Acta Astronautica 219 (2024) 662–669

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

On the need to assess and mitigate the risk from uncontrolled re-entries of artificial space objects in view of the current and future developments in space activities

Carmen Pardini *, Luciano Anselmo

Space Flight Dynamics Laboratory, Institute of Information Science and Technologies (ISTI), National Research Council (CNR), Via G. Moruzzi 1, 56124, Pisa, Italy

ARTICLE INFO

Keywords:
Uncontrolled re-entries
Re-entry risk
Casualty expectancy
Casualty probability
Orbital stages
Spacecraft

ABSTRACT

From 1 January 2010 to 24 August 2023, 566 orbital stages and 511 spacecraft with a radar cross section >1 m^2 have re-entered without control the Earth's atmosphere. The total returned mass was 1650 metric tons, corresponding to a mean of 115 metric tons per year. 77% of the mass belonged to orbital stages, 23% to spacecraft. The uncontrolled re-entries of orbital stages are currently dominated by China, accounting for more than half of the decaying mass, while for spacecraft 2/3 of the mass belongs to American satellites. 60% of the re-entries occurred within 2 years of the launch. The ground casualty expectancy due to orbital stages was always predominant over that from spacecraft, by an average factor of nearly three. From 2010 to 2018, the total casualty probability remained substantially stable, with a mean annual value just over 1%. Since 2019, instead, the annual casualty probability of both spacecraft and orbital stages progressively increased, reaching a total value of around 3% in 2022 and 2023 (extrapolated). Even assuming a stable launch activity, in the coming years, when many of the recently launched spacecraft will start to re-enter, the casualty expectancy of orbital stages will remain basically the same, while that of spacecraft might progressively increase by a factor of 20. This would lead to an annual casualty probability of about 20%, even more in case of a further growth in launch activity, very likely based on current forecasts. The quick implementation of widespread and effective mitigation measures, like controlled de-orbiting and design for demise, is therefore necessary, to prevent the situation from deteriorating too much.

1. Introduction

Since 2005, when a 44-year low (52) was hit, orbital launches have progressively increased again, stimulated by private actors, new space powers (China and India), emerging countries, and the transition to multi-object payloads and large satellite constellations. Since 2021, all records from the 1960s, 1970s and 1980s have been broken and the number of operational satellites is expected to increase tenfold over the next decade. This sustained level of space activity, even if constrained at the current level (~200 orbital launches and ~2000 satellites per year), might lead – among other things – to an increase of the risk on the Earth due to uncontrolled re-entering space objects, both spacecraft and orbital stages.

As far as we know, the re-entry of fragments from decaying orbital objects has fortunately not caused any casualties so far. But even if the present risk from uncontrolled re-entries is still relatively small, compared with all other hazards faced in everyday life, such risk was found to slightly grow during the last five years, and it might still increase substantially in the near future, due to the current trends in space activities.

Following up on the analyses carried out over the past decade [1–12], the statistics and ground casualty risk of uncontrolled re-entries of large spacecraft and orbital stages were revisited, updated and extended in this paper, by covering the period from the beginning of January 2010 to 24 August 2023 (13.6 years). The re-entries were characterized in terms of number, mass and estimated casualty risk on ground, also including the country of origin of the decaying objects.

The revised analysis was carried out to assess how the re-entry risk has evolved since 2010, when the so-called "new space economy" was still to come, and to estimate how this risk might evolve in the near future, marked by a level of space activity never seen before. Recommendations drawn from the results presented will then conclude the

* Corresponding author.
E-mail addresses: carmen.pardini@isti.cnr.it (C. Pardini), luciano.anselmo@isti.cnr.it (L. Anselmo).

https://doi.org/10.1016/j.actaastro.2024.03.057
Received 15 November 2023; Received in revised form 5 February 2024; Accepted 28 March 2024
Available online 29 March 2024

paper.

2. Uncontrolled re-entries: Numbers and masses

In this paper the attention was focused on the spacecraft and orbital stages classified as "large" (i.e. with a radar cross section >1 m^2) by the 18th US Space Control Squadron. From 1 January 2010 to 24 August 2023, 566 orbital stages and 511 spacecraft (1077 in total) have re-entered without control the Earth's atmosphere.[1] The total returned mass was 1650 metric tons, corresponding to the re-entry of 115 metric tons per year, on average.[2] 77% of this mass belonged to orbital stages, with an annual average of 89 metric tons, while the remaining 23% to spacecraft, with an annual average of 26 metric tons.

Fig. 1 shows the annual number of uncontrolled re-entries of large spacecraft and orbital stages, while Fig. 2 shows the corresponding masses. The main feature of Fig. 1 is the significant increase of the number of uncontrolled re-entries of large spacecraft observed since 2018. The mean annual increase, by almost 7 times, was mainly due to constellation satellites, typically smaller and lighter than the average "large" spacecraft of the pre-mega-constellation era, so the corresponding mean annual growth of the re-entering mass was limited to 45%, that is to about 10 metric tons per year.

The uncontrolled re-entries of orbital stages, on the other hand, did not increase very much in numerical terms (less than 30% as annual average), also for the widespread adoption of controlled de-orbiting, in particular by the Falcon 9 second stage, but the corresponding mass re-entering uncontrolled each year grew by an average of 46%, that is 35 metric tons, since 2018 (Fig. 2), due to the increasing number of orbital launches and to the growing fraction of massive Chinese rocket bodies (see Section 3).

In summary, from 2010 to 2017, large orbital stages re-entered uncontrolled three times more often than large spacecraft, but since 2018 the situation has reversed, with the uncontrolled re-entries of large spacecraft prevailing by 55%. However, concerning the corresponding re-entering mass, the dominance of large orbital stages was unaffected since 2010, steadily prevailing by more than three times over large spacecraft.

3. Uncontrolled re-entries per country

Of course, not all countries contribute to the problem in the same way and, as might have been expected, it is the major space powers that have the greatest impact.

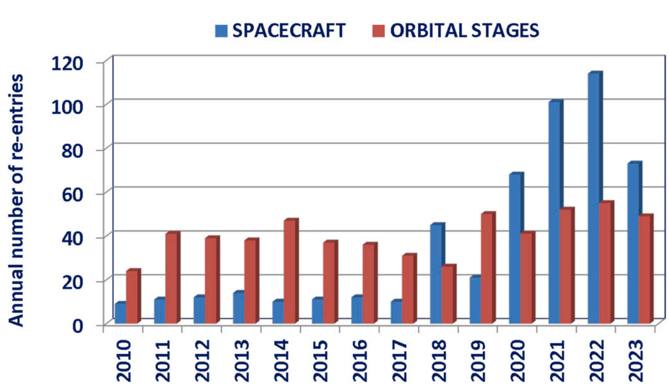

Fig. 1. Annual number of uncontrolled re-entries of large spacecraft and orbital stages, from 1 January 2010 to 24 August 2023.

