket bodies are involved. Detailed computer simulations [2] [14] [15] and the analysis of retrieved spacecraft and rocket body components [9] led to the conclusion that, also in the case of objects not specifically designed to survive the re-entry mechanical and thermal loads, a mass fraction between 5% and 40% of sufficiently massive bodies is able to reach the Earth surface [2] [9] [16].

Presently, a few computer codes are available in Europe, Japan, Russia and the United States to model in detail the fragmentation and eventual demise of complex structures during re-entry, taking into account both the thermal and dynamical aspects. The most known are the Space-Craft Atmospheric Re-entry and Aerothermal Break-up tool (SCARAB) [15] [17] and the Object Re-entry Survival Analysis Tool (ORSAT) [14]. Over the years, they have been compared against a few test cases, showing a reasonable qualitative and quantitative agreement. Further information can be obtained from the record of past re-entry observations and from the inventory of recovered debris [9]. The realistic computer simulations carried out so far show that the fragmentation details of decaying satellites are strongly dependent on the object characteristics and constituent materials, so any specific case, involving either spacecraft or rocket bodies, may present a particular signature. However, some general figures may offer a reasonable picture of what can be typically expected.

First of all, it was observed that magnesium and aluminum structures tend to fail at an altitude of approximately 78 km, to which most of the satellite catastrophic breakups are therefore associated [9]. Fragments or components made of high melting point materials, like titanium, stainless steel or glass, often are able to survive, reaching the ground, but also some pieces made of low melting point materials can occasionally hit the surface of the Earth because released at relatively high altitude and strongly decelerated, or because shielded by other resistant components, or simply because too massive to be completely melted in the available time [9].

The surviving debris ground footprint is aligned with the re-entry trajectory and is typically 1000-2000 km long. The cross-track dispersion is generally limited to less than a few tens of kilometers for the potentially hazardous fragments, but smaller particles may be found further away, blown by the winds. Often, but not necessarily always, heavy fragments fall first toward the forefoot, while the light ones impact the ground, with a certain time delay, toward the heel of the debris footprint, i.e. closer to the re-entry point. The impact time dispersion among the surviving fragments in the 1 g – 100 kg mass range can be around 15-30 minutes. Considering the relatively short time (2-5 minutes) spent by the faster fragments to fall through the airspace (from 15 km height to ground impact), a slight increase of the time dispersion window by the same amount can include the risk interval for overflying aircraft as well.

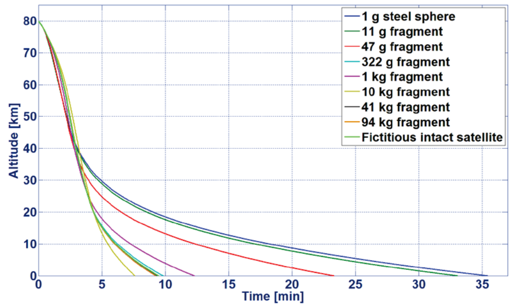

Figure 4. Time of flight of re-entry debris from the breakup altitude (80 km) to ground impact. In addition to realistic fragments, a 1 g steel sphere and a fictitious intact satellite of 1000 kg were considered as well.

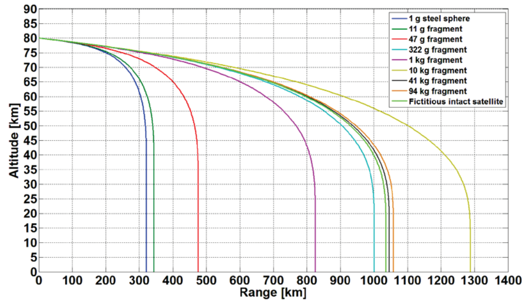

Figure 5. Downrange distribution of re-entry debris from the breakup altitude (80 km) to ground impact. In addition to realistic fragments, a 1 g steel sphere and a fictitious intact satellite of 1000 kg were considered as well.

