OVERVIEW OF SOME BASIC REQUIREMENTS FOR A REENTRY PREDICTION SERVICE FOR CIVIL PROTECTION APPLICATIONS

Carmen Pardini[(1)], Luciano Anselmo[(2)]

[(1)] ISTI/CNR, Via G. Moruzzi 1, 56124 Pisa, Italy, Email: Carmen.Pardini@isti.cnr.it
[(2)] ISTI/CNR, Via G. Moruzzi 1, 56124 Pisa, Italy, Email: Luciano.Anselmo@isti.cnr.it

ABSTRACT

Even though the overall risk represented by the uncontrolled reentry of artificial space objects is still extremely low compared to many other hazards faced every day by individuals and societies, some of these events are receiving a growing attention from the media and the public, often involving the national authorities in charge of civil protection. When political authorities, government agencies, journalists, the public, and the judiciary are involved in the process, reentry predictions are no longer just a scientific task restricted to the technical community. This makes the assignment much more complicated and sensitive, further worsened by the fact that reentry predictions still remain affected by considerable and unavoidable uncertainties, making impossible, in most of the cases, the identification of a specific reentry time and location even in the last few hours.

This paper reviews the challenges faced in such situations, presenting the solutions devised in Italy, in particular during the last twenty years, to meet the specific requirements of the national civil protection system, and address the legal and liability aspects.

1 INTRODUCTION

Over the last decade, there was typically one sizable spacecraft or rocket body uncontrolled reentry every week. On average, one or two reentries per year involved objects with a dry mass greater than five metric tons. Even though the overall risk represented by these events is still low compared to many other hazards faced in everyday life, several uncontrolled reentries received a great deal of attention from the media and the public, also involving the national authorities in charge of civil protection.

Based on our personal experience, spanning back to the uncontrolled reentry of the soviet nuclear powered satellite Cosmos 1402, in 1983, when political authorities, government agencies, journalists and the public are part of the loop, the reentry prediction process diverges a lot from a purely physical-mathematical exercise. For this specific problem, the situation is made even more complicated by the fact that reentry predictions remain affected by considerable and unavoidable uncertainties, mainly driven by the atmospheric drag perturbation, making impossible the pinpointing of a specific reentry time and location even in the last few hours.

A particularly critical aspect concerns the content and format of the information provided. In addition to the need of clarity and the avoidance of any ambiguous or contradictory remark, one big challenge is to be as much accurate and precise as possible without resorting to complex technical concepts, familiar to the experts but not to the other people involved. Moreover, from the point of view of the civil protection authorities, some information generated during the prediction process, for instance the “nominal” reentry time and place, is completely useless, while they need and ask for other pieces of knowledge which are not typically provided when the prediction task is carried out for scientific research.

Finally, a further issue, especially sensitive in Italy, is that of civil and criminal liability in case of adverse effects resulting from the event under scrutiny, that the judiciary has applied in the past also in the case of natural phenomena for which scientific forecasts are difficult (e.g. atmospheric weather), or even impossible (as earthquakes). This paper will review all these problems and will detail the solutions adopted so far.

2 UNCONTROLLED REENTRIES

Based on what was observed during the last decade and after a careful analysis to sort out the controlled reentries, the current situation can be summarized as follows [1][2][3]:

1. On average, approximately 90 metric tons reenter in the atmosphere uncontrolled every year;
2. Objects with an average mass of about two metric tons reenter uncontrolled every 10 days;
3. Objects with a mass greater than 5 metric tons reenter once, or twice, per year;
4. More than 80% of the uncontrolled reentries of massive space objects involve spent orbital stages;
5. Slightly more than three-quarters of the events might lead, a priori, to a fall of fragments on the Italian territory, even though with extremely small overall probability.

Proc. 1st NEO and Debris Detection Conference, Darmstadt, Germany, 22-24 January 2019, published by the ESA Space Debris Office
Ed. T. Flohrer, R. Jehn, F. Schmitz, (http://neo-sst-conference.sdo.esoc.esa.int, January 2019)

In general, the dry mass, the structure and the composition of a reentering object are the leading indicators of the possible risk in terms of kinetic impact on the ground of the surviving fragments. However, in some cases, the risk coming from purely mechanical impacts may be far exceeded by the toxicity of chemical or radioactive substances carried on board and possibly able to be released on the ground, as happened, for example, in 1978, with the nuclear powered Soviet satellite Cosmos 954, whose radioactive debris precipitated on the Canada's Northwest Territories [4], and in 2008, when the release on the ground of a substantial amount of frozen hydrazine from a spherical tank of the failed American satellite USA 193 was feared, leading to the destruction of the spacecraft with a sea-launched missile approximately three weeks before its uncontrolled reentry [5].

More than 70% of the uncontrolled reentries of intact objects involve small eccentricity final orbits (≤ 0.01) and only 3% final eccentricities > 0.1 [3][6]. Therefore, in most of the cases, the complex interaction between the decaying space objects and the Earth's thermosphere plays the dominant role in the trajectory evolution, preventing the accurate prediction of a reentry location and time even a few hours before the event. For this reason, in nearly all the relevant cases, the reentry predictions of uncontrolled artificial objects are characterized by considerable uncertainties [7].

The intrinsic uncertainties of the atmospheric drag modeling combine with another important aspect of the reentry monitoring and prediction process. In fact, the tracking and orbit determination of reentering objects is a complex and expensive task, needing a global network for maximum effectiveness. But also the best systems currently available are not able to guarantee a complete coverage for any object of interest, and because the absolute uncertainty of a reentry prediction is roughly proportional to how old the last propagated orbit is, the desirability of having coverage holes as small as possible is quite evident.

