Uncontrolled Re-Entries of Spacecraft and Rocket Bodies: A Statistical Overview over the Last Decade

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Abstract

More than 24,400 catalogued orbiting objects have re-entered so far into the Earth's atmosphere since the beginning of the space age. The associated returning mass, close to 30,000 metric tons, was mainly concentrated in intact objects, i.e. payloads and spent upper stages, accounting for nearly 29% of the re-entered objects. During the 10 years from 2008 to 2017, almost 450 large intact objects have re-entered without control, with a total returning mass of approximately 900 metric tons. Since the beginning of 2018 until mid-November, nearly 86 metric tons of returned materials were associated with almost 65 uncontrolled re-entries of large intact objects, three of which with a mass exceeding 5 metric tons: the Zenit-3F second stage 2017-086D, the C-25 cryogenic upper stage 2017-031B, and the Chinese space station Tiangong-1.

After an overview of the most critical historic re-entry events, the attention will be focused on the re-entries of massive objects occurred without control from 2008 to 2017, by categorizing them in terms of relevance, re-entry frequency, returned mass, distribution in inclination, overflown latitude bands, eccentricity and perigee/apogee altitudes before re-entry. Cases in which spacecraft and rocket bodies components were retrieved, and eyewitnesses sightings were reported, will be presented as well. Finally, the relevant re-entries occurred without control in 2018 will be discussed, while conclusions will be drawn concerning the potential growing risk on the ground and in mid-air due to fragments surviving the re-entry.

Keywords: re-entered objects, uncontrolled re-entries, re-entry frequency, returned mass, re-entry risk, casualty expectancy.

1. Introduction

As of 5 November 2018, a total of 3362 payloads, 3853 rocket bodies and 17,231 orbital debris have re-entered into the Earth's atmosphere [1]. Since the beginning of the Space Age, this corresponded, on average, to the re-entry of one intact object (either payload or upper stage) every 3 days, plus the re-entry of one piece of debris every 31 hours. The associated returning mass, close to 30,000 metric tons, was mainly concentrated (~98%) in intact objects. During the 10 years from 2008 to 2017 re-entered, on average, 49 payloads, 40 rocket bodies and 355 debris per year, i.e. one intact object every 4 days.

Even though the potential risk posed on the ground and in mid-air by the surviving components is often roughly a function of the re-entering object mass, and the debris can be therefore generally neglected, the estimation of the number (and mass) of the intact objects which re-entered in the atmosphere without control is not straightforward, because in addition to the spacecraft associated with the manned space programs and to other controlled re-entries carried out for safety reasons, many classified military payloads systematically adopted controlled re-entries. Moreover, during the last decade, there was a positive trend involving the controlled re-entry of upper stages as well [2].

The database on "Satellite Decay & Re-Entry Data", compiled and maintained by the US Space-Track Organization (www.space-track.org), was used to acquire information on the "large", i.e. with a radar cross-section (RCS) > 1 m^2, intact objects plunged into the Earth's atmosphere from the beginning of 2008 until mid-November 2018. Therefore, from the data so obtained, the known controlled re-entries were sorted out in order to have a list of all the events occurred without control in the time span analysed.

Concerning the decade 2008-2017, it was found that almost 450 large intact objects had re-entered without control into the Earth's atmosphere, with an associated returning mass of about 900 metric tons, corresponding to an average re-entered mass of approximately 90 metric tons per year [3,4]. Whether between 5% and 30% of the 90 metric tons had survived re-entry, between 4500 kg and 27,000 kg of manmade debris might have crossed the airspace and hit the ground each year in the time span considered. The first half of 2018 was instead characterized by the re-entry of three massive objects, involving two spent upper stages and the Chinese space station Tiangong-1. However, in spite of a not negligible amount of mass suspected to have survived re-entry, and of at least fourteen events, from 2008 to 2018, in which spacecraft and rocket bodies components were retrieved, trivial damages to property occurred and no case of personal injury was confirmed.

Nevertheless, it cannot be excluded that uncontrolled re-entries of space objects might become of greater concern in the future, as a consequence of the increased use of space and growing population density on the ground. Moreover, even if the risk related to the re-entry of manmade space objects is still extremely low compared to other commonly accepted risks related to the lifestyle, or workplace and household safety, it cannot be commonly accepted as being inevitable. A growing number of national and international guidelines and standards consider 10^{-4} as the acceptable upper limit for the expected number of human casualties in each single re-entry. However, the uncontrolled re-entry of objects probably violating such casualty upper limit may be relatively frequent, even if generally unknown to governments and the public at large. As a matter of fact, there are several upper stages, with masses around 4 metric tons or more, which still mostly re-enter without control [3,4]. Moreover, it should not be ignored that also space vehicles intended for a controlled re-entry at the end of their mission may sometimes suffer failures, compromising the success of the planned targeted de-orbiting strategy. Finally, the planned deployment, in the coming decades, of mega-constellations consisting of thousands of satellites, to be de-orbited at the end-of-life for preventing the growth of orbital debris, might result into a significant integrated casualty expectancy even if each single spacecraft were compliant with the 10^{-4} threshold.

After an overview of the most relevant historic uncontrolled re-entries, involving both massive space objects or satellites with hazardous substances on board, this paper presents a statistical survey of the re-entries of spacecraft and upper stages during the 10 years from 2008 to 2017. The uncontrolled re-entries occurred since the beginning of 2018 until mid-November are discussed as well, by highlighting in particular those of two massive upper stages (a Zenit-3F second stage and a C-25 cryogenic upper stage) and that of the space station Tiangong-1.