As an example, Fig. 4 and 5 show the results of a simplified re-entry breakup simulation, with the fragmentation occurring at the altitude of 80 km. In addition to realistic spacecraft fragments able to survive up to ground impact and lying in the 10 g – 100 kg mass range, a 1 g steel sphere and a fictitious intact parent object of 1000 kg were simulated as well. It should be noted that all fragments move down nearly along the local vertical through the airspace, i.e. perpendicularly to the ground (Fig. 5), and that the fictitious intact parent object, as very often is the case in practice, lies inside the dynamic envelope defined by the fragments, generally closer to the heaviest ones (Fig. 4 and 5). This is just the consequence of the fact that the ballistic coefficient of an intact satellite is generally included in the range of those corresponding to its fragments.

7. RECENT RE-ENTRY EXAMPLES

From September 2011 to November 2013, we have followed the re-entry of four decaying spacecraft for the Italian civil protection authorities: UARS (5668 kg), ROSAT (2426 kg), Phobos-Grunt (13,535 kg, reducing to 2350 kg if the liquid propellant carried on board was excluded) and GOCE (1002 kg) [3] [4]. For UARS, a detailed re-entry risk assessment had been carried out by NASA using ORSAT, in order to estimate the spacecraft component demise altitude, surviving mass and kinetic energy at ground impact [18]. The fragmentation of the other three spacecraft had been instead modeled in detail by Hyperschall Technologie Göttingen (HTG) using SCARAB [17] [19]. Basic information with a varying degree of completeness and detail, concerning the fragments generated and their spread in ground impact time and footprint (down range and cross-track), was therefore available, or deduced, for the definition of the regional re-entry risk zones and the associated time windows.

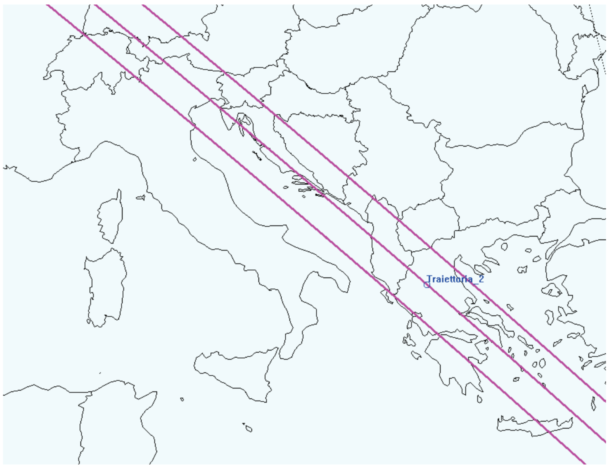

Figure 6. Last re-entry opportunity over Italy (descending central track), finally excluded just 5 hours before the UARS orbital decay. The corresponding risk time window for debris ground impact and airspace crossing was 01:34 – 02:12 UTC on Saturday 24 September 2011, and the cross-track safety swath defining the risk zone was ±100 km.

In the UARS case, the risk zones and time windows for Italy were issued about 64 hours ahead of re-entry. Even though the global uncertainty window was still quite wide (30 hours), the satellite re-entry tracks possibly affecting the Italian territory were already reduced to just two, each with an associated risk time window of 38 minutes (including the airspace up to the altitude of 10 km). Due to the lack of specific information concerning the possible cross-track dispersion of the fragments, based on past experience and on the expected trajectory inaccuracies, a quite conservative ground swath of ±100 km around the simulated re-entry tracks was assumed. However, most of the Italian territory was excluded anyway from a possible debris fall.

From that point onward, the main purpose of the new re-entry predictions was to check if the two regional risk zones and time windows would have remained or not inside the progressively updated and shrinking global uncertainty window. The risk zones themselves, and their associated time windows, did not need any substantial revision, due to their conservative definition, and were left unchanged. The last “surviving” risk zone (Fig. 6) fell finally out of the global uncertainty window 5 hours before re-entry, and only at that point any residual hazard for the Italian territory and airspace could be excluded.