Unfortunately, even the current configuration of the most capable system, i.e. the US Space Surveillance Network, is able to issue, before reentry, a last orbit determination with an epoch preceding the orbital decay by approximately 5 hours, on average [8]. However, this also means that, taking into account the time needed for tracking acquisition, data processing and state vector public release, the typical last orbit may become available just before reentry, or in the couple of hours immediately preceding the event. No much time might therefore be available to incorporate it in the ongoing analysis by third parties involved in the prediction process.

Going in further details, only in 20% of the cases the last issued orbits refer to the last 2 hours, or less, again in terms of orbit determination reference epoch, meaning that they can become openly available just before reentry, or immediately after. In 50% of the cases the last issued orbits refer to more than 4 hours before reentry, to more than 7 hours in 20% of the cases, to more than 10 hours in 10% of the cases, and to more than 15 hours in 5% of the cases, with quite obvious negative implications on the absolute uncertainties of the last reentry predictions released for civil protection applications [8].

3 PREDICTION UNCERTAINTY

The specific error sources directly linked to drag modeling, even when the best practices are adopted and the best data available are used, can be detailed as follows:

1. Error in the estimation of the ballistic parameter of the reentering object;
2. Uncertainty of the ballistic parameter evolution;
3. Uncertainty of the solar activity forecasts;
4. Uncertainty of the geomagnetic activity forecasts;
5. Uncertainty of the prediction, intensity and impact of solar and geomagnetic storms;
6. Atmospheric density model biases, in particular the variable components;
7. Atmospheric density model stochastic errors;
8. Thermospheric winds, in particular during major geomagnetic storms.

Apart from this, inaccurate orbit determinations can also contribute to the prediction errors, but the past experience has shown that in most cases ($> 90\%$) the available orbit determinations issued by reliable sources are reasonably accurate and the outliers can be easily identified and removed from the analysis, then strongly constraining their impact on the reentry prediction errors compared with drag modeling [7].

Recently, an extensive analysis was carried out to quantify the global impact of the above mentioned error sources, based on operational reentry prediction campaigns starting 10-15 days before orbit decay, and spanning a wide range of object types and space weather conditions [9]. In general, a relative error, in the residual lifetime, of $\pm 20\%$ includes nearly 90% of the cases, while a relative error of $\pm 30\%$ almost includes 95% of them. During the last 48 hours preceding the reentry, a relative error of $\pm 20\%$ may be not able to include 90% of the occurrences, while a relative error of $\pm 30\%$ may comprise more than 98% of the cases. Finally, during the last 24 hours, a relative error of $\pm 20\%$ is able to include more than 90% of the cases, while a relative error of $\pm 30\%$ still covers nearly 98% of them [9].

In conclusion, based on our experience, acquired over nearly four decades and many reentry campaigns, a relative prediction uncertainty of $\pm 30\%$ is highly recommended for high priority targets presenting an interest from a civil protection point of view, in order to guarantee a confidence level of at least 95% [9]. In fact, in several relevant situations, we have clearly found that targeting a confidence level of 90%, or less, is not sufficient to guarantee a smooth and efficient interaction with the national civil protection authorities and the operational peripheral entities put on alert in such cases. Last, but not least, a too low confidence level may also complicate the communications with the media and the public during the critical final days preceding the reentry.

4 BASIC CIVIL PROTECTION ASPECTS OF UNCONTROLLED REENTRIES

Uncontrolled reentries considered at "risk" are typically events with an associated global casualty expectancy between 10^{-4} and 10^{-2}. The current cumulative annual global casualty expectancy is probably $< 10^{-2}$. The corresponding individual risk is therefore extremely low, if compared with the hazards commonly faced in the everyday life, with a probability of being personally injured of less than 1 over 700 billion per year. Moreover, in more than 60 years of space activity, nobody has been harmed, so far, by an uncontrolled object reentering from orbit.

Concerning the protection of people on the ground, the very low risk associated with uncontrolled reentries of artificial objects from space is an obvious good news. Another good news is represented by the fact that the imminent reentry of artificial space objects can be very often predicted days, weeks or months before the event, an advantage not granted for some of the most devastating accidents, technological failures or natural catastrophes. However, as previously explained, in the vast majority of cases it is not possible to fix a precise reentry location and time even very close to the reentry event. In fact, due to the intrinsic physics of atmospheric satellite reentry from nearly circular orbits, by far the most frequent occurrence, the time uncertainty window cannot be reduced below a significant fraction of the residual lifetime and, due to the fast motion of the reentering objects, this translates into large along-track uncertainties, spanning one sub-satellite orbit track or more even a few hours before satellite decay.

A good representative example is provided by the reentry, in June 2016, of a 4-ton Chinese CZ-2C second stage (2012-064D), with an inclination of about 97°. Figs. 1, 2 and 3 show how the ground track uncertainty window (± 30% of the residual lifetime) shrank with the approaching reentry. Only less than one day before the event it became possible to start the progressive reliable exclusion of large areas of the Earth surface, like South America and Australia (Figs. 1 and 2). But also with the latest prediction issued by ISTI/CNR, using an orbit determination with an epoch preceding the reentry of about 6 hours, the uncertainty window still included a ground track circling the Earth 2.5 times (Fig. 3), corresponding to about 100 000 km!

