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The risk of casualties from the uncontrolled re-entry of spacecraft and orbital stages

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

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A B S T R A C T

From the beginning of 2010 to the end of 2022, 951 intact objects (spacecraft and orbital stages) with a radar cross-section greater than one square meter re-entered the Earth's atmosphere uncontrolled. The total returned mass was about 1500 t, with a mean of 116 t per year, mostly concentrated (80 %) in orbital stages. On average, objects with a mass greater than 500 kg re-entered every 8 days, those exceeding 2000 kg every 2 weeks, and those above 5000 kg around 3 times per year. Only 4 % of the re-entries came from orbits with an eccentricity greater than 0.1, while 41 % were from nearly circular orbits with eccentricity lower than 0.001. 52 % of the re-entries occurred in the northern hemisphere and 48 % in the southern one. The areas of the planet most affected were those between 30° and 60° north. However, excluding the polar regions, the re-entry flux per unit area was relatively uniform, from 60° south to 60° north, implying a ground casualty risk mainly driven by the population density. 84 % of orbital stages and 19 % of spacecraft exceeded a casualty expectancy of 10^{-4}, the ceiling recommended by several guidelines and standards worldwide. The total ground casualty expectancy over the 13 years analyzed was estimated to be 0.194, corresponding to a probability of injuring or killing at least one person of about 18 %. After remaining relatively stable from 2010 to 2018, the casualty expectancy and probability have grown systematically from then on, leading in 2022 to a chance of casualty of 2.9 %, with orbital stages and spacecraft contributing, respectively, 72 % and 28 %.

1. Introduction

The current cumulative annual global casualty expectancy for uncontrolled re-entries of orbital stages and spacecraft is of the order of 10^{-2}. Hence, the corresponding individual risk is still extremely low, if compared with the hazards commonly faced in everyday life, with a probability of being personally injured of the order of 1 in 800 billion per year. However, this risk is increasing, due to the rapid growth of space launch activities and to the rise in world population. Moreover, during the last decades there has been a growing consensus, at the international level, in considering a casualty expectancy of 10^{-4} as the risk limit not to be exceeded for any individual uncontrolled re-entry [1–5], while the introduction of collective risk limits is currently considered for large space systems, like mega-constellations [6,7].

In order to assess the current situation in light of these developments, the analyses we have done over the past decade [8–11] have been revisited and updated, for the period between 2010 and 2022, focusing the attention on the uncontrolled re-entry of large intact objects (orbital stages and spacecraft). In Section 2, a complete characterization of uncontrolled orbital re-entries is presented, in terms of number, type, orbit, mass and geographical distribution, to provide the community with data useful for assessing the size and evolution of the phenomenon, the latitudes of the planet most affected, and the grouping of orbital eccentricities before decay, these latter impinging upon the re-entry prediction process (relative importance of perturbations, re-entry prediction accuracy, definition of uncertainty windows). The casualty risk on the ground, and its evolution, are then estimated in Section 3, assuming the technical standard approach recommended by NASA [2], in order to be compliant and comparable with most of the rules adopted internationally. A brief discussion of the results and a general recommendation conclude the paper.

2. Uncontrolled re-entries of large intact objects

Considering only the intact objects classified as "large" (i.e. with a radar cross section > 1 m^2) by the 18th US Space Con-

* Corresponding author.
E-mail address: Carmen.Pardini@isti.cnr.it (C. Pardini).

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Table 1
Large orbital stages re-entered without control from 2010 to 2022, with the associated returned mass.

Year	Annual number of re-entered orbital stages	Associated returned mass [kg]
2010	26	53,078
2011	43	104,327
2012	39	81,193
2013	38	65,681
2014	47	87,779
2015	38	71,420
2016	37	102,809
2017	32	61,992
2018	27	53,758
2019	50	107,096
2020	40	93,266
2021	52	151,476
2022	56	163,283
Total	**525**	**1197,158**
Average	**40.39**	**92,089.08**

Table 2
Large spacecraft re-entered without control from 2010 to 2022, with the associated returned mass.

Year	Annual number of re-entered spacecraft	Associated returned mass [kg]
2010	6	9189
2011	10	19,541
2012	8	24,751
2013	13	23,661
2014	10	22,711
2015	11	21,279
2016	11	13,807
2017	10	11,505
2018	45	38,931
2019	21	24,789
2020	67	18,758
2021	102	36,578
2022	112	42,285
Total	**426**	**307,785**
Average	**32.77**	**23,675.77**

trol Squadron, from 1 January 2010 to 31 December 2022, 525 orbital stages and 426 spacecraft (951 in total) have re-entered without control the Earth's atmosphere.[1] The total returned mass was around 1500 t, corresponding to the re-entry of almost 116 t per year, on average.[2]

80 % of this mass was concentrated in orbital stages, with an annual average of approximately 92 t, and the remaining 20 % in spacecraft, with an annual average of about 24 t. Concerning spacecraft, 65 % had a mass below 500 kg, 18 % exceeded 1 t, 10 % were over 2 t, and only 1 % was above 5 t. Re-entering orbital stages were decisively more massive than spacecraft, with only 14 % below 500 kg. 73 % were more massive than 1 t, 56 % and 7 % exceeded, respectively, 2 and 5 t, while just under 1 % was above 10 t.

Based on what was observed in the period analyzed, objects with a mass greater than 500 kg re-entered uncontrolled about every 8 days, those with a mass exceeding 2000 kg re-entered approximately every 2 weeks, those with a mass above 4000 kg re-entered about every 2 months, and those with a mass greater than 5000 kg re-entered approximately 3 times per year. 74 of the re-entered orbital stages had a mass greater than 4000 kg. Concerning the re-entries from large satellite constellations, 61 Iridium satellites re-entered without control between 2017 and 2020, with a total associated mass of approximately 40 t. Regarding Starlink, 257 satellites re-entered from the beginning of 2020 to the end of 2022, with a total associated mass of about 63 t.

2.1. Annual number of re-entries and returned mass

The annual number of large orbital stages and spacecraft re-entered without control between 2010 and 2022 is shown in Tables 1 and 2, together with the associated returned mass. In 2021, the total returned mass of orbital stages, amounting to nearly 151 t, was approximately 64 % higher than the average between 2010 and 2022, that is 92 t. Additionally, an ever larger increase, of about 77 % with respect to the average, was observed in 2022, as a result of a further intensification of space activities. Regarding spacecraft, a consistent growth of the number of re-entry events was observed since 2020, mostly caused by the disposal of satellites from the Starlink constellation. As for the spacecraft returned mass, it increased by approximately 79 % in 2022, compared with the average during the analyzed period.

2.2. Evolution of the ratio between re-entry events involving large orbital stages and spacecraft

From 2010 to 2022, the ratio between the number of re-entry events involving large orbital stages and spacecraft was gradually decreasing, going from just over 4, in 2010, to about 0.5 in 2022 (Fig. 1, blue curve). This means that while in 2010 the number of re-entering stages was 4 times that for spacecraft, presently the latter are twice as many as the former. The situation then reversed, as natural consequence of the disposal of numerous satellites from large constellations operating in low Earth orbit. A typical example is represented by Starlink, of which 106 satellites re-entered without control in 2022, 90 in 2021, and 61 in 2020.