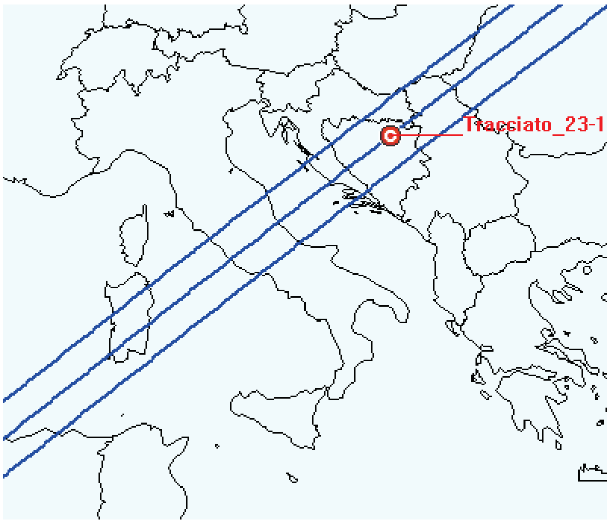

Figure 7. Last re-entry opportunity over Italy (ascending central track), finally excluded 18.5 hours before the ROSAT orbital decay. The corresponding risk time window for debris ground impact and airspace crossing was 09:17 – 09:47 UTC on Sunday 23 October 2011, and the cross-track safety swath defining the risk zone was ±85 km.

During the ROSAT campaign, the risk zones and time windows for Italy were issued around 88 hours ahead of re-entry. At that time the global uncertainty window was 51 hours wide and there were still five re-entry opportunities possibly affecting the Italian territory, each with an associated risk time window of 30 minutes (including the airspace crossing, from 10 km to ground impact). Based on the information available, implying a maximum cross-track dispersion of the fragments of ±40 km (further reduced to ±7 km by later HTG simulations), and on the estimated cross-track re-entry trajectory error, found to be less than a few tens of kilometers over the last few days, an initial, and very conservative, ground safety swath of ±90 km around the computed re-entry tracks was assumed.

Again, from that point onward, the main purpose of the following predictions was to check which of the identified re-entry opportunities would have remained inside the progressively updated and shrinking global uncertainty window. The risk zones themselves, and their associated time windows, were only subjected to minor updates, due to their conservative definition, but the swath amplitude was reduced to ±85 km in order to take into account the decreasing trajectory propagation uncertainty. Around 65 hours ahead of spacecraft decay, the number of re-entry opportunities included in the 39 hours wide global uncertainty window was reduced to three, while two further opportunities were eliminated approximately 29 hours before re-entry, when the global uncertainty window had shrunk to 21 hours and the only regional risk zone still in place was that shown in Fig. 7. It finally dropped outside the global uncertainty window about 18.5 hours before re-entry, excluding from that point onward any residual hazard for Italy (and Europe).

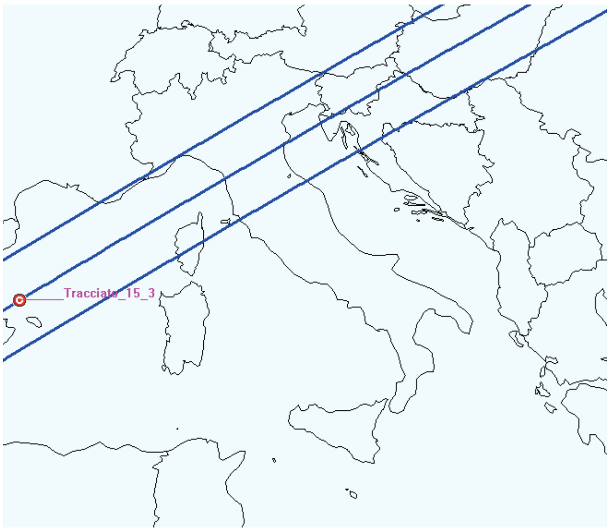

Figure 8. Re-entry opportunity over Italy (ascending central track) included in the final global uncertainty window before the Phobos-Grunt orbital decay. The corresponding risk time window for debris ground impact and airspace crossing was 18:14 – 18:44 UTC on Sunday 15 January 2012, and the cross-track safety swath defining the risk zone was ±120 km.