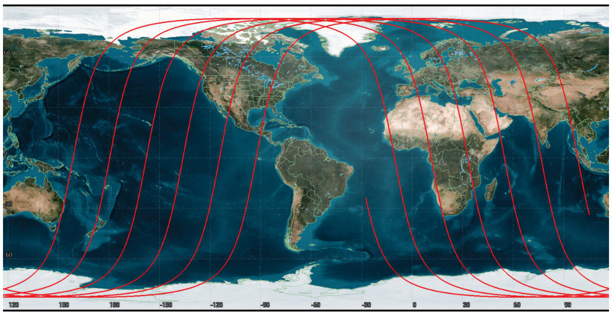

Figure 1. Ground track corresponding to the reentry uncertainty window for the object 2012-064D, estimated about 15 hours before reentry

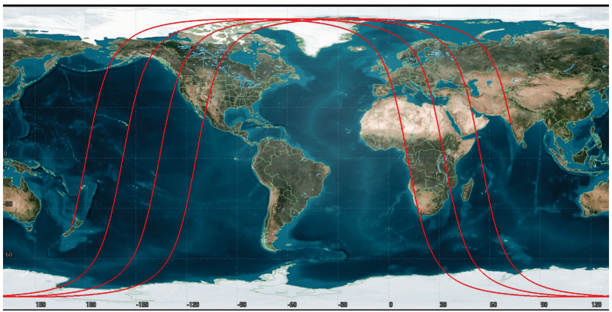

Figure 2. Ground track corresponding to the reentry uncertainty window for the object 2012-064D, estimated about 9 hours before reentry

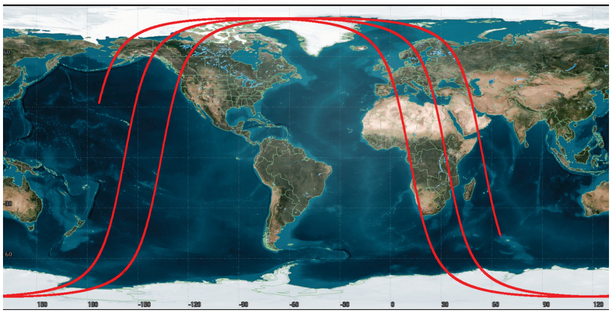

Figure 3. Ground track corresponding to the reentry uncertainty window for the object 2012-064D, estimated about 6 hours before reentry (last prediction issued)

At last, the stage reentered over the Pacific Ocean. Fig. 4 shows the final reentry predictions released by ISTI/CNR and the US Joint Space Operations Center (JSpOC), superimposed to the last ground track uncertainty window issued by ISTI/CNR (in red). The post-reentry assessments are shown as well. That from ISTI/CNR, with the ground track uncertainty in white, was based on orbit computations, while that of JSpOC was probably based on classified satellite observations.

In conclusion, from a civil protection point of view, the uncontrolled reentries of artificial space objects can be currently characterized by:

1. An extremely low individual and collective risk;
2. The impossibility, in most of the cases, of predicting the exact location and time in which the event will take place, even a few hours before its occurrence.

Therefore, taking into account these two fundamental facts, any effective procedure, product and information exchange for civil protection applications must be devised accordingly.

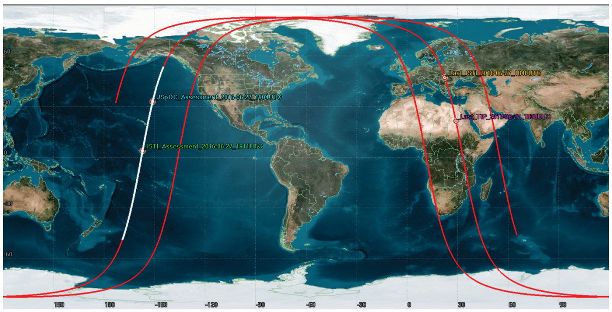

Figure 4. ISTI/CNR and JSpOC last reentry predictions, and post-reentry assessments, superimposed to the last ground track uncertainty window (in red) issued by ISTI/CNR for the object 2012-064D (the ISTI/CNR post-reentry assessment, with the uncertainty in white, was based on orbit computations, while the JSpOC assessment was probably based on classified satellite observations)

5 RELEVANT INFORMATION FOR CIVIL PROTECTION APPLICATIONS

The typical reentry prediction outputs are of no, or very limited, use for civil protection applications. As a matter of fact, the "nominal" reentry predictions, obtained with orbit propagations applying the best combination of estimated parameters and perturbation models, are absolutely useless for civil protection planning, due to their intrinsic large uncertainties, as widely discussed in this paper. The global uncertainty window provides relevant information, identifying the time interval during 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 [10].

For the same reasons, real-time fragmentation analyses, simultaneously ran with nominal reentry predictions, are clearly meaningless. In fact, being the reentry point so uncertain, there is no advantage to complicate further the operations with a time consuming task, affected as well by considerable uncertainties and unknowns. The real value of detailed fragmentation analyses, if enough information is available on the reentering object, is in performing them, once and for all, before the reentry campaign, in order to use the results for the evaluation of the global risk, and for the optimal definition of the risk time windows and affected areas for the geographical regions of interest. There is, then, no need to repeat this kind of analysis further during a campaign, either associated with nominal reentry predictions or not: to be useful, the results must be already available before the reentry campaign, not during or at the end of it.

The locations possibly at risk in a given area, for instance in Italy, cannot be identified reasonably ahead of reentry using the information coming from standard predictions. Therefore, a new approach was conceived at ISTI/CNR and applied in Italy during real reentry prediction campaigns, specifically for civil protection applications [11][12][13][14]. 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 flown over 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» [10].