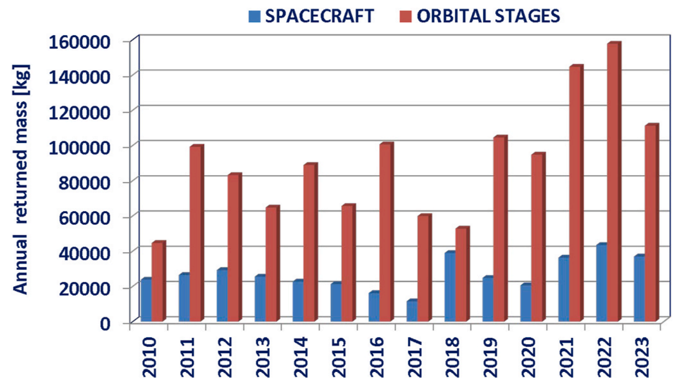

Fig. 2. Large spacecraft and orbital stages mass (kg) re-entered uncontrolled from 1 January 2010 to 24 August 2023.

3.1. Uncontrolled re-entries of large orbital stages

Starting from the largest source of uncontrolled re-entry mass, i.e. orbital stages, the scene is dominated by just three players, accounting for about 90% of the total number (Figs. 3 and 4) and mass (Figs. 5 and 6): China (PRC), the countries of the former Soviet Union (CIS) – mainly Russia and, to a lesser extent, Ukraine – and the United States (US). India (IND), France (FR) and Japan (JPN) account for another 9%, while Iran (IRAN), Israel (ISRA) and North Korea (NKOR) contribute to the remaining 1%.

Focusing the attention on the key players, Fig. 7 shows how the number of uncontrolled re-entries of large orbital stages evolved since 2010, while Fig. 8 does the same for the mass. Both plots highlight China's rapid rise, the slow decline of Russia (CIS) and the slight increase of the US contribution. Since 2019, China has largely prevailed in the uncontrolled re-entry of large orbital stages, crossing the threshold of 100 metric tons in 2022. Chinese rocket bodies accounted for 43% of the mass of orbital stages re-entered uncontrolled during the period considered, from 1 January 2010 to 24 August 2023, followed by CIS (34%), by the US (15%), and by India, France and Japan (8% in total), as shown in Figs. 6 and 9.

Narrowing the focus to what has happened from 2018 onward, the Chinese percentage has grown to 55%, followed by CIS (22% and declining), the US (15% and stable), India (5%), Japan (2%) and France (1%), as shown in Fig. 10. No re-entry of Iran's orbital stages was recorded in this time frame, while one light orbital stage re-entered both for Israel (170 kg) and North Korea (50 kg).

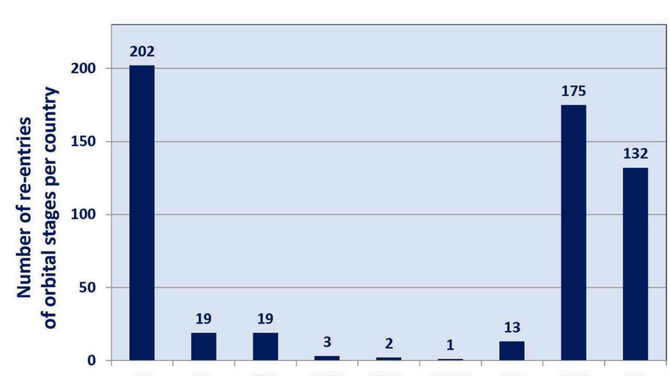

Fig. 3. Number of uncontrolled re-entries of large orbital stages per country, from 1 January 2010 to 24 August 2023.

[1] These numbers were estimated using the database of the US Space-Tack organization at https://www.space-track.org.

[2] The main source of mass data was the ESA's DISCOS database at https://discosweb.esoc.esa.int/.

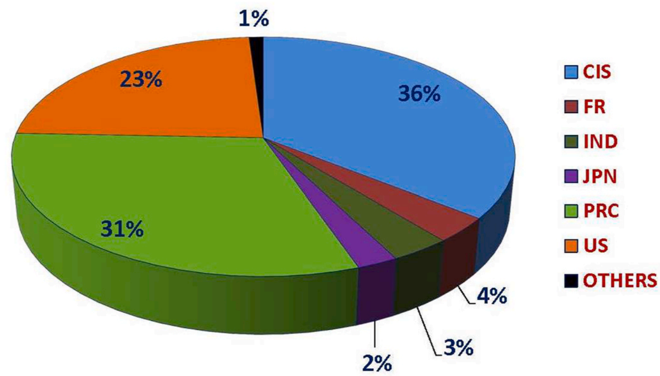

Fig. 4. Fractional contribution – by country – to the number of uncontrolled re-entries of large orbital stages, from 1 January 2010 to 24 August 2023.

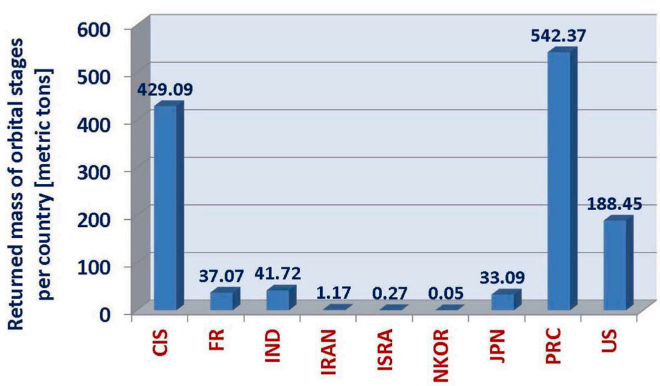

Fig. 5. Returned mass (metric tons) per country, associated with large orbital stages, from 1 January 2010 to 24 August 2023.