On the contrary, the ratio between the returned mass associated with orbital stages and spacecraft shows a totally different evolution (Fig. 1, green curve). In fact, in the period analyzed, the returned mass from orbital stages was always larger than that from spacecraft, with a minimum ratio occurred in 2018 (~1.4) and a maximum in 2016 (~7.4). Moreover, this ratio remained around 4 since 2019, showing that the contribution in re-entering mass from orbital stages has recently been at least 4 times greater than that deriving from spacecraft.

2.3. Orbit eccentricity before re-entry

Large orbital stages, re-entered uncontrolled between 2010 and 2022, were generally characterized by relatively low values of the orbit eccentricity before re-entry (Fig. 2). Only 6 % of the re-entries came from elliptical orbits with an eccentricity (e) larger than 0.1. About 29 % of the events were from nearly circular orbits ($e < 0.001$), 38 % came from orbits with low eccentricity ($0.001 < e < 0.01$), and 27 % from orbits with low to moderate eccentricity ($0.01 < e < 0.1$). During the same period, most of the large spacecraft re-entered without control came from quasi circular orbits (56 %), with only 2 % from highly elliptical trajectories (Fig. 3). 33 % came from orbits with low eccentricity and just 9 % from orbits with low to moderate eccentricity.

2.4. Latitude bands overflown

On the basis of the distribution in inclination of the 525 large orbital stages and 426 large spacecraft re-entered without control

[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/.

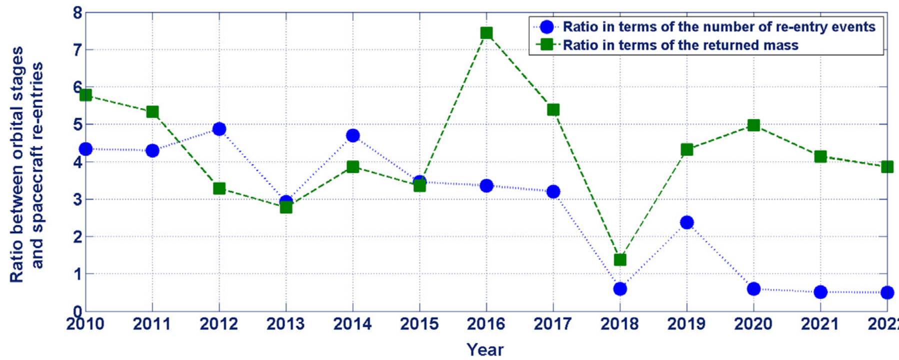

Fig. 1. Evolution of the ratio between re-entered orbital stages and spacecraft, in term of number of re-entry events (in blue) and returned mass (in green).

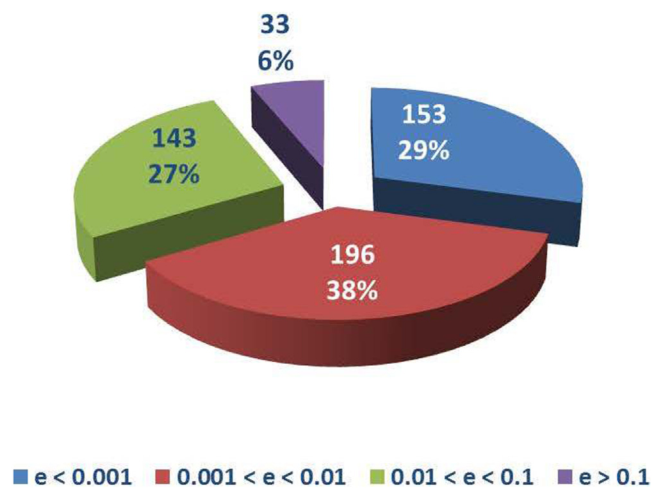

Fig. 2. Orbit eccentricity distribution before re-entry of large orbital stages decayed between 2010 and 2022.

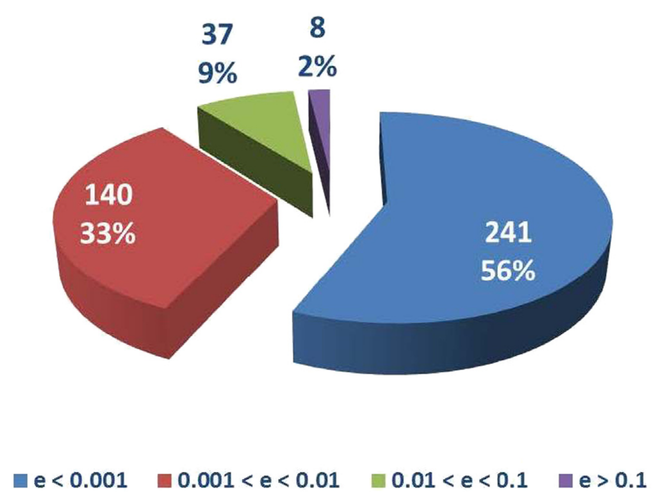

Fig. 3. Orbit eccentricity distribution before re-entry of large spacecraft decayed between 2010 and 2022.

between 2010 and 2022, the overflown latitude bands were identified. For orbital stages, it resulted that nearly 96 % overflew regions of the planet with latitude boundaries, north and south, > 10°; 92 % with boundaries > 20°; 75 % with boundaries > 30°; 70 % with boundaries > 40°; 63 % with boundaries > 50°; 36 % with boundaries > 60°; 25 % with boundaries > 70°, and 24 % with boundaries > 80° (Fig. 4). Just to give an example, the European continent might potentially have been affected by more than

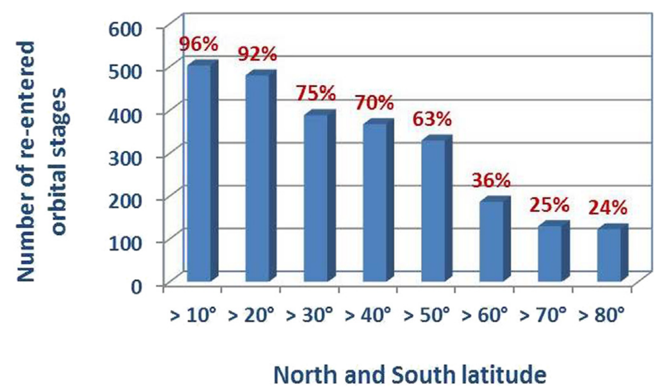

Fig. 4. Percentage of orbital stages, re-entered without control between 2010 and 2022, overflying latitude bands of assigned amplitude.

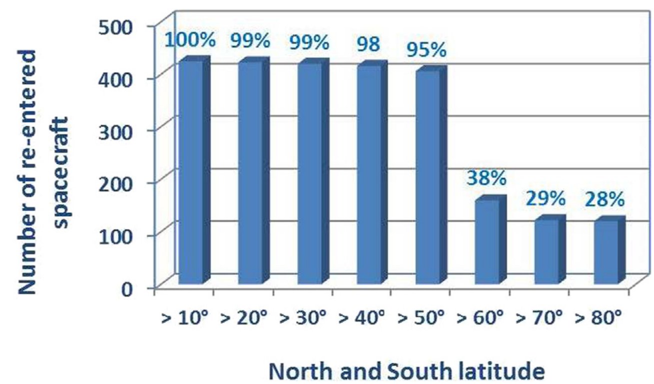

Fig. 5. Percentage of spacecraft, re-entered without control between 2010 and 2022, overflying latitude bands of assigned amplitude.