During the Phobos-Grunt campaign, the risk zones and time windows for Italy were issued about 57 hours ahead of re-entry. At that time the global uncertainty window was 28 hours wide and there were three re-entry opportunities possibly affecting the Italian territory, each with an associated risk time window of

30 minutes (including the airspace crossing, from 10 km to ground impact). Conservatively assuming a quite improbable propellant tank explosion at high altitude during re-entry and taking into account the estimated cross-track trajectory error, a ground safety swath of ±120 km around the computed re-entry tracks was considered. In spite of this, most of the Italian territory was already excluded from a possible debris fall. Ten hours before orbital decay, two out of three re-entry opportunities moved outside the 7 hours wide global uncertainty window, but the last one, shown in Fig. 8, remained in play until the very end, i.e. until it was confirmed that such a pass over Europe had not occurred, being the probe re-entered before crossing the Atlantic Ocean.

Concerning GOCE, the risk zones and time windows for Italy were issued around 61 hours ahead of re-entry. At that time the global uncertainty window was 67 hours wide and there were still six re-entry opportunities possibly affecting the Italian territory, each with an associated risk time window of 40 minutes (including the airspace crossing, from 12 km to ground impact). Based on the information available, implying a maximum cross-track dispersion of the macroscopic fragments of ±15 km, and taking into account the uncertainty surrounding the actual endurance of the spacecraft active attitude control system, in addition to the possible cross-track re-entry trajectory errors and wind effects on the smallest relevant particles, an initial, and very conservative, ground safety swath of ±200 km around the computed re-entry tracks was assumed.

Figure 9. Last re-entry opportunity grazing Italy (ascending central track). The corresponding risk time window for debris ground impact and airspace crossing was 18:44 – 19:24 UTC on Sunday 10 November 2013, and the cross-track safety swath defining the risk zone was ±120 km.

Approaching the orbital decay, as the global uncertainty window underwent its natural contraction, the number of re-entry opportunities over Italy was progressively reduced to four at minus 56 hours, to three at minus 40 hours and to only two at minus 25 hours, when the global uncertainty window had shrunk to 23.5 hours. The last opportunity was finally excluded 14 hours before re-entry, thanks to a significant contraction (to ±120 km) of the ground safety swath, which previously had included northwestern Italy, close to the border with France, and western Sardinia (Fig. 9).

8. CONCLUSIONS

Even though the re-entry predictions of uncontrolled satellites are intrinsically affected by substantial uncertainties until orbital decay, over the years a set of prediction products was specifically developed for the civil protection community and applications. It is easily applicable to areas of 2000 × 2000 km^2, i.e. ten times those of a country like Italy, and consists of regional risk zones and associated time windows, which can be accurately defined at least 3-4 days ahead of re-entry.

Such information can be updated, if needed, for instance by reducing the surface of the risk zone associated with a certain re-entry opportunity, but in practice remains relatively stable and accurate until re-entry, not much affected by the actual trajectory evolution due to the varying air drag, because these effects are already taken into account when defining the risk zones. The main purpose of the subsequent re-entry predictions is instead checking if the identified regional risk zones and time windows are remaining or not inside the progressively updated and shrinking global uncertainty window. If, finally, all of them move out of the global uncertainty window, any residual re-entry risk for the region of interest can be excluded; otherwise a risk zone identified at least three days in advance will remain alerted until the re-entry has occurred.

As demonstrated by the experience with the Italian civil protection authorities, these products are relatively easy to understand also for people not familiar with orbital dynamics. Moreover, they are timely, compact, unambiguous and remarkably stable, all qualities that make them very useful for civil protection applications.

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