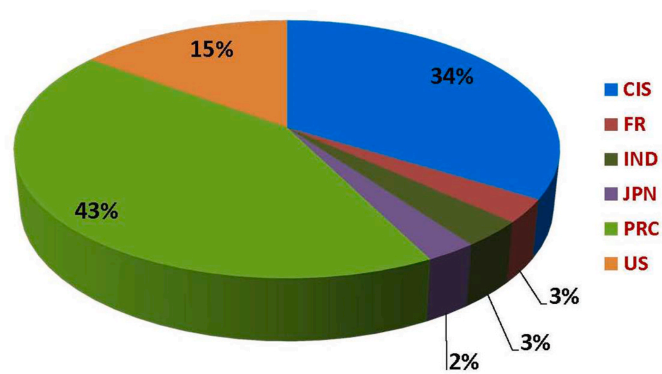

Fig. 6. Fractional contribution – by country – to the mass of uncontrolled re-entries of large orbital stages, from 1 January 2010 to 24 August 2023.

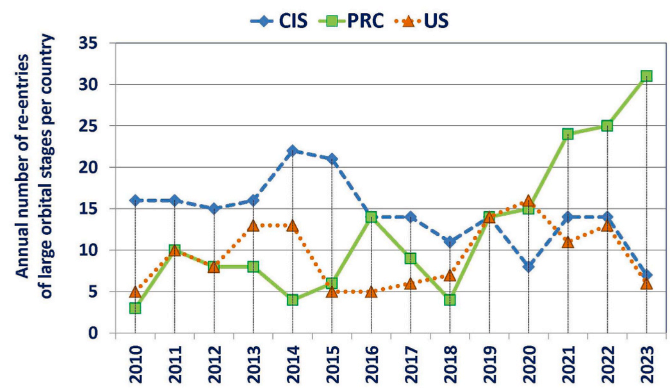

Fig. 7. Annual number of uncontrolled re-entries of large orbital stages due to the three main players, from 1 January 2010 to 24 August 2023.

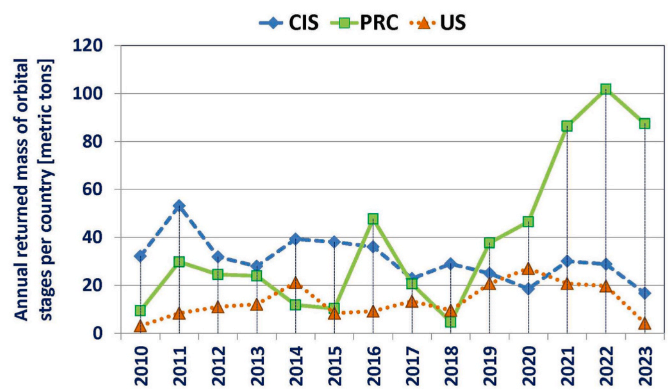

Fig. 8. Mass (metric tons) of large orbital stages re-entered uncontrolled from 1 January 2010 to 24 August 2023, due to the three main players.

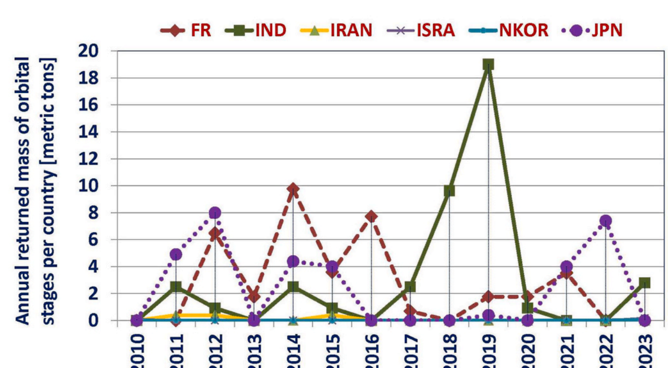

Fig. 9. Mass (metric tons) of large orbital stages re-entered uncontrolled from 1 January 2010 to 24 August 2023, due to the rest of the world.

3.2. Uncontrolled re-entries of large spacecraft

Switching the attention to large spacecraft re-entering without control, again the scene is dominated by just three players, accounting for about 95% of the total number (Figs. 11 and 12) and mass (Figs. 13 and 14), that is the United States, CIS and China. The remaining 5% is instead associated with spacecraft from Japan (JPN), India (IND), Germany (GER), European Space Agency (ESA), Indonesia (INDO), South Africa (SAFR), Taiwan (TWN), New Zealand (NZ) and Argentina (ARGN), in order of decreasing returned mass.

Fig. 15 shows how the number of uncontrolled re-entries of large spacecraft, from the three main players (US, CIS and PRC), evolved since 2010, while Fig. 16 does the same for the mass. Both plots highlight the sudden rise of re-entries of US spacecraft, linked to the operation of satellite constellations and dominating all other number and mass contributions since 2018. Regarding the numbers, those of CIS and China remained roughly stable during the period considered, while for the mass it was again roughly stable for China and declining for CIS.

From the beginning of 2010 to the first eight months of 2023, the large American satellites accounted for 43% of the spacecraft mass re-entered uncontrolled, nearly matched by the CIS satellites with 42%. Well behind China in third place, with 9%. However, considering what has occurred since 2018, the American percentage has grown to 67%, that of CIS has decreased to 19%, that of China has remained basically

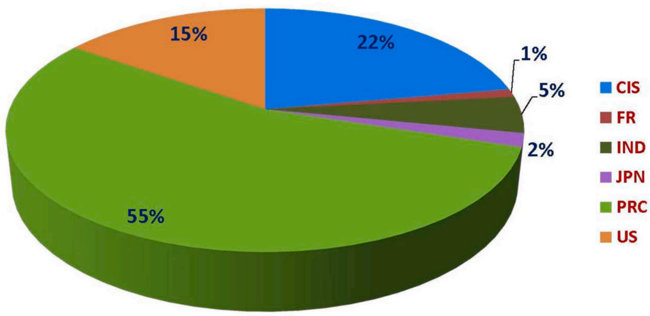

Fig. 10. Fractional contribution – by country – to the mass of uncontrolled re-entries of large orbital stages, from 1 January 2018 to 24 August 2023.