70 % of the uncontrolled re-entries involving large orbital stages between 2010 and 2022.

In the case of spacecraft, regions of the planet within 10° of latitude, north and south, were overflown in all re-entry events considered. 99 % of them overflew latitude bands with boundaries > 30°; 98 % with boundaries > 40°; 95 % with boundaries > 50°; 38 % with boundaries > 60°; 29 % with boundaries > 70°, and 28 % with boundaries > 80° (Fig. 5). Between 98 % and 99 % of these re-entries, then practically all, might potentially have affected the European territory.

2.5. Geographical distribution of re-entries

The geographical distribution, in terms of latitude and longitude, of uncontrolled re-entries of large orbital stages and space-

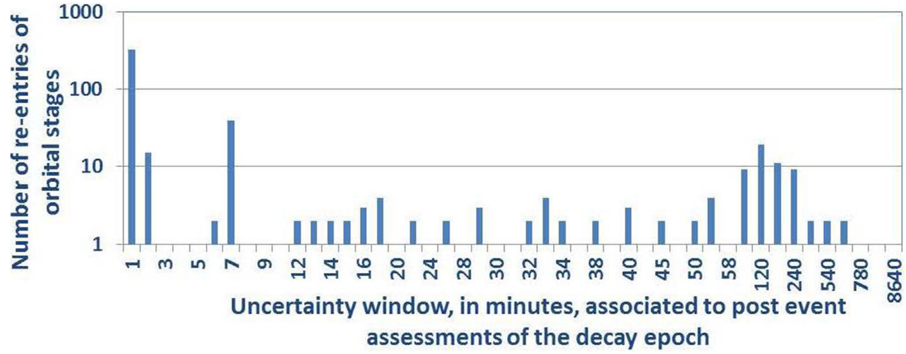

Fig. 6. Uncertainty window associated with the post-event assessment decay epoch (TIP messages) for the uncontrolled re-entries of orbital stages occurred between 2010 and 2022.

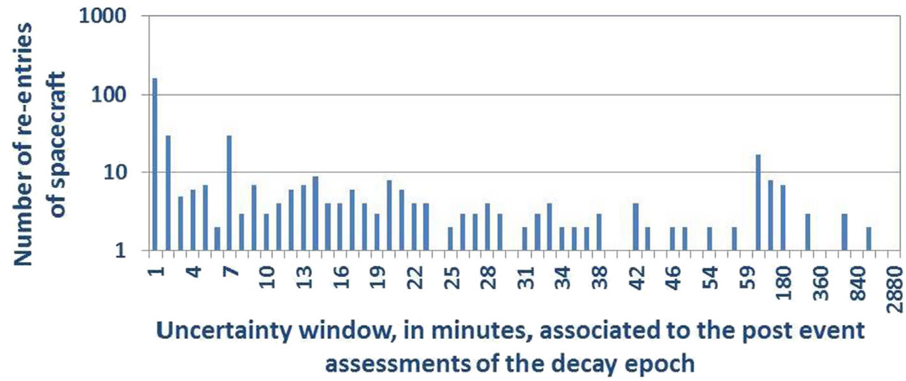

Fig. 7. Uncertainty window associated with the post-event assessment decay epoch (TIP messages) for the uncontrolled re-entries of spacecraft occurred between 2010 and 2022.

craft was obtained through the Tracking and Impact Prediction (TIP) messages issued by the 18th US Space Control Squadron. In particular, the TIP message corresponding to the post-event assessment for each re-entry event was taken into account. Herein, to each decay epoch is associated an uncertainty window, which can range from a minimum of ±1 min to even a few days, in the most doubtful cases. For the re-entries analyzed, this uncertainty window varied between ±1 min, in 485 cases, and ±8640 min (±6 days) for an orbital stage re-entered on 22 March 2019.

Of the 498 large orbital stages for which the TIP messages were available, 325 (65 %) had an uncertainty window of ±1 min associated with the post-event assessment decay epoch, 39 (~8 %) a window of ±7 min, 19 (~4 %) a window of ±120 min, and so on (Fig. 6). Concerning the 423 (almost all) large spacecraft for which the TIP messages were available, a lower percentage (~38 %), compared to orbital stages, had an uncertainty window of ±1 min associated with the decay epoch. The other windows were more scattered (Fig. 7), and the maximum was ±2880 min (±2 days) for a satellite re-entered on 30 June 2011.

Finally, considering the latitude and longitude corresponding to the decay epoch of the 921 large intact objects (498 orbital stages and 423 spacecraft) for which the TIP messages were available, irrespective of the uncertainty window, the geographical distribution of the re-entries is plotted in Fig. 8. Fig. 9 shows instead the re-entry distribution as a function of latitude, while Fig. 10 does the same as a function of longitude.

As expected, the longitudinal distribution of uncontrolled re-entries was roughly uniform, with maximum deviations from the mean of about 20 % for spacecraft and about 25 % for orbital stages, while the latitudinal distribution was affected by the orbital inclinations of the re-entering objects. However, in order to have a more accurate picture, the analysis was focused on the subset of cases for which a claimed error of ±1 min was associated with the decay epochs of the TIP post-event assessments. During the period considered, this applied to 325 orbital stages and to 160 spacecraft. The resulting re-entry distribution as a function of latitude is presented in Fig. 11.

Compared with Fig. 9, the distribution shown in Fig. 11 appears less symmetrical with respect to the equator. However, the main features of Fig. 9 are confirmed, or further enhanced, in Fig. 11. Among them, the peak of orbital stage re-entries between 10° and 20° north, the secondary peak between the equator and 30° south, and a higher occurrence of spacecraft re-entries at mid-latitudes, both north and south, mainly due to the many re-entries (59 % of the total) of the Starlink satellites, with inclination around 53°.

77 (48 %) out of 160 spacecraft re-entries occurred in the southern hemisphere, while 83 (52 %) in the northern hemisphere. The same fraction of re-entries per hemisphere was observed for orbital stages, with 156 (48 %) out of 325 occurring in the southern hemisphere and 169 (52 %) in the northern hemisphere.

The geographical distribution of uncontrolled re-entries of large intact objects is a function of launch patterns, mission orbits, end-of-life practices and the underlying complex dynamics of orbital decay. It is therefore bound to change over time. From September 1992 to December 1996, for example, there was a prevalence of decays in the northern hemisphere as well (56.5% vs. 43.5 %) [12], while from 2004 to 2015 it was found a prevalence of re-entries occurring in the southern hemisphere (53.5% vs. 46.5 %) [8].