Our solution of the problem consists in identifying the risk time window for each flown over 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, for instance Italy [14]. The procedure adopted at ISTI/CNR to assess the regional risk time windows for a finite area embracing Italy may start a few days before the final decay, but preferably during the last 36-48 hours (this is to focus the attention on a relatively low number of sub-satellite tracks flying over the target area), by simulating a reentry opportunity for each pass over the area of interest still included in the 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 breakup of the reentering object, obtained from a detailed fragmentation analysis, if available, or by analogy with previous similar cases, in the quite frequent eventuality that no specific information has been issued;
2. The variation of the initial conditions leading to reentries in different parts of the area considered,

along the trajectory, as well as the trajectory propagation errors.

Considering the reentry of typical spacecraft or upper stages, the amplitude of the risk time windows for Italy are around 30-40 minutes, including the potential impacts with aircraft flying in the overlying airspace up to an altitude of 18 km [10][11][12][13][14].

Finally, a cross-track safety margin, with respect to each reentry ground track for the area of interest, is estimated, 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 trajectory of the reentering object;
2. The cross-track trajectory uncertainty due to the mismodeled evolution of the orbital decay;
3. The effects of the prevailing or predicted winds in the stratosphere and troposphere.

Limiting the attention to the relevant fragments and depending on the specific nature of the reentering parent object, the cross-track safety margin may vary from ± 90 km to ± 200 km around 3-4 days before reentry, and from ± 70 km to ± 120 km during the last 24-48 hours [10][11][12][13][14].

Therefore, the volume of airspace which could be potentially crossed by the reentering debris is the region of space extending up to the relevant geodetic altitude (e.g. 18 km), centered on the reentry ground track and with a cross-track safety swath of ± 90-200 km, which may progressively drop to ± 70-120 km as the reentry is approaching.

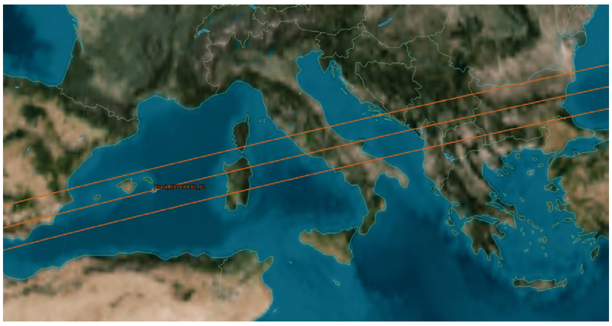

Figure 5. Potential reentry track over Italy (central line) still included in the global uncertainty window 9.5 hours before the Tiangong 1 orbital decay, with a cross-track swath of ± 100 km (the corresponding alert time window for possible debris crossing of the Italian airspace, up to 18 km, or impact on the ground, opened at 3:58 UTC and closed at 4:28 UTC on 2 April 2018)

Taking, for example, the case of Tiangong 1, Fig. 5 represents a potential risk area for Italy associated with a reentry risk window of half an hour in the early hours of 2 April 2018. This reentry opportunity was still included in the global uncertainty window about 9.5 hours before the Tiangong 1 orbital decay. The volume of space possibly affected by the debris fall extended ± 100 km perpendicularly to the sub-satellite reentry ground track, on the Earth surface, and 18 km in altitude, above the geodetic ellipsoid. The risk time window, from 3:58 to 4:28 UTC, applied to all the Italian territory and airspace included in that volume. Finally, with the last prediction issued 5 hours before the satellite decay, the reentry opportunity depicted in Fig. 5 was ruled out and most of the Italian territory, with the exception of some small islands in the middle of the Mediterranean Sea, was excluded from any residual risk [15].

6 GROUND TRACK UNCERTAINTY

Unfortunately, the huge along-track uncertainty associated with the global reentry time windows represents only one aspect of the problem of finding the locations on Earth possibly affected by the uncontrolled reentry. 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 reentry 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 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 [14].

Table 1. 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 global 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. 1).

Figure 6. Predicted sub-satellite ascending ground track over Italy of a reentering satellite in nearly circular orbit at sun-synchronous inclination

Figure 7. Eastward drift of the sub-satellite ascending ground track over Italy caused by an ascending nodal crossing anticipated by 10 minutes

Due to the fact that even 24 hours before reentry 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 several entities, during the final days preceding the reentry, not only useless for civil protection applications, but also misleading, as shown in Figs. 6, 7 and 8. Typically, only the ground track plots propagated less than 12 hours before reentry 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 that described in the previous section.

Figure 8. Westward drift of the sub-satellite ascending ground track over Italy caused by an ascending nodal crossing delayed by 10 minutes

7 STANDARD INFORMATION ISSUED DURING REENTRY CAMPAIGNS

The cooperation between the Italian National Research Council (CNR), through its CNUCE (up to 2002) and ISTI (since 2002) Institutes in Pisa, and the Italian civil protection authorities has a long history, started in 1979, with the uncontrolled reentry of Skylab. Since then, all the reentry prediction campaigns with civil protection involvement up to 2018, including the nuclear alerts of Cosmos 1402 (1983) and Cosmos 1900 (1988), and the reentry of the Salyut 7 space station with the heavy module Cosmos 1686 attached, were carried out in Italy by the CNR in Pisa.