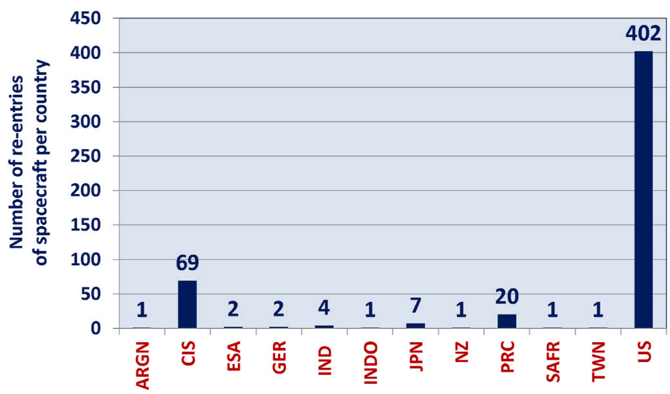

Fig. 11. Number of uncontrolled re-entries of large spacecraft per country, from 1 January 2010 to 24 August 2023.

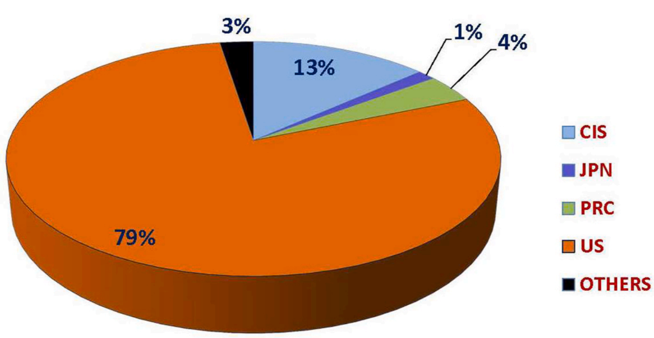

Fig. 12. Fractional contribution – by country – to the number of uncontrolled re-entries of large spacecraft, from 1 January 2010 to 24 August 2023.

stable at 8%, while India has attained 3% (Fig. 17).

3.3. Synopsis on uncontrolled re-entries of large intact objects

In summary, the uncontrolled re-entries of large orbital stages are currently dominated by China, accounting for more than half of the decaying mass, while for large spacecraft 2/3 of the mass belongs to American satellites.

4. Distribution of uncontrolled re-entries in terms of the launch elapsed time

Once the launch has occurred, after how long does uncontrolled re-entry occur?

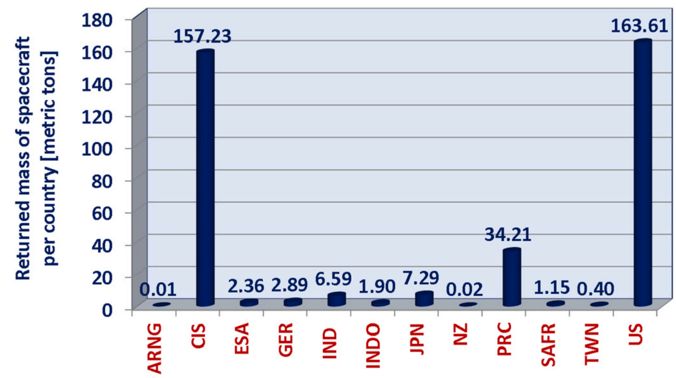

Fig. 13. Returned mass (metric tons) per country, associated with large spacecraft, from 1 January 2010 to 24 August 2023.

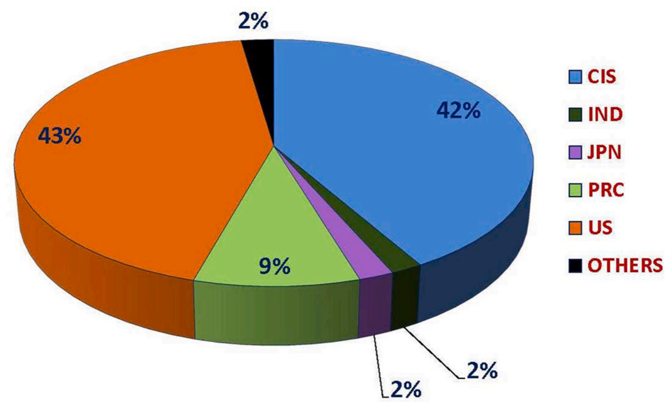

Fig. 14. Fractional contribution – by country – to the mass of uncontrolled re-entries of large spacecraft, from 1 January 2010 to 24 August 2023.

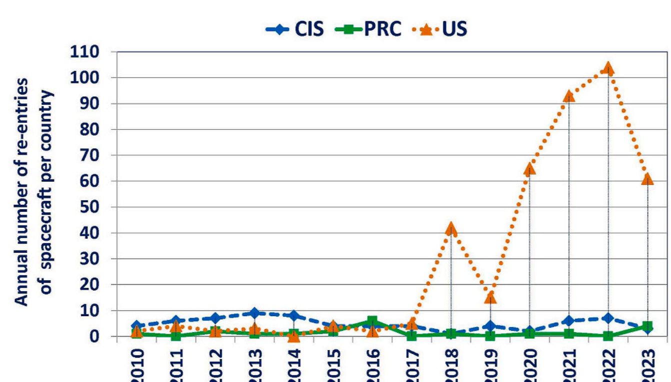

Fig. 15. Annual number of uncontrolled re-entries of large spacecraft due to the three main players, from 1 January 2010 to 24 August 2023.

4.1. Large orbital stages

Fig. 18 provides the answer for large orbital stages. As expected for upper stages, that typically conclude their mission within a few hours after the launch, the number of re-entries decreases with increasing orbital lifetime, which is basically driven by the final orbit reached after payload deployment.

During the period considered, half of the re-entries (284) occurred within 180 days of the launch, 34% (194) in the first 30 days, and 25% (142) in the first 10 days. Most of the latter (98, or 69%) were Russian Soyuz second stages, but all the four Chinese CZ-5B massive first stages

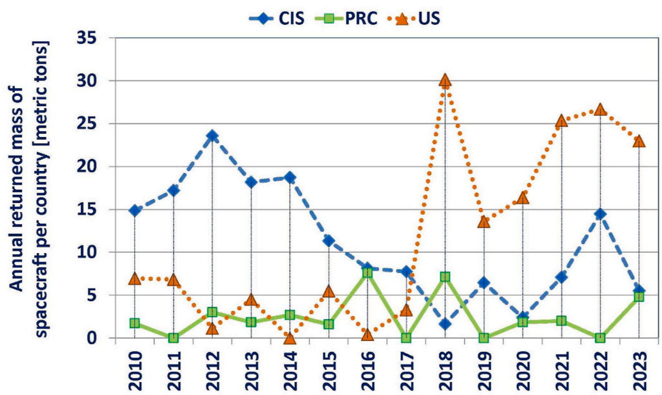

Fig. 16. Large spacecraft mass (metric tons) re-entered uncontrolled from 1 January 2010 to 24 August 2023, due to the three main players.