2.6. Uncontrolled re-entry flux

Based on the previous data for a total of 485 intact objects (325 orbital stages and 160 spacecraft), with a claimed re-entry error of ±1 min between 2010 and 2022, the flux of re-entered objects over

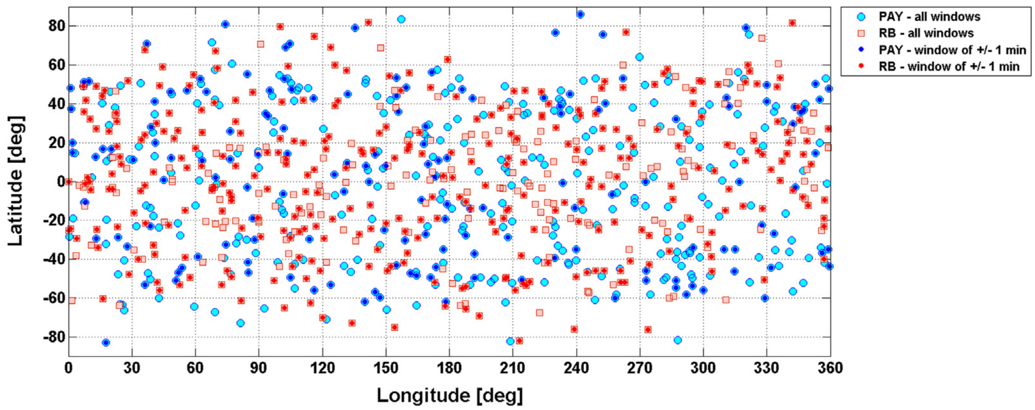

Fig. 8. Geographical distribution of uncontrolled re-entries occurred between 2010 and 2022: orbital stages (in red those with uncertainty window of ±1 min; in pink those with greater uncertainties) and spacecraft (in blue those with uncertainty window of ±1 min; in light blue those with greater uncertainties).

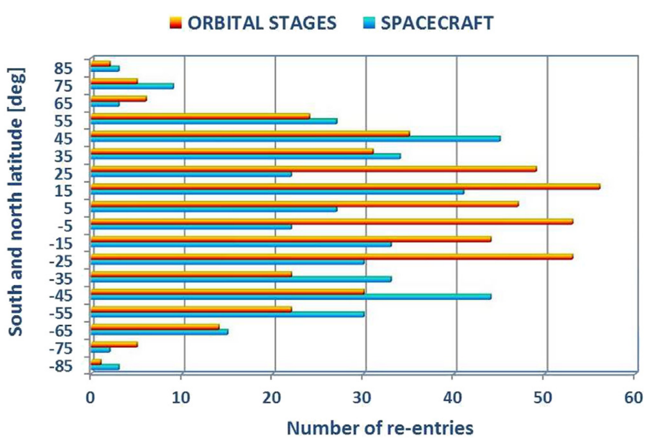

Fig. 9. Distribution per latitude bands of the number of uncontrolled re-entries of orbital stages and spacecraft occurred between 2010 and 2022.

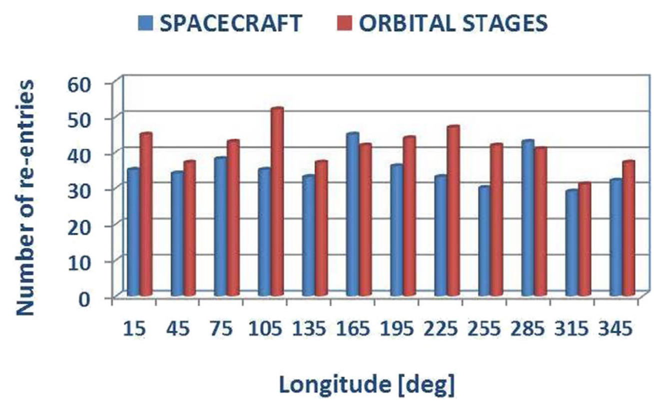

Fig. 10. Distribution per longitude bands of the number of uncontrolled re-entries of orbital stages and spacecraft occurred between 2010 and 2022.

six latitude bands of the Earth's surface was computed (Fig. 12), dividing the number of re-entered objects in each band by the area of the corresponding latitude band. The relative re-entry flux per unit area, compared with the average value over the total Earth surface, is given in Table 3.

For orbital stages, the re-entry flux was higher than average between 30° south and 60° north. For spacecraft, it was higher than average at mid-latitudes, between 30° and 60°, both north and south. Overall, the areas of the planet most affected by the uncontrolled re-entry of large intact objects were those between 30° and 60° north. However, excluding the polar regions, with latitudes

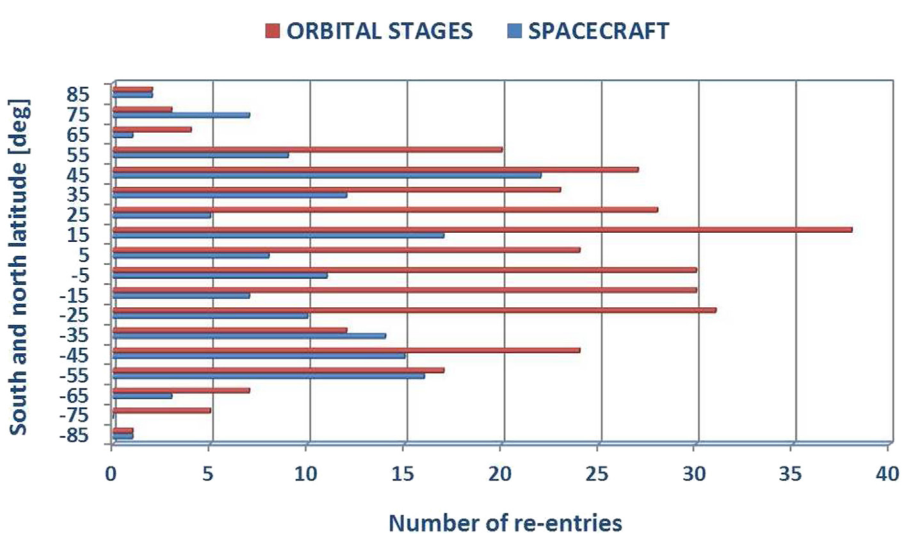

Fig. 11. Distribution per latitude bands of the number of uncontrolled re-entries of orbital stages and spacecraft occurred between 2010 and 2022, and characterized by an uncertainty window of ±1 min.

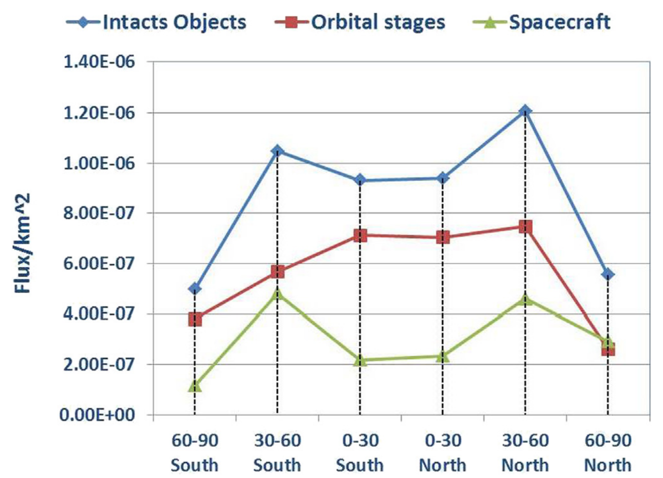

Fig. 12. Flux of uncontrolled re-entries per unit area, occurred from 2010 to 2022 and characterized by an uncertainty window of ±1 min, over six latitude bands of the Earth's surface.