Based on nearly 40 years of experience, the quality of the information relevant for civil protection applications has reached, from our point of view, a good and effective level of development. During a reentry campaign, the information bulletins issued by the Space

Flight Dynamics Laboratory of ISTI/CNR, compiled for the Italian Space Agency (ASI) and the Civil Protection Department of the Italian Presidency of the Council of Ministers, contain:

1. The main physical characteristics of the reentering object;
2. Information regarding the class of risk, in terms of global casualty expectancy and latitude band flown over by the object;
3. The characterization of the risk, if mechanical (impact), chemical, nuclear, or a combination of them;
4. The orbital parameters of the object based on the last orbit determination available;
5. The evolution of the situation since the previous bulletin, regarding the status of the object, for instance its attitude, and the solar-terrestrial environmental conditions affecting the atmospheric density;
6. The last nominal reentry prediction at a conventional reference altitude, for instance 80 km;
7. The amplitude of the global uncertainty window, as a function of the selected confidence level;
8. The associated sub-satellite ground tracks;
9. The salient facts concerning the fragmentation of the object during the reentry;
10. The risk time windows for the Italian territory and the overlying airspace still included in the global uncertainty window;
11. The corresponding risk ground tracks with the associated safety swaths intersecting the Italian territory.

The information related to the list items from 1 to 7 can be included in the bulletins since the beginning of the campaign, typically from 1 to 2 weeks before reentry. Regarding the fragmentation details, the relevant information is provided as soon as available, if coming from external sources, or during the last week, if deduced from internal analysis. Finally, the information about the items 8, 10 and 11 can generally be issued in the last 36-72 hours.

Specifically for civil protection applications, when the potential risk reentry tracks for Italy are identified and computed, a file with the geodetic coordinates (latitude and longitude) for each risk reentry track and corresponding time window is generated for the Italian territory and issued to the national authorities. The coordinates file has a header containing the following information:

1. Title, with the track identification and the version number (in fact, tracks may be updated approaching the reentry time);
2. Geodetic coordinate system (e.g. WGS-84);
3. The indication of the geographic area (mainly Italy, in our case);
4. Type of risk (for instance, falling debris crossing the altitude range from 18 km to the ground);
5. Recommended cross-track safety swath amplitude (typically from ± 90 km to ± 200 km around 3-4 days before reentry, and from ± 70 km to ± 120 km during the last 24-48 hours);
6. Start of the risk time window (UTC);
7. End of the risk time window (UTC).

Often, after the reentry, a final bulletin is issued with the best post-event estimates of the reentry area, using the last available orbit determinations, and sometimes including a characterization of the event as well, if eyewitness accounts are available and/or fragments are recovered on the ground.

8 COMMON PROBLEMS AND CRITICALITIES

During the reentry campaigns carried out in Pisa for the Italian civil protection authorities over the last four decades, some problems, of varying criticality, manifested themselves in several occasions. It should be however remarked that a lot of improvement was attained during the last twenty years, with the adoption of tailored products and outputs [10][12][13][14], leading to a better understanding and practical applicability of the results issued by ISTI/CNR, compared with standard reentry predictions.

Among the problems still met, even sporadically, the following can be listed:

1. Long orbit determination gaps during the last 48 hours before reentry;
2. Lack of direct communication in critical moments between the technical structure set up at the Department of Civil Protection and the personnel involved in operational reentry predictions;
3. The availability, at government level, of (apparently) conflicting results coming from different sources, leading to confusion and wrong conclusions.

The first problem derives from the fact that even global space surveillance networks have coverage holes, and if these holes occur in the wrong place and time relative to a potential risk reentry over Italy, further progress may not be possible for many hours regarding a reduction of the uncertainty window and the possible exclusion of our country from any residual hazard. This kind of problem, occurred several times at critical moments in the past, cannot be solved by Italy alone, requiring a substantial international cooperation. However, the ongoing national activities aiming at acquiring an independent orbit determination capability – already proposed and discussed at the beginning of the 1990s – are certainly a move in the right direction [15].

The second problem might be solved quite easily. During the final phases of a reentry campaign, with the excited overlapping of information from different sources and the multiple requests coming from various subjects, a focused direct communication between the technical structure set up at the Department of Civil Protection and the CNR personnel involved directly in operational reentry predictions could save a lot of time, avoid confusion and provide immediate answers to any question or doubt.

A direct communication link might also easily solve the problems encountered when the Department of Civil Protection receives (apparently) conflicting information coming from different sources, for instance foreign organizations or governments, but also news agencies around the world. In some cases the information is just false or inaccurate (e.g. fake reentry accounts), but in others the problem is just created by a data misinterpretation from personnel not familiar with orbital dynamics and reentry predictions. In both situations, a prompt and direct contact with the CNR personnel involved directly in the reentry predictions would again be quite effective in dispelling any doubt in most of the occurrences.

In any case, the use of information coming from different sources requires a lot of care, as well as the timely advice of experts familiar with uncontrolled reentry predictions, in order to clarify any true or apparent discrepancy among the available data. If conflicting information occurs, either apparent or not, no operational decision or press release should be made before having first explained the inconsistency or the disagreement.

9 DEFINITION OF POTENTIALLY DANGEROUS REENTRIES

During the last decades there was a growing consensus at international level in considering a casualty expectancy of 10^{-4} as the risk threshold for assuming an uncontrolled reentry at risk or not. However, the risk evaluation is left to the object owner/operator and only in very few cases there is an open disclosure of the expected casualty expectancy before the uncontrolled reentry of a spacecraft or upper stage. Moreover, if this were the case, a quite frequent violation of the risk threshold should be probably expected, may be once a week, or at least once a month.

This situation is clearly unsatisfactory. On one side, intact objects frequently reenter without an open disclosure of the expected casualty risk, but, on the other side, the accepted threshold might be violated so often to request, if openly disclosed, a status of permanent reentry alert, with a heavy load on the scarce human and facility resources available, an unacceptable commitment by civil protection personnel, given the very low risk levels, and the unavoidable addiction of the media and the public. A reasonable compromise could be maintaining the 10^{-4} threshold as a design and mitigation guideline for space systems, but assuming instead a casualty expectancy of 10^{-3}, or more, for triggering a reentry prediction campaign for civil protection purposes.