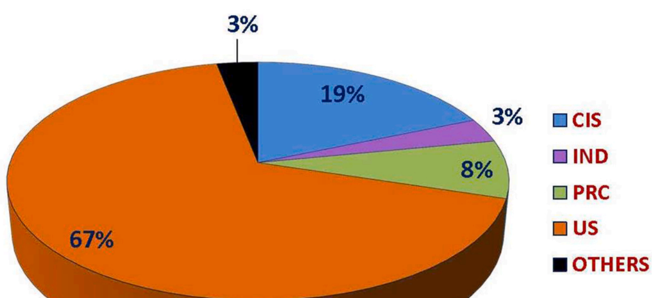

Fig. 17. Fractional contribution – by country – to the mass of uncontrolled re-entries of large spacecraft, from 1 January 2018 to 24 August 2023.

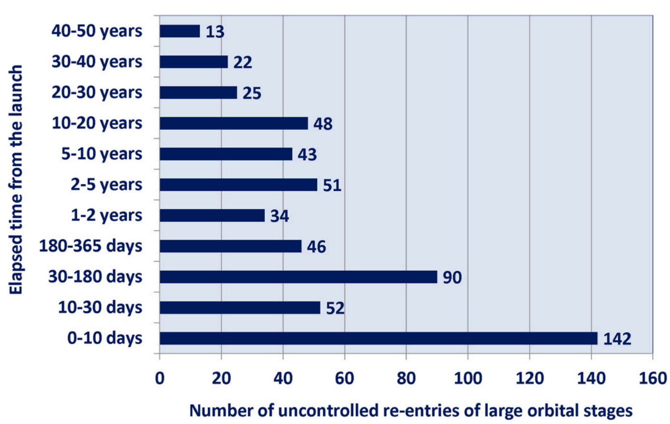

Fig. 18. Large orbital stages: Distribution of uncontrolled re-entries as a function of the launch elapsed time (from 1 January 2010 to 24 August 2023).

orbited so far were included as well, together with other 13 Chinese, 7 Russian and 20 American rocket bodies. It is also worth mentioning that 96 stages decayed within 3 days, and 49 within 2 days, offering not much time to set up accurate re-entry prediction campaigns. Among these rapidly decaying orbital stages, the clear majority were Russian Soyuz second stages, being 96% of those re-entering within 72 h and 78% of those re-entering within 48 h.

4.2. Large spacecraft

Regarding large spacecraft (Fig. 19), the situation is of course quite different, because the orbital lifetime is driven by mission duration and critical failure rate. Over the period considered, the orbital lifetime of the re-entered spacecraft had a peak between one and two years. 230 spacecraft (45%) had a lifetime longer than two years, 138 (27%) shorter than one year, 76 (15%) shorter than 180 days, 30 (6%) shorter than 30 days, and only 10 (2%) shorter than 10 days. Therefore, for uncontrolled spacecraft, more than enough time is typically available to set up a re-entry prediction campaign, which is important, since re-entry modeling and forecasts for spacecraft are generally more complicated than those for orbital stages, the latter being simpler in geometry and mass distribution.

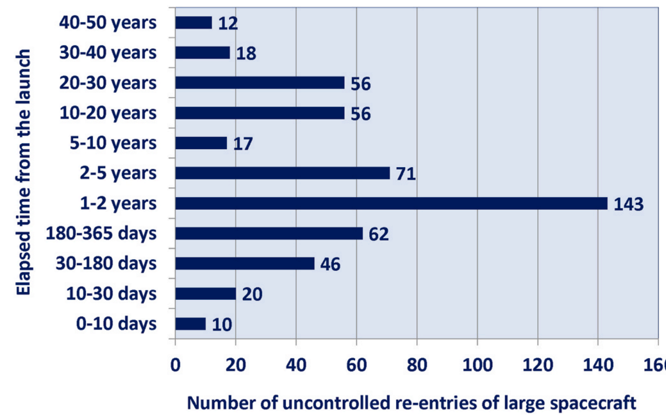

Fig. 19. Large spacecraft: Distribution of uncontrolled re-entries as a function of the launch elapsed time (from 1 January 2010 to 24 August 2023).

5. Evaluation of the casualty risk

Several space agencies and organizations have defined guidelines and standards to limit the risk of uncontrolled re-entries [13–19]. In order to check the compliance of re-entries with the ground safety requirements, explicit methods have been proposed and recommended for the definition and computation of the casualty expectancy. In this paper we adopted the approach chosen by NASA, and described in Section 4.7 (pages 49–53) of [19], only considering human casualty risk on the ground. The method resorts to several simplistic assumptions, but further complications were not considered worthwhile by NASA because there is no universally accepted formulation for the variables at play, the consequences of the various effects are often opposed, and there are many statistical uncertainties to make any refinement of the formulation debatable [19].

For unsheltered people on the ground, the crucial metric adopted to estimate the potential risk from re-entering fragments is the debris casualty area (DCA). For a piece of debris reaching the ground, DCA is a function of the average debris cross-section plus a term for its interaction with the cross-section of an individual. The total debris casualty area (TDCA) for a re-entry event is the sum of the contributions of all surviving fragments with a terminal energy greater than 15 J [15,19]. The corresponding total human casualty expectancy is then obtained by multiplying TDCA by the average population density in the band of latitudes overflown by the re-entering object [19].

Having a detailed knowledge of the re-entering object design, structure and materials, the surviving fragments and their associated TDCA may be inferred with sophisticated and highly specialized software tools, the availability of which, however, is restricted and relatively expensive [20–25]. Moreover, even when these simulations are carried out, the results often remain confidential. Consequently, only for a small subset of objects is this type of detailed analysis freely available to independent researchers.

To overcome these hurdles, some analysts have developed simplified semi-empirical relationships, fitting the freely available data, to estimate the approximate TDCA of objects whose detailed design and properties are unknown [26]. We too obtained, in a previous work [8,11], various relationships for TDCA, fitting the data of a sample of spacecraft and orbital stages with simple mathematical functions in terms of the re-entering dry mass (*M*). Among the various formulas obtained, the following was adopted in this paper to estimate the total debris casualty area of each re-entry event:

$$TDCA = 0.05627\ M^{0.7563} \tag{1}$$

where *TDCA* is given in m^2 and *M* in kg. Eq. (1) was chosen because its global results were close to the average of all eight fitting relationships used in Refs. [8,11].