Table 3
Relative re-entry flux per unit area, compared with the average value over the total Earth surface (2010–2022).

Latitude band	Spacecraft	Orbital stages
from −90° to −60°	37.3 %	59.5 %
from −60° to −30°	153.7 %	88.8 %
from −30° to 0°	70.0 %	111.6 %
from 0° to 30°	75.0 %	110.4 %
from 30° to 60°	146.8 %	117.3 %
from 60° to 90°	93.3 %	41.2 %

exceeding 60°, the re-entry flux was relatively uniform from 60° south to 60° north, roughly implying a ground casualty risk manly driven by the population density. This is quite similar to what was found from 2004 to 2015, although in that case the maximum flux was observed between 30° and 60° south [8].

3. Evaluation of the casualty risk on the ground between 2010 and 2022

Specific guidelines and standards to minimize the risk to human life and property on the ground have been defined, over the years, by several space agencies and organizations [1–5]. This led to a growing consensus in considering a casualty expectancy of 10^{-4} as the risk threshold not to be exceeded for any individual uncontrolled re-entry. The main factors affecting the estimations of the risk of human casualties include the number of debris expected to reach the surface of the Earth, the kinetic energy of each surviving fragment and the amount of the world population potentially at risk [10,11].

A crucial metric to represent and evaluate the potential risk from re-entering debris is the so-called total debris casualty area (A_C), which for a re-entry event is the sum of the casualty areas of all the pieces able to survive the harsh re-entry conditions [2]. The human casualty expectation, better known as the casualty expectancy (E_C), is obtained – for unsheltered people – as the product of the total debris casualty area (A_C) and the average population density (P_D) in the latitude band overflown by the re-entering object, that is:

$$E_C = A_C \times P_D \tag{1}$$

For instance, a world-wide casualty expectancy of 1:10,000 can be currently (2022) reached in a single uncontrolled re-entry event if the total casualty area of the surviving fragments is between 4 and 11 m^2, depending on the orbital inclination of the re-entering object (Fig. 13). For inclinations lower than 20° and higher than 60°, the average population density is lower and a higher total casualty area is needed to obtain a given casualty expectancy (between 6 and 11 m^2 below 20° and from 6 to 9 m^2 above 55°). For intermediate inclinations, between 20° and 55°, the mean population density is higher and a total casualty area as small as 5 m^2 may be sufficient to exceed the 10^{-4} casualty expectancy threshold for orbit inclinations between 24° and 43°.

3.1. Total debris casualty area

Very detailed information on the design and the materials used to build the object under scrutiny is needed to obtain realistic estimates of the casualty area. However, this crucial information is missing in most of the cases and detailed fragmentation analyses are only available for a very limited subset of re-entry events. Therefore, in all cases where this information is not available, it is necessary to resort to alternative, albeit coarser, methods to estimate the casualty area.

In a previous work [10,11], various relationships for A_C were obtained starting from the estimate of the casualty area available for a sample of space objects (spacecraft and orbital stages), mostly already re-entered, and then fitting the results obtained with simple mathematical functions in terms of the re-entering mass (M).

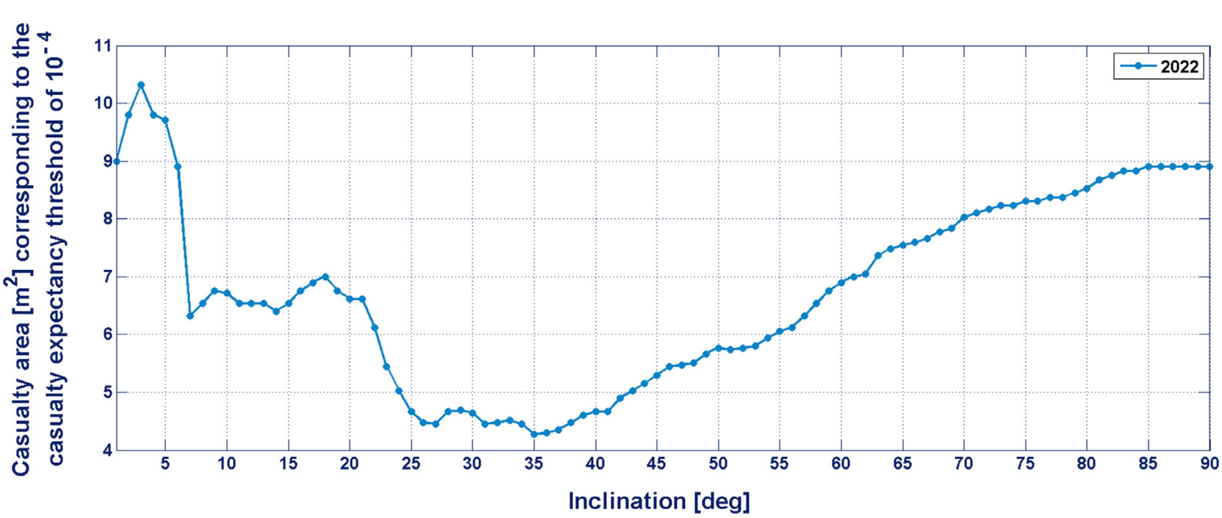

Fig. 13. Casualty area corresponding to the casualty expectancy threshold of 10^{-4}, estimated in 2022 as a function of the orbit inclination of re-entering objects.

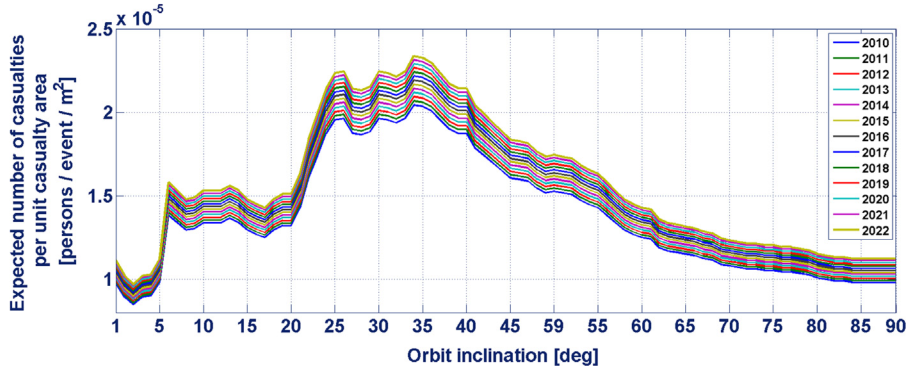

Fig. 14. Expected number of casualties per unit casualty area versus inclination, from 2010 to 2022.