Even so, however, the lack of casualty expectancy estimations could not be solved in most of the cases. A possible way to get around this problem might be using the dry mass of a reentering object as an indirect indicator of casualty risk, which is certainly plausible, from a statistical point of view, when the hazard derives from the ground impact of fragments. Moreover, mass is generally the best known parameter for space objects, depending on the operational orbit and the launcher performance.

Table 2. ISTI/CNR uncontrolled reentry magnitude scale and alert color code definition

Dry mass M_0 of the reentering object [kg]	**Reentry magnitude M_R**	**Associated casualty expectancy E_c (order of magnitude)**
$M_0 \leq 50$	$M_R < 0$	$E_c < 10^{-5}$
$50 < M_0 \leq 500$	$0 \leq M_R < 1$	$10^{-5} \leq E_c < 10^{-4}$
$500 < M_0 \leq 5\,000$	$1 \leq M_R < 2$	$10^{-4} \leq E_c < 10^{-3}$
$5\,000 < M_0 \leq 50\,000$	$2 \leq M_R < 3$	$10^{-3} \leq E_c < 10^{-2}$
$50\,000 < M_0 \leq 500\,000$	$3 \leq M_R < 4$	$10^{-2} \leq E_c < 10^{-1}$
$500\,000 < M_0 \leq 5 \times 10^6$	$4 \leq M_R < 5$	$10^{-1} \leq E_c < 1$

In Pisa, we introduced a ranking approach based on the reentering dry mass (M_0), but not only, since 1995 [16]. In 2017, the definition of the "magnitude" M_R of uncontrolled reentries was slightly modified as follows [7]:

$$M_R = \log_{10} (M_0 \text{ [kg]} / 100) + 0.3. \quad (1)$$

This definition can be used to evaluate roughly the order of magnitude of the global casualty expectancy E_C for nearly circular orbits using the following simplified relationship:

$$E_C \sim 10^{M_R - 5}. \quad (2)$$

The reentry magnitude scale defined by Eq. 1 is detailed in Tab. 2 as a function of the reentering dry mass, together with the order of magnitude of the casualty expectancy evaluated by means of Eq. 2 and the associated ISTI/CNR alert color code. According to these definitions, we propose that an uncontrolled reentry could be declared relevant, from a civil protection point of view, either if $M_0 > 5000$ kg and $M_R \geq 2$, or if $E_C \geq 10^{-3}$ in the cases in which this latter information is directly available from other reliable sources using the results of detailed fragmentation analyses.

According to the currently adopted definitions of the total casualty area, it might also be introduced a different treatment of spacecraft and upper stages, assuming a greater casualty expectancy for the former ones, if the mass is the same, because the latter are typically made of less structural components, even if generally larger [17]. However, this may be tricky, because the large majority of the uncontrolled reentry events currently leading to the recovery of fragments on the ground are actually linked to rocket bodies [3][6].

Special attention and a case by case analysis would, of course, be needed if the main risk of an uncontrolled reentry does not derive from the impact of fragments on the ground, but from the presence on board of chemical or radioactive toxic substances capable of producing a significant contamination. In such circumstances, the reentering dry mass is only part of the problem and tailored approaches should be used to estimate the casualty expectancy.

10 OPEN ISSUES

Based on the previous discussion, four are the main "policy" open points concerning the uncontrolled reentry of a space object relevant from a civil protection point of view:

1. The selection of a reasonable alert threshold for the global and/or national casualty expectancy, the exceeding of which would lead to the set up and execution of a dedicated reentry campaign;
2. Which sources to consider reliable for the calculation of the casualty expectancy and which alternative criteria to adopt if this information is unavailable;
3. Who declares the opening of a reentry campaign;
4. Who decides the closure of a campaign and based on which criteria.

The first two issues were already discussed in the previous section, at least partially. Concerning the third one, so far the opening of a campaign for civil protection was a spontaneous process, not based on independently agreed procedures, rather following an unsolicited suggestion by some national experts, the news, or what others were doing in other countries. This situation is obviously unsatisfactory and should be overcome in the future.

The closure of a campaign still represents an open issue as well. Of course, all the campaigns carried out in the past were closed at a certain point, but no standard procedure was adopted. Eyewitness sightings sometimes occur, but the information may take hours or days to emerge. The same applies to the eventual recovery of debris on the ground. In some cases the reentry is confirmed by the object "no-show" on a predicted pass over a radar, optical or visual observer's site. However, in most cases, the reentry is confirmed only by global military sensor networks, extrapolating the last tracking data available, or resorting to classified information, as the infrared observations of the American satellites used to detect worldwide the launch of ballistic missiles. This information can be issued very fast, after several hours, or even after days, and in around 10% of the cases there can be significant, and often inexplicable, discrepancies among the post-event observations/assessments issued by different organizations.

It would therefore be desirable to devise a campaign closing procedure applicable at least to Italy, when the civil protection authorities are included in the loop. This need is particularly felt when the national territory remains included in the uncertainty window until the reentry actually occurs. In such situations, the lack of reliable reentry reports in the country within a given time interval from the regional risk windows might be used to terminate the national alert status, but no easy and general solution is at hand, also due to the unavoidable proliferation of false alarms or fake news around events which receive a lot of worldwide media attention. In fact, as demonstrated, for instance, by the uncontrolled reentry of the BeppoSAX spacecraft, in 2003, three further days after the decay of the Italian satellite were needed for a detailed debunking of all the fake or inaccurate reentry reports coming from Ecuador and Malaysia.