The casualty expectancy results obtained with the approach just described are affected by several uncertainties, starting with the approach recommended by the NASA standard [19]. The casualty area estimates are individually uncertain as well, being obtained from a simplified relationship – Eq. (1) – fitting the distribution of a reduced sample of mostly simulated cases. And even debris casualty areas simulated with state of the art software tools can be affected by uncertainties of at least a factor of two. In addition, the current prevalence in the re-entry record of a few specific types of objects, like the Starlink satellites, the Falcon 9 second stages, or some kinds of Chinese rocket bodies, might lead to biases, for instance if Starlink satellites and Chinese rocket bodies demise more, and Falcon 9 second stages demise less than assumed.

However, with the information available, a formal and reliable quantitative estimation of the underlying uncertainties and biases was not possible. Moreover, several of the assumptions and of the uncertainty sources have opposite effects. The results presented here must then be considered the best possible estimate with the data and knowledge available to us. Integrated over the past, these results are also compatible with the re-entry history recorded so far, are consistent with the best practices used to manage international recommendations and standards, and are relevant to assess general trends and relative values.

Figs. 20 and 21 summarize the results obtained for the casualty expectancy and probability, respectively, from 1 January 2010 to 24 August 2023. Throughout the period considered, the risk due to large orbital stages was always predominant over that from spacecraft, by an average factor of nearly three. However, from 2010 to 2018, the total casualty risk remained substantially stable, with a mean annual casualty probability which was just over 1%. Since 2019 the situation has changed, due to the acceleration of new space activities. The casualty expectancies of both spacecraft and orbital stages progressively increased, resulting in a mean annual casualty probability around 3% in 2022 and 2023 (extrapolated). This means that the global re-entry risk has essentially tripled over the past five years, despite the increasing use of controlled de-orbiting for upper stages and massive spacecraft. In other words, the great growth of space activities recently occurred has more than offset, so far, all the efforts put in place to mitigate the problem.

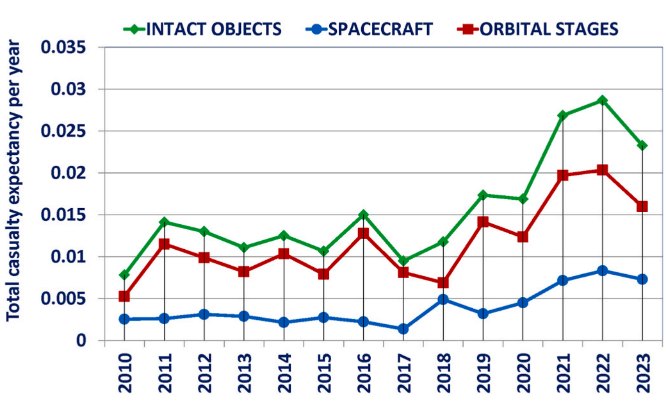

Fig. 20. Annual global casualty expectancy associated with the uncontrolled re-entry of large spacecraft, orbital stages or both (intact objects), from 1 January 2010 to 24 August 2023.

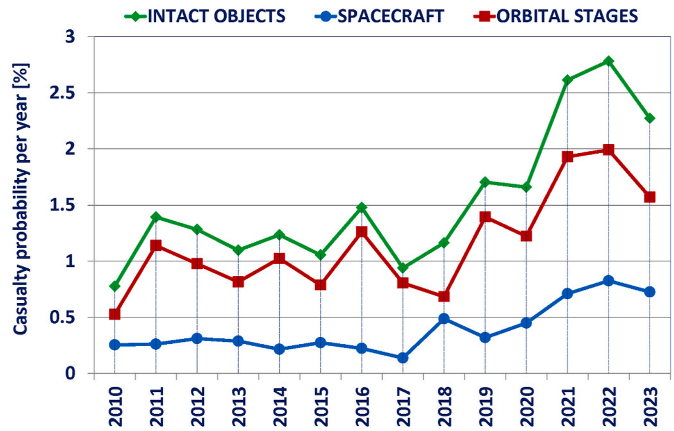

Fig. 21. Annual global casualty probability associated with the uncontrolled re-entry of large spacecraft, orbital stages or both (intact objects), from 1 January 2010 to 24 August 2023.

But not all countries contribute to the re-entry risk in the same way. Again, as expected from the results presented in Section 3, the main contributors are China, CIS (basically Russia) and the Unites States, accounting for 92% of the casualty expectancy due to large orbital stages and 95% of the casualty expectancy due to large spacecraft, during the whole time interval considered.

5.1. Risk due to large orbital stages by country

The evolution, per country of origin, of the casualty expectancy due to large orbital stages is shown in Fig. 22. At the beginning of the 2010s, Russian upper stages were the leading contributors, but over the following 12 years their impact slowly declined. Concerning the American rocket bodies re-entering uncontrolled, the associated casualty expectancy slowly increased over the period analyzed, but only in 2020 exceeded that of the Russian stages. China, instead, has become the largely dominant contributor in recent years, more than three times as much as Russia or the United States. Regarding other countries, only India, France and Japan have occasionally given not negligible contributions.

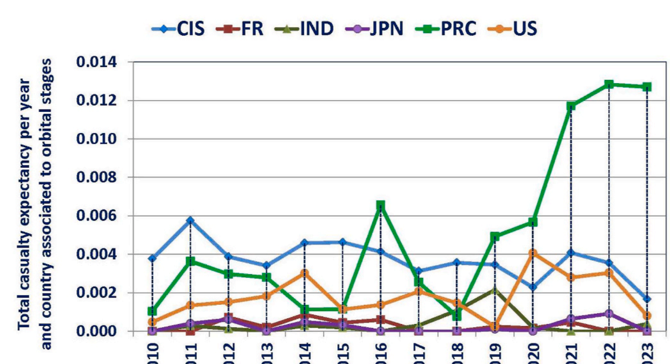

Fig. 22. Annual global casualty expectancy associated with the uncontrolled re-entry of large orbital stages, by country of origin (from 1 January 2010 to 24 August 2023).

As previously pointed out, some types of Chinese rocket bodies might demise more than assumed, while the opposite might occur in the case of the Falcon 9 second stages,[3] biasing the outcome of Fig. 22, but we have no specific information to refute, or support and quantify, such assertions, so the results presented here represent the best we can do with the knowledge we have.