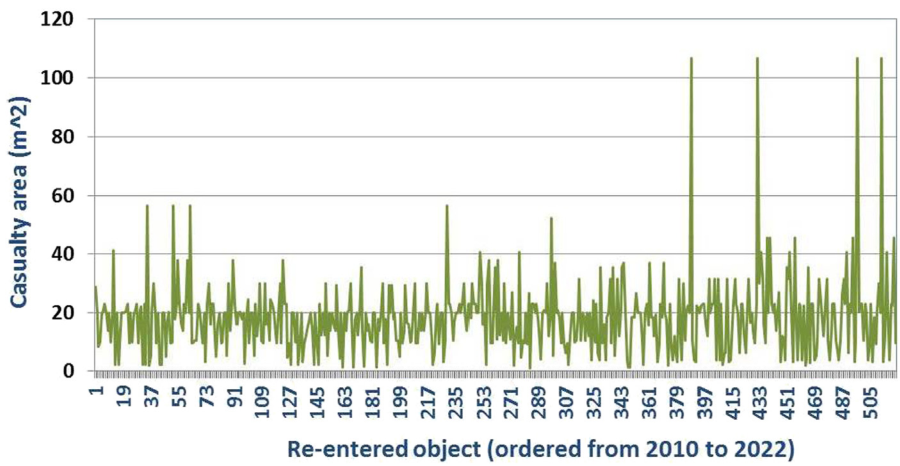

Fig. 15. Casualty area associated with orbital stages re-entered uncontrolled from 2010 to 2022.

Among the various relationships obtained [10,11], the following was adopted in this paper to estimate the total debris casualty area:

$$A_C = 0.05627 M^{0.7563} \quad (2)$$

where A_C is given in m^2 and M in kg.

3.2. Expected number of casualties per unit casualty area

The casualty expectancy E_C (Eq. (1)) can be obtained by multiplying the object's casualty area, in terms of the re-entering mass of the object, by the expected number of casualties per unit casualty area, corresponding to the re-entry year and to the orbit inclination of the decaying object. The latest was available in [10,11], and its evolution in time is herein represented from 2010 to 2022 (Fig. 14).

3.3. Casualty expectancy and casualty probability

The casualty probability $P(k)$, where k is the number of victims, can be obtained, from the average number of the expected casualties E_C, using the following Poisson distribution:

$$P(k) = \frac{E_C^k \cdot e^{-E_c}}{k!} \quad (3)$$

Herein E_C was estimated by multiplying the expected number of casualties per unit casualty area by the casualty area obtained with Eq. (2).

3.4. Casualty area of orbital stages re-entered uncontrolled from 2010 to 2022

Eq. (2) was used to compute the casualty area of the 525 orbital stages re-entered between 2010 and 2022, as a function of the returned mass associated with them (Fig. 15). The 4 highest peaks observed in Fig. 15 (A_C > 100 m^2) refer to the first stages of the Chinese launcher CZ-5B, with a mass of 21,600 kg each, re-entered without control from 11 May 2020 to 4 November 2022. The peaks that follow, in order of height, belong to 5 Soviet upper stages, including one from SL-16 (Zenit-2) and 4 from SL-23 (Zenit-3), which re-entered between 19 March 2011 and 27 January 2018, with mass ranging from 8360 to 9300 kg [9]. There are then 5 upper stages of the Chinese rocket CZ-2F (7000 kg), 6 of the Chinese launcher CZ-7 (6000 kg), 4 Indian upper stages (5300 kg) of the GSLV launcher, 15 American second stages (4300 kg) of the Falcon 9 rocket, and many others of 4 t, or less.

The total casualty area associated with large orbital stages re-entered uncontrolled from 2010 to 2022 was 9553 m^2, with an average casualty area per object of about 18 m^2.

3.5. Casualty area of spacecraft re-entered uncontrolled from 2010 to 2022

Also for the 426 spacecraft re-entered uncontrolled between 2010 and 2022, Eq. (2) was used to compute the casualty area as a function of the re-entering mass (Fig. 16). The two highest peaks in Fig. 16 (A_C > 40 m^2) correspond to the Progress-M 27 M cargo ship, with a mass of 7289 kg, re-entered on 8 May 2015 [8], and to the Tiangong-1 space station, with a mass of 7150 kg, re-entered

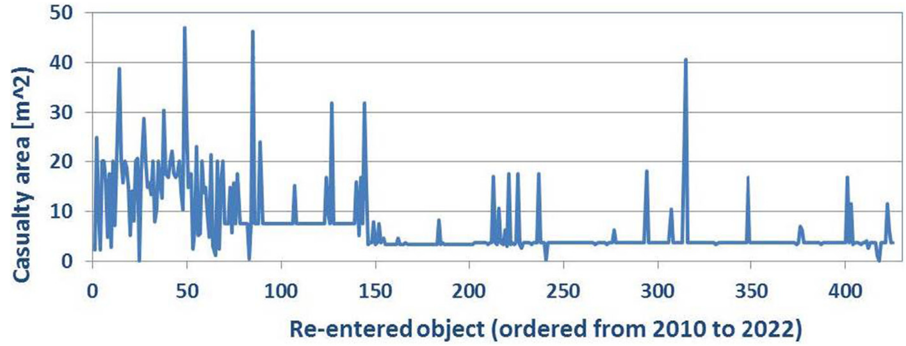

Fig. 16. Casualty area associated with spacecraft re-entered uncontrolled from 2010 to 2022.

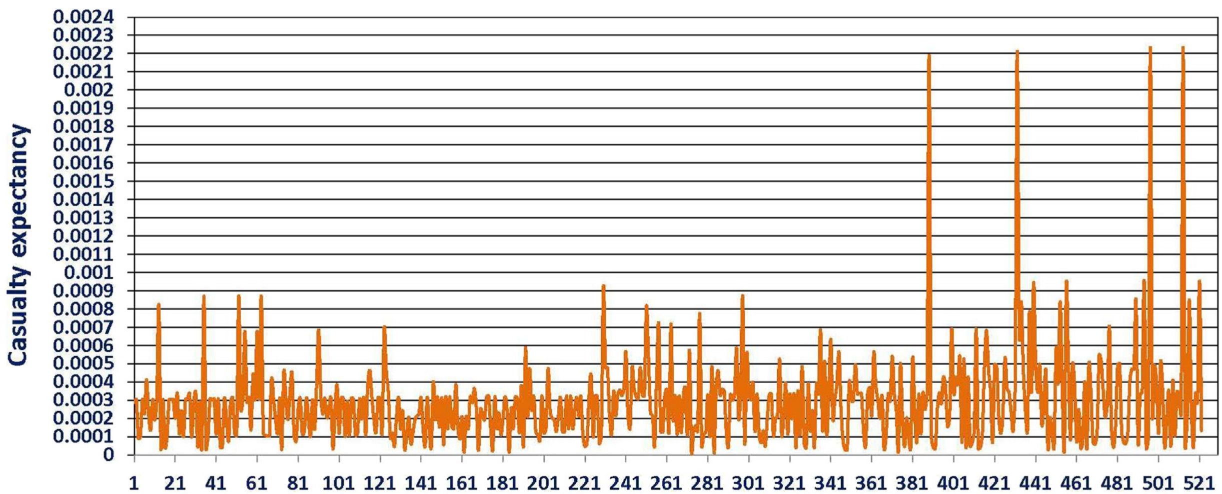

Fig. 17. Casualty expectancy associated with orbital stages re-entered uncontrolled from 2010 to 2022.

on 2 April 2018 [13]. The peak around 40 m^2 is associated with the Russian payload IPM-3/PERSEY, re-entered on 5 January 2022 with a mass around 6000 kg. The NASA satellite UARS, re-entered on 24 September 2011 with a mass of 5668 kg [14], accounts for the peak just below 40 m^2 (the first in the figure from left to right).