11 LEGAL AND LIABILITY PROBLEMS

In Italy, a further critical aspect, whose importance has increased considerably during the last decade, is the growing involvement of the judiciary in the assessment of technical-scientific forecasts of extremely complex natural events, either inherently unpredictable, such as earthquakes [18], or affected by significant levels of uncertainty, like meteorological phenomena and their possible consequences. To further complicate the situation, there is the total lack of homogeneity in the accusations formulated by the judges, which can oscillate from "procured alarm", if on the basis of certain forecasts a precautionary warning is proclaimed, but then nothing serious happens, to "culpable disaster", if an event causes damage and casualties, but has not been foreseen, or was foreseen in a different area, or of a lighter strength.

A paradigmatic case was represented by the trials following the tragic earthquake that in 2009 hit the Italian town of L'Aquila, causing more than 300 deaths, about 50 000 homeless and some tens of billions of euro of damages. By 2010, local prosecutors and judges pressed forward with civil and criminal proceedings against the head and deputy of the Civil Protection Department, and three seismologists, a volcanologist and two seismic engineers of the National Commission for the Forecast and Prevention of Major Risks, an official government advisory committee including renowned experts in several relevant fields.

A reconstruction of the trials, which went through three degrees of judgment, and of the prosecutors and judges arguments, is obviously outside the scope of this paper. The deputy head of the Civil Protection Department and the six scientists were initially sentenced to six years of jail for "involuntary multiple manslaughter", but at the end of the long legal process, in 2015, the six scientists were acquitted, while the deputy head of the Civil Protection Department remained convicted with a reduced jail term of two years for the reassuring public declarations issued before the earthquake. Then, in 2016, also the head of the Civil Protection Department was finally acquitted in a separate trial, ending a seven-year legal saga.

During and after this sad story, a lot of effort has been fielded by prosecutors, judges and many analysts to point out that the trials were not about science, i.e. on the predictability of earthquakes, but about errors in communication. However, this is a deeply flawed argumentation. In fact, the "unjustifiably reassuring" character of the statements issued "before" the quake could be ascertained as such only "after" the quake, i.e. after the occurrence of an event that both the prosecutors and the judges recognized as "unpredictable". Therefore, the attribution of responsibility for releasing statements which could have prevented the individual adoption of simple precautionary measures, such as sleeping outdoors, to face an unpredictable event that could have happened after a day, a month or 1000 years, clearly links the claimed communication fault with the status of the earthquake prediction science, and the current inability to make reliable predictions [18] to a post-event liability.

The negative consequences of these judicial disputes and attitudes cannot be underestimated. The activity of the National Commission for the Forecast and Prevention of Major Risks was since then heavily hampered, because the risk of legal consequences limits, of course, the ability to scientifically evaluate and express motivated assessments on natural events characterized by considerable uncertainties. Even contrasting the alarmist claims by charlatans and incompetents becomes much more difficult and delicate.

This was precisely the case that led to the L'Aquila story. In fact, the "offending" meeting of the National Commission for the Forecast and Prevention of Major Risks, which resulted in the seven-year legal saga, had been convened just to deny the widely advertised claims of a laboratory technician, not belonging to the geophysical science community, who had predicted a strong earthquake in Sulmona, a small town about 50 km from L'Aquila, after measuring increased levels of radon released by the ground. The use of radon emissions had been investigated as possible earthquake precursor since the 1970s, but at the end also this line of research had proved itself useless for predicting earthquakes, leading to inconsistent results [18]. However, the more than legitimate attempt of debunking an alarmist claim regarding a different town, and based on a rationale and method not supported by decades of scientific research, backfired on the commission when the totally unrelated event in L'Aquila occurred, following a seismic swarm quite common in Italy and unfortunately not usable to predict the occurrence of large earthquakes.

Another consequence, further stimulated by other legal proceedings dealing with extreme meteorological events, is that currently we are experiencing weather and/or hydro-geological alerts, of "yellow" condition or higher, practically every week, somewhere in Italy. These kinds of alerts obviously imply the set up of specific procedures, precautionary measures and personnel activation by local administrations, with a not negligible cost. It is useless to say that only in a minimum part of the cases critical situations materialize, and often the population becomes so addicted to the frequent alerts to be caught completely unprepared when something serious really occurs, sometimes with tragic outcomes.

The previous discussion is, of course, quite relevant for the reentry predictions as well. Even though the probability of having victims and property damage in Italy is extremely low, if that were to happen, the intervention of the judiciary would be inevitable. Again, the prediction process is affected by considerable and intrinsic uncertainties, even though the situation is comparable or better with respect to weather forecasts, and absolutely more favorable compared to earthquakes. Anyway, the information issued to the civil protection authorities and the communications to the general public remain extremely critical and sensitive, and must be managed with care.

One immediate repercussion of the legal and liability problems is the adoption of very conservative and prudent estimates for the reentry uncertainty windows and the areas of the country possibly affected by debris impact. As a result, a confidence level higher than 95% is now currently targeted with the definition of the uncertainty windows issued to civil protection authorities, and further extensions are possible, close to the reentry, if a decay opportunity over Italy falls just outside the limits of the window. A similar conservative approach is adopted regarding the possible cross-track dispersion of the fragments around the nominal reentry trajectory.

Of course, based on our experience, it would be impossible to provide meaningful reentry predictions and remain, at the same time, 100% safe on the legal and liability front. However, we think that over the years we obtained substantial progress in this direction, acting simultaneously both on the technical and communication sides of the problem.