5.2. Risk due to large spacecraft by country

The evolution, per country of origin, of the casualty expectancy due to large spacecraft is shown in Fig. 23. Even in this case Russia was the leading contributor at the beginning of the 2010s, and again this contribution slowly decreased over the period considered. Since 2018, the dominant player has become the United States, due to the huge numbers of satellites launched and the corresponding increase of uncontrolled re-entries. China, despite being in the third position, has so far only episodically contributed to significant casualty expectancies, followed, still much further behind, by Japan and India.

As already mentioned, the current prevalence in the re-entry record of Starlink satellites might bias the last part of the US curve in Fig. 23, in particular if the SpaceX claim of a full demisability of the objects would be applicable. In that case, the US global casualty expectancy for re-entered spacecraft should be reduced by about 70% in 2020 and by about 90% in 2021 and 2022 (for 2023 the results were still partial when the article was submitted). However, with the information available, we were unable to independently and convincingly support the full demisability claim, so it was not applied to the results summarized in Fig. 23.

5.3. Overall risk due to large intact objects

In summary, there is currently (2022–2023) an annual probability around 3% that a fragment of an intact object re-entering the atmosphere uncontrolled will strike someone on the surface of the Earth. 70% of the casualty expectancy is associated with the uncontrolled re-entries of orbital stages, 30% with the re-entries of satellites. Concerning the current (2022–2023) contribution by country of origin of the re-entering objects, China accounts for 51% of the overall re-entry risk, followed by the United States (30%) and by Russia (14%). Considering, instead, the period 2010–2023, China accounted for 35% of the total casualty expectancy, followed by Russia (31%) and by the United States (26%).

6. Evolution of the risk in the near future

Assuming for the near future the current level of space activity, with around 200 launches and 2000 new satellites per year, the expected risk from uncontrolled re-entries may be estimated under the assumption that no further mitigation measures are taken. Today, the casualty expectancy from re-entering spacecraft is less than half of that from uncontrolled orbital stages. In the coming years, however, when many of the recently launched spacecraft will start to re-enter, the casualty expectancy of upper stages will remain basically stable, of the order of 0.02–0.03 per year, while that of satellites might progressively increase by a factor of 20, to 0.20 per year. This would lead to an annual casualty probability of about 20%.

Such unfavorable outcome might be avoided requiring the generalized adoption of controlled de-orbiting for orbital stages and satellites, although this may result in a fractional increase in the mass of spacecraft and rockets, and of combustion products released into the environment during launches. For orbital stages, in particular those belonging to the most recent rockets, controlled re-entries are already frequently adopted, and it is hoped that the new launchers under development will increasingly implement this requirement. However, for several old

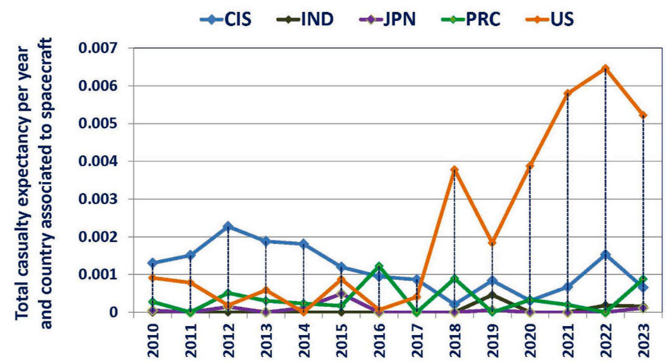

Fig. 23. Annual global casualty expectancy associated with the uncontrolled re-entry of large spacecraft, by country of origin (from 1 January 2010 to 24 August 2023).

launchers still in use today, especially by China and Russia, a controlled de-orbiting will probably not be feasible, so an annual casualty expectancy of 0.01–0.02 due to orbital stages cannot be eliminated quickly.

Concerning the satellites, we are talking about of completely new systems, with design, development and deployment times short enough to implement various appropriate solutions, as controlled re-entry, design for demise and, in certain cases, active removal by a chaser spacecraft. Presently, it is not possible to accurately predict how successfully the uncontrolled re-entries of new spacecraft will be avoided. There are, for instance, many claims of the adoption of design for demise, but with the information available such claims can neither be confirmed nor quantified in terms of effectiveness. It is therefore unclear by how much the growth in casualty expectancy due to uncontrolled spacecraft re-entry will be kept in check. Also because, in the next decade, even many more satellites than 2000 per year could be launched, further complicating the problem [8,9].

7. Conclusions and recommendations

Since 2018, large spacecraft are re-entering without control more often than large orbital stages, but the latter are still prevailing on the former in terms of mass by more than three times. Currently, the associated global casualty probability is around 3% per year, 70% of which is due to orbital stages and 30% to spacecraft.

However, the situation is changing fast. In the coming years, in fact, while the casualty expectancy of upper stages might remain basically stable, that of satellites might progressively increase by a factor of 20, just maintaining the current level of space activity. This could lead to an annual casualty probability of about 20%, a value that many would consider too high and unacceptable. And a further increase in space launches, very likely based on current projections, would only exacerbate the problem even more [8,9].

It is therefore necessary to take effective mitigation measures as soon as possible, for instance requiring the generalized adoption of controlled de-orbiting for large orbital stages and satellites. For the latter, a promising possibility may also be represented by the development and widespread use of effective design for demise components, thereby significantly reducing the mass capable of surviving re-entry. Already today there are, for instance, many claims of the adoption of these technologies, but such claims can neither be confirmed nor quantified in terms of actual achievements.

In any case, to attain significant results under the current conditions, the problem must be addressed now, while new launchers and large constellations of low-orbit satellites are being developed and deployed, otherwise the situation is likely to spiral out of control within a decade.

[3] According to one of the reviewers of this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The work described in this paper was carried out in the framework of the research project "Safety and Sustainability of Space Activities", funded by CNR-ISTI (No. DIT.AD012.151), and of the ASI-Politecnico di Milano agreement No. 2023-37-HH.0 on "Technical and Scientific Activities to Support CSSA/ISOC and Simulation of Sensor Architectures for SST". The authors would also like to thank the US Space Track Organization for the catalog of unclassified space objects, and the European Space Agency for the DISCOS database.