The total casualty area associated with spacecraft re-entered uncontrolled from 2010 to 2022 was 3059 m^2, with an average casualty area per object of about 7 m^2.

3.6. Casualty expectancy for orbital stages re-entered uncontrolled from 2010 to 2022

Using Eqs. (1) and 2, the casualty expectancy estimated for the 525 orbital stages re-entered between 2010 and 2022 is illustrated in Fig. 17. As for the casualty area, the highest peaks were associated with the 4 first stages of the Chinese launcher CZ-5B, but, in addition to these, most of the re-entered stages (approximately 84 %; see Fig. 18) were characterized by a casualty expectancy exceeding the alert threshold of 10^{-4}. No stage had a casualty expectancy below 10^{-5}, while 84 (16 %) had E_C between 10^{-5} and 10^{-4} (Fig.18). Fig. 17 also highlights a slow and gradual increase of the casualty expectancy during the last few years, mainly caused by the re-entry of many Chinese stages, including those related to the CZ-5B launcher.

3.7. Casualty expectancy for spacecraft re-entered uncontrolled from 2010 to 2022

Using Eqs. (1) and 2, the casualty expectancy estimated for the 426 spacecraft re-entered between 2010 and 2022 is illustrated

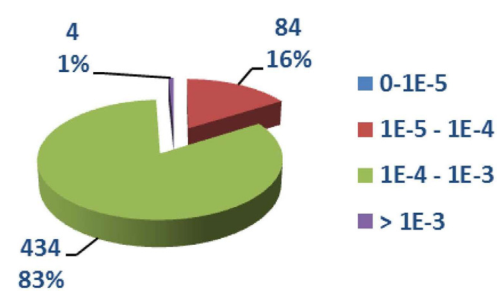

Fig. 18. Distribution, per casualty expectancy interval, of the re-entries of large orbital stages occurred uncontrolled between 2010 and 2022.

in Fig. 19. As for the casualty area, the highest peaks correspond to the re-entry of the most massive vehicles, with some small changes in trend, compared with Fig. 16, caused by different contributions from the population density at various epochs and inclinations. Moreover, contrarily to the behavior observed for orbital stages (Fig. 17), the casualty expectancy related to re-entering spacecraft has been generally quite low in recent years. The only exception was represented by the Russian payload IPM-3/PERSEY, in January 2022, with an estimated casualty expectancy slightly higher than 5×10^{-4}. For most of the spacecraft re-entered in the last few years, mainly represented by those of the Starlink constellation – with a re-entering mass around 227 kg for 60 of these and 260 kg for the remaining 197 – E_C was below the alert threshold. The estimated casualty expectancy for each Starlink satellite was about 6.4×10^{-5}, using Eq. (2) to compute the casualty area.

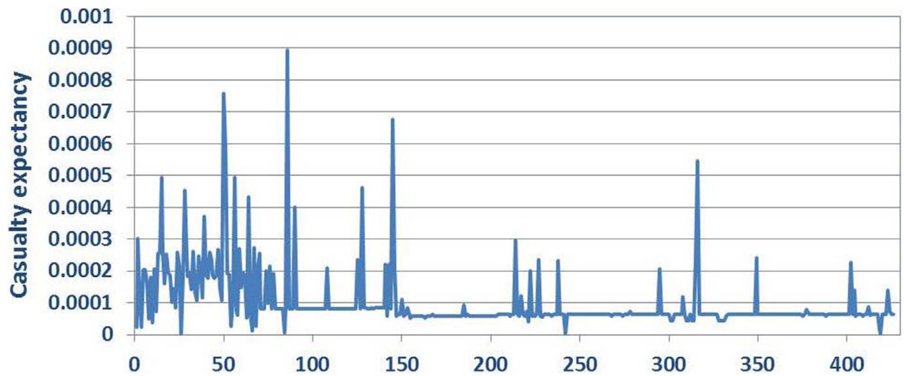

Fig. 19. Casualty expectancy associated with spacecraft re-entered uncontrolled from 2010 to 2022.

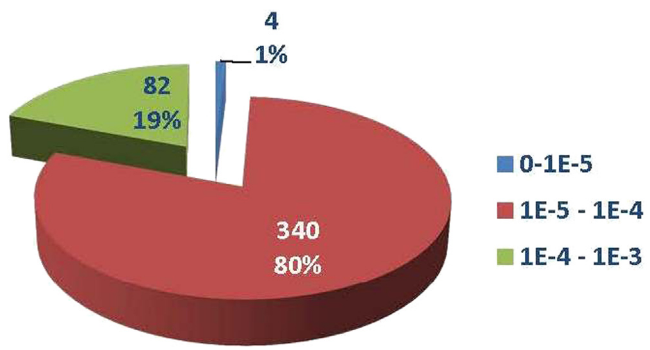

Fig. 20. Distribution, per casualty expectancy interval, of the re-entries of large spacecraft occurred uncontrolled between 2010 and 2022.

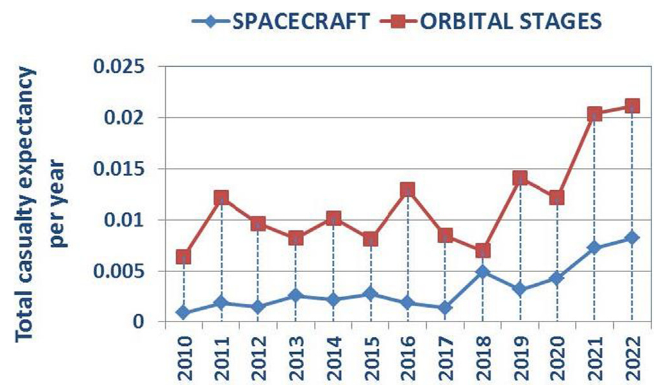

Fig. 21. Cumulative annual global casualty expectancy associated with uncontrolled re-entries of large spacecraft and orbital stages occurred between 2010 and 2022.

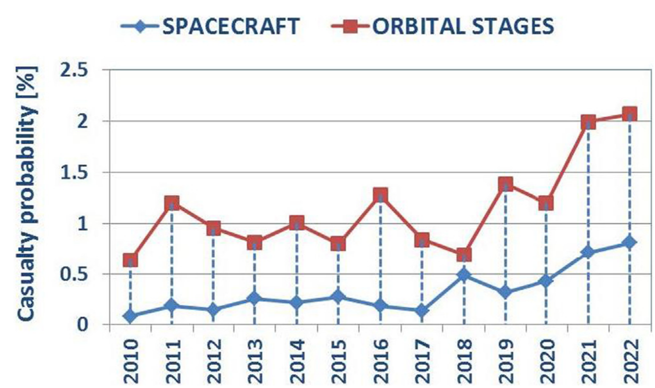

Fig. 22. Casualty probability associated with uncontrolled re-entries of spacecraft and orbital stages occurred between 2010 and 2022.