12 CONCLUSIONS

Since our first involvements in reentry prediction campaigns of objects characterized by higher than average "media visibility" and casualty risk, as the nuclear powered Cosmos 1402, in 1983, and the space station Salyut 7, in 1991, we became aware of the very specific problems and the psychological pressure created by the interaction with the national civil protection authorities during real operations. This is the reason why we spent so many efforts in trying to understand their requests and needs, trying to convert the physical and engineering information, analyses and results in formats and products easy to understand and unambiguous, to the maximum extent as possible, for people with a technical background, but lacking a particular preparation in space engineering, orbital dynamics and reentry physics.

At the same time, similar attention was paid to providing clear and accurate information to the media and the public. Being both clear and accurate is not easy, indeed it is very complicated, but this task deserves every effort, not only as a service to the citizens and the taxpayers, but also to prevent legal and liability problems.

Much work remains to be done and other progresses and improvements can certainly be achieved, but the results already obtained in these directions are certainly satisfactory and have greatly improved the situation compared to forty years ago, when the involvement of our laboratory on these issues began.

13 ACKNOWLEDGMENTS

The research described in this paper was partially supported by the Italian Space Agency (ASI) order to ISTI/CNR issued, on 19 September 2018, in the framework of the H2020 Project 2-3S5T2016-17, Grant Agreement n. 785257.

14 REFERENCES

1. Pardini, C. & Anselmo, L. (2013). Re-entry Predictions for Uncontrolled Satellites: Results and Challenges. In *Proc. 6th IAASS Conference "Safety is Not an Option"* (Ed. L. Ouwehand), ESA SP-715 (CD-ROM), ESA Communications, European Space Agency, Noordwijk, The Netherlands.

2. Pardini, C. & Anselmo, L. (2018). Uncontrolled Reentries of Massive Space Objects. In *4th International Space Debris Re-entry Workshop*, ESA/ESOC, Darmstadt, Germany.

3. Pardini, C. & Anselmo, L. (2018). Uncontrolled Re-entries of Sizable Spacecraft and Rocket Bodies: A Potential Threat in the Airspace and on the Ground. In *42nd COSPAR Scientific Assembly*, Presentation PEDAS.1-0012-18, Pasadena, California, USA.

4. Angelo, J.A. Jr. & Buden, D. (1985). *Space Nuclear Power*, Orbit Book Company, Malabar, Florida, USA.

5. Pardini, C. & Anselmo, L. (2009). USA-193 Decay Predictions with Public Domain Trajectory Data and Assessment of the Post-intercept Orbital Debris Cloud. *Acta Astronautica* **64**, 787-795.

6. Pardini, C. & Anselmo, L. (2018). Uncontrolled Re-entries of Spacecraft and Rocket Bodies: A Statistical Overview over the Last Decade. Submitted to the *Journal of Space Safety Engineering* (Ref: JSSE_2018_22, December 5).

7. Anselmo, L. & Pardini, C. (2018). *Uncontrolled Re-entries: Characterization, Monitoring, Predictions and Operational Procedures for Civil Protection Applications*, ISTI/CNR, Pisa, Italy.

8. Pardini, C. & Anselmo, L. (2016). The Uncontrolled Reentry of Progress-M 27M. *Journal of Space Safety Engineering* **3**, 117-126.

9. Pardini, C. & Anselmo, L. (2018). Assessing the Risk and the Uncertainty Affecting the Uncontrolled Re-entry of Manmade Space Objects. *Journal of Space Safety Engineering* **5**, 46-62.

10. Pardini, C. & Anselmo, L. (2018). Reentry Predictions of Potentially Dangerous Uncontrolled Satellites: Challenges and Civil Protection Applications. In *Stardust Final Conference: Advances in Asteroids and Space Debris Engineering and Science* (Eds. M. Vasile, E. Minisci, L. Summerer & P. McGinty), Astrophysics and Space Science Proceedings, Vol. 52, Springer International Publishing AG, Switzerland, pp265-282.

11. Anselmo, L. (2003). Risk Analysis and Management of the BeppoSAX Reentry, *ISTI Technical Report* 2003-TR-23, ISTI Institute, CNR, Pisa, Italy.

12. Anselmo, L. & Pardini, C. (2005). Computational Methods for Reentry Trajectories and Risk Assessment. *Advances in Space Research* **35**, 1343-1352.

13. Anselmo, L. & Pardini, C. (2013). Satellite Reentry Predictions for the Italian Civil Protection Authorities. *Acta Astronautica* **87**, 163-181.

14. Pardini, C. & Anselmo, L. (2015). Satellite Re-entry Prediction Products for Civil Protection Applications. In *Proc. 7th IAASS Conference "Space Safety is No Accident"* (Eds. T. Sgobba & I.

Rongier), Springer International Publishing, Switzerland, pp453-462.

15. Vellutini, E. & al. (2018). Monitoring the Final Orbital Decay and the Re-entry of Tiangong-1 with the Italian SST Ground Sensor Network. In *Proc. 69th International Astronautical Congress*, Paper IAC-18-A6.7.7, Bremen, Germany.

16. Anselmo, L. & Pardini, C. (2002). The Management of the Mir Reentry in Italy. In *Proc. International Workshop on Mir Deorbit* (Ed. W. Flury), ESA SP-498, European Space Agency, Darmstadt, Germany, pp83-90.

17. Wilde, P.D. & Ailor, W. (Eds.) (2013). Re-entry Operations Safety. In *Safety Design for Space Operations* (Eds. T. Sgobba, F.A. Allahdadi, I. Rongier & P.D. Wilde), Elsevier Ltd., United Kingdom, pp603-794.

18. Hough, S.E. (2016). *Predicting the Unpredictable: The Tumultuous Science of Earthquake Prediction*, Princeton University Press, Princeton, New Jersey, USA.