References

[1] R. Patera, Hazard analysis for uncontrolled space vehicle reentry, J. Spacecraft Rockets 45 (2008) 1031–1041.
[2] C. Pardini, L. Anselmo, Re-entry predictions for uncontrolled satellites: results and challenges, in: Proceedings of the 6th IAASS International Space Safety Conference "Safety in Not an Option", Montreal, Canada, 21-23 May 2013, ESA SP-715 (CD-ROM), European Space Agency (ESA), ESTEC, Noordwijk, The Netherlands, September 2013 paper s13_3.
[3] C. Pardini, L. Anselmo, The uncontrolled reentry of Progress-M 27M, J. Space Saf. Eng. 3 (2016) 117–126.
[4] C. Pardini, L. Anselmo, Assessing the risk and the uncertainty affecting the uncontrolled re-entry of manmade space objects, J. Space Saf. Eng. 5 (2018) 46–62.
[5] C. Pardini, L. Anselmo, Uncontrolled re-entries of spacecraft and rocket bodies: a statistical overview over the last decade, J. Space Saf. Eng. 6 (2019) 30–47.
[6] W.H. Ailor, Hazards of reentry disposal of satellites from large constellations, J. Space Saf. Eng. 6 (2019) 113–121.
[7] W.H. Ailor, Large Constellation Disposal Hazards, Center for Space Policy and Strategy, The Aerospace Corporation, El Segundo, California, USA, January 2020.
[8] C. Pardini, L. Anselmo, The kinetic casualty risk of uncontrolled re-entries before and after the transition to small satellites and mega-constellations, in: Proceedings of the 11th IAASS International Space Safety Conference "Managing Risk in Space", Virtual Venue, 19-21 October 2021, International Association for the Advancement of Space Safety (IAASS), October 2021, pp. 336–346.
[9] C. Pardini, L. Anselmo, The kinetic casualty risk of uncontrolled re-entries before and after the transition to small satellites and mega-constellations, J. Space Saf. Eng. 9 (2022) 414–426.
[10] M. Byers, E. Wright, A. Boley, C. Byers, Unnecessary risk created by uncontrolled rocket reentries, Nat. Astron. 6 (2022) 1093–1097.
[11] C. Pardini, L. Anselmo, The risk of casualties from the uncontrolled re-entry of spacecraft and orbital stages, in: Proceedings of the 12th IAASS International Space Safety Conference "Making Space Travel Safer", Osaka, Japan, 22-24 May 2023, International Association for the Advancement of Space Safety (IAASS), October 2023, pp. 13–23.
[12] E. Wright, A. Boley, M. Byers, Improving casualty risk estimates for uncontrolled rocket body reentries, in: Proceedings of the 12th IAASS International Space Safety Conference "Making Space Travel Safer", Osaka, Japan, 22-24 May 2023, International Association for the Advancement of Space Safety (IAASS), October 2023, pp. 32–40.
[13] J.K. Cole, L.W. Young, T. Jordan-Culler, Hazards of Falling Debris to People, Aircraft, and Watercraft, Sandia Report SAND97-0805-UC-706, Sandia National Laboratories, Albuquerque, New Mexico, USA, 1997.
[14] W.G. Esa Space Debris Mitigation, ESA Space Debris Mitigation Compliance Verification Guidelines, ESSB-HB-U-002, ESA/ESTEC, Noordwijk, the Netherlands, 2015.
[15] Range Commanders Council Range Safety Group Risk Committee, Common Risk Criteria for National Test Ranges, RCC 321-16, U.S. Army White Sands Missile Range, New Mexico, USA, 2016.
[16] International Organization for Standardization, Space Systems – Space Debris Mitigation Requirements, International Standard ISO 24113, 2019.
[17] U.S. Government,, Orbital Debris Mitigation Standard Practices, November 2019 Update, 2019.
[18] Inter-Agency Space Debris Coordination Committee, IADC Space Debris Mitigation Guidelines, IADC-02-01, Revision 2, 2020.
[19] NASA, Process for Limiting Orbital Debris. NASA-STD-8719.14C, NASA Technical Standard, National Aeronautics and Space Administration, Washington (D.C.), USA, 2021.
[20] JAXA, Manual for Re-entry Survivability Analysis, Tsukuba, Japan, 2016. JAXA-CAA-109029.
[21] C. Ostrom, B. Greene, A. Smith, R. Toledo-Burdett, M. Matney, J. Opiela, J. Marichalar, J. Bacon, C. Sanchez, Operational and technical updates to the object reentry survival analysis tool [ORSAT], in: Proceedings of the 1st International Orbital Debris Conference (IOC), Sugar Land, Texas, USA, 9-12 December 2019.
[22] R. Kanzler, B. Fritsche, T. Lips, A. Breslau, A. Pagan, G. Herdrich, M. Spel, S. Sanvido, S. Lemmens, SCARAB4 – Extension of the high-fidelity re-entry break-up simulation software based on new measurement types, in: Proceedings of the 8th European Conference on Space Debris, Virtual Venue, Darmstadt, Germany, 20-23 April 2021 published by the ESA Space Debris Office, http://conference.sdo.esoc.esa.int.
[23] C. De Persis, S. Lemmens, Destructive re-entry analysis tools: state of the art, latest advances, and open points, in: Proceedings of the 12th IAASS International Space Safety Conference "Making Space Travel Safer", Osaka, Japan, 22-24 May 2023, International Association for the Advancement of Space Safety (IAASS), October 2023, pp. 746–756.
[24] M. Spel, P. van Hauwaert, E. Constant, I. Midani, V. Ledermann, T. Martinez, S. Galera, J. Annaloro, Towards the next generation spacecraft reentry tool: PAMPERO roadmap, in: Proceedings of the 12th IAASS International Space Safety Conference "Making Space Travel Safer", Osaka, Japan, 22-24 May 2023, International Association for the Advancement of Space Safety (IAASS), October 2023, pp. 757–769.
[25] J. Annaloro, S. Galera, A. Bellucci, N. Pillet, G. Laur, P. Omaly, New methodology to model the atmospheric re-entry of a satellite with DEBRISK V3, in: Proceedings of the 12th IAASS International Space Safety Conference "Making Space Travel Safer", Osaka, Japan, 22-24 May 2023, International Association for the Advancement of Space Safety (IAASS), October 2023, pp. 770–779.
[26] S. Lemmens, Order of magnitude analysis for on-ground casualty area from uncontrolled re-entries, in: ESA Memo GEN-REN-MO-00228-OPS-GR, European Space Operations Centre (ESOC), ESA, Darmstadt, Germany, 2018.