As summarized in Fig. 20, 81 % of the re-entered large spacecraft were characterized by $E_C < 10^{-4}$, while 19 % exceeded the risk threshold of 10^{-4}. Therefore, although the situation, from 2010 to 2022, was much better than for orbital stages, about one in five large re-entering spacecraft still surpassed the recommended risk ceiling.

3.8. Cumulative annual global casualty expectancy

For large orbital stages, the total casualty expectancy from 2010 to 2022 resulted to be around 1.51×10^{-1}, corresponding to a global casualty probability of approximately 14 %. Its average annual value was 1.16×10^{-2}, equivalent to a global casualty probability slightly above 1 % per year. For large spacecraft, the total casualty expectancy was 4.27×10^{-2}, implying a global casualty probability of about 4 %. The average annual E_C was 3.28×10^{-3}, corresponding to a global casualty probability of about 0.3 % per year.

The evolution of the cumulative annual global casualty expectancy is shown in Fig. 21, both for spacecraft and orbital stages. Concerning large spacecraft, it was below the 2010–2022 average from 2010 to 2017. It increased by nearly 46 %, with respect to the average, in 2018, due to the re-entry of 41 satellites of the Iridium constellation, then approached again the average in 2019, with a cumulative value around 3.2×10^{-3}. Afterwards, a progressive increase of the cumulative casualty expectancy was observed, mainly caused by the re-entry of many satellites of the Starlink constellation. The increase with respect to the average was around 144 % in 2022, even if only 5 % of the spacecraft had a casualty expectancy exceeding the 10^{-4} threshold that year.

Regarding large orbital stages, the cumulative annual global casualty expectancy was below the 2010–2022 average, or marginally above (in 2011 and 2016), up to 2018, then it definitely increased in the following years, growing by nearly 76 % in 2021 and by approximately 82 % in 2022, compared with the average. In 2022, almost 79 % of the uncontrolled re-entries of large orbital stages had a casualty expectancy exceeding the 10^{-4} threshold, and the total casualty expectancy associated with them was 0.0212 (Fig. 21).

3.9. Casualty probability

The annual probability that uncontrolled re-entries could have injured or killed at least one person on the ground was estimated using Eq. (3), and the results obtained are shown in Fig. 22. For spacecraft, this was below 0.5 % until 2020, then reached 0.8 % in 2022. Therefore, the casualty probability associated with the uncontrolled re-entry of spacecraft is still quite low, but the disposal of satellites from the current planned mega-constellations could

Table 4
Cumulative annual casualty expectancy (E_C) and casualty probability for large intact objects (spacecraft and orbital stages) re-entered uncontrolled from 2010 to 2022.

Year	Total E_C per year	Casualty probability [%]
2010	0.0073	0.72
2011	0.0141	1.39
2012	0.0120	1.19
2013	0.0108	1.07
2014	0.0123	1.22
2015	0.0108	1.07
2016	0.0148	1.46
2017	0.0098	0.97
2018	0.0119	1.17
2019	0.0173	1.70
2020	0.0163	1.61
2021	0.0276	2.69
2022	0.0293	2.85

significantly increase the likelihood of casualties on the ground in the coming years [10,11].

For re-entering orbital stages, the re-entry risk was always significantly higher, at least in the period analyzed, than that represented by spacecraft. In 2022, the total casualty expectancy associated with spacecraft was 0.0082, corresponding to a probability of having at least one victim of 0.8 %. The casualty expectancy associated with orbital stages was instead 0.0212, corresponding to a probability of having at least one victim on the ground of a little more than 2 %. Chinese upper stages accounted for nearly 65 % of the total risk, Russian/Soviet stages for about 15 %, and American stages for approximately 15 % (with 8 % associated with Falcon 9 second stages). Therefore, in 2022, the risk represented by the uncontrolled re-entry of orbital stages slightly exceeded 72 % of the total.

A global casualty probability of the order of 2 % per year may still seem quite low, but it can no longer be ignored, also because it has grown nearly four times from 2010 to 2022 and may increase even more in the coming years, as a consequence of the rapid growth of space launch activities, if a significant fraction of orbital stages will continue to re-enter without control [15,16].

Between 2010 and 2022, the cumulative annual casualty expectancy and probability due to the uncontrolled re-entry of large intact objects, i.e. spacecraft and orbital stages, are summarized in Table 4. Globally, during the 13 years from the beginning of 2010 to the end of 2022, the total casualty expectancy from uncontrolled re-entries of large intact objects was estimated to be 0.194, corresponding to a casualty probability of about 18 %. On an annual basis, the chance of injuring or killing at least one person on the ground varied between 0.7 %, in 2010, and 2.9 %, in 2022. The mean annual value was 1.47 % ± 0.63 %, but from 2010 to 2018 it was 1.14 % ± 0.22 % and relatively stable. Only after 2018 did a significant upward trend begin to appear, multiplying in 2022 by almost a factor of four the casualty probability estimated for 2010.

4. Conclusions

Following previous analyses [8-12,15], the statistics and ground casualty risk of uncontrolled re-entries of large spacecraft and orbital stages were revisited and updated, for the 13 years from the beginning of 2010 to the end of 2022. The fragments from decaying space objects have fortunately not caused any casualties so far, and the individual risk from uncontrolled re-entries is still relatively small. However, the global risk was found to have increased distinctly since 2018, and it may further grow in the coming years, due to the significant evolution of space activities. In any case, it can no longer be ignored.

In 2022, almost 79 % of the uncontrolled re-entries of orbital stages and 5 % of those of spacecraft had a casualty expectancy exceeding 10^{-4}, namely the upper limit recommended by several safety and mitigation guidelines, standards and national laws adopted worldwide. Still in 2022, the global probability of having at least one person on the ground injured or killed by a debris from uncontrolled re-entries reached 2.9 %, a value certainly not negligible and attributable for almost 3/4 to orbital stages.

These results may be affected by several uncertainties, beginning with the adoption of the standard method recommended by NASA [2] for estimating the casualty expectancy. The casualty area estimates are individually uncertain as well, being obtained from a simplified relationship fitting the distribution of a reduced sample of (mostly simulated) cases. Finally, the results for spacecraft might be currently biased by the re-entries from a single constellation, namely Starlink, which could be much more, or much less, demising than assumed. That said, the approach taken is consistent with the international standards used for re-entry risk assessment and that is the best we can do now with the available information.

Therefore, based on our assessments, any initiative and effort aimed at changing the present situation, leading to widespread use of controlled re-entries not only for spacecraft, but for orbital stages as well, can only be welcome. An important step in this direction is undoubtedly represented by the «Letter to Space Agency Leaders on reducing risks from uncontrolled reentries of rocket bodies and other space objects», promoted by the Outer Space Institute of the University of British Columbia, in Vancouver, Canada. [16].

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.

CRediT authorship contribution statement

Carmen Pardini: Conceptualization, Software, Formal analysis, Data curation, Writing – review & editing, Project administration. **Luciano Anselmo:** Conceptualization, Writing – review & editing.

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