2. Relevant historic uncontrolled re-entries

2.1 Uncontrolled re-entries of massive space objects

In terms of mass and number of fragments, the most critical re-entry event occurred so far was that involving the space shuttle orbiter Columbia, with a mass of 82 metric tons, which disintegrated over Texas on 1 February 2003. This tragic accidental breakup led to 84,000 recovered fragments in Texas, Louisiana and Arkansas, corresponding to 38% of the initial mass. In that occasion, the ground casualty expectancy exceeded 0.1, but, aside from the lives of the seven astronauts of the crew, nobody else was injured [5]. On 11 July 1979, the first American space station, Skylab (Figure 1), with a mass of 74 metric tons, scattered about 500 debris, with a mass of 20 metric tons, across the Australian Outback. The second stage of the Saturn V used to launch it (S-II-13), with a mass of 45 metric tons, had instead re-entered on the Atlantic Ocean, west of Madeira, on 11 January 1975 [6]. The 40 tons Soviet space station Salyut 7, with the heavy module Cosmos 1686 attached (Figure 2), broke up over southern Argentina on 7 February 1991 and at least three major fragments were retrieved [7]. Other cases involving the uncontrolled re-entry of experimental space stations were those of the Soviet Cosmos 557 and Salyut 2, each with a mass around 18 metric tons, on 22 and 28 May 1973, respectively, and that of the Chinese Tiangong-1, of more than 7 metric tons, on 2 April 2018 [8]. In total, around 50 uncontrolled re-entries involved objects of 7 metric tons or more [6].

Fig. 1. Skylab (courtesy of NASA).

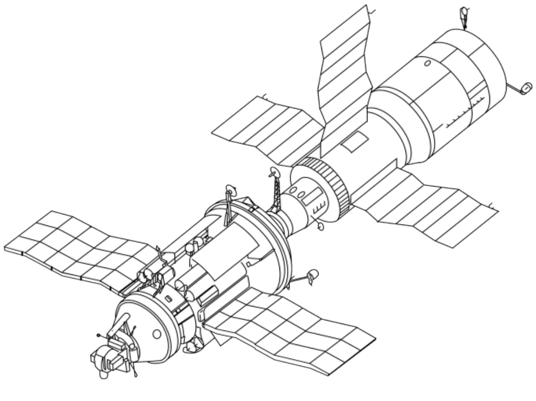

Fig. 2. Salyut 7 (right) docked with Cosmos 1686 (left) (courtesy of NASA).

2.2 Uncontrolled re-entries with hazardous substances

In general, the dry mass of a re-entering object and the materials of which it is made are the leading indicators of the possible risks on the ground, because more mass and fragments are able to survive, the higher will be the corresponding casualty expectancy due to kinetic impact. However, in specific 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.

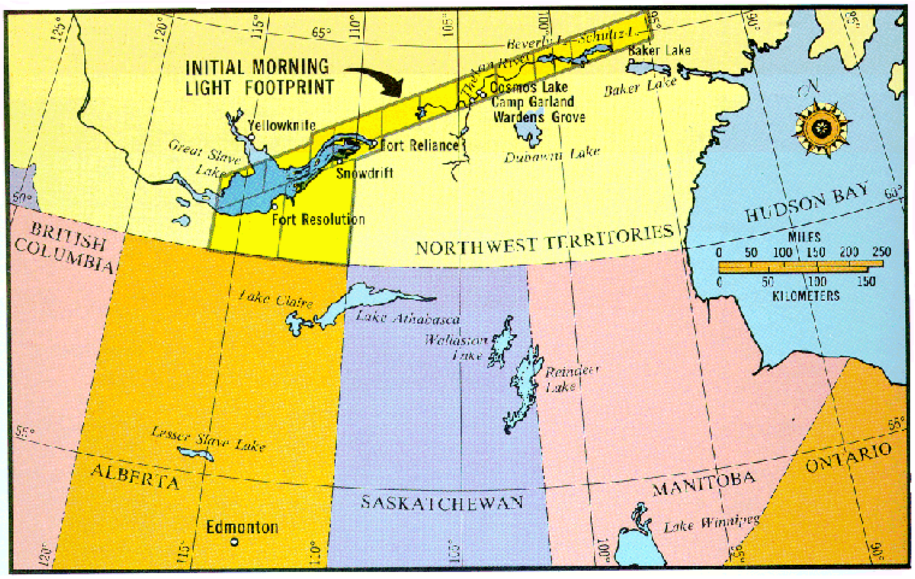

Fig. 3. Footprint of the Cosmos 954 debris as calculated from data obtained on final orbit and from visual observations (courtesy of Natural Resources Canada).

Fig. 4. First Cosmos 954 debris found (courtesy of Natural Resources Canada).

This became very clear with the uncontrolled re-entry, on 24 January 1978, of Cosmos 954, a Soviet military satellite for oceanic radar surveillance equipped with a nuclear reactor for generating electric power [9]. Probably two satellites of the same US-A model (from Upravlenniye Sputnik Aktivny, i.e. Controlled Active Satellite) had been previously involved in launch failures, on 25 January 1969 and on 25 April 1973 [10], but the nuclear reactors had not been still activated and basically contained approximately 30 kg of uranium, more than 90% enriched with the fissile isotope 235, but no significant amount of very radioactive fission products. For Cosmos 954, however, the situation was completely different. At the end of the very short mission, just 43 days [10], the satellite and the nuclear reactor were intended to be re-orbited into a graveyard circular orbit at an altitude of 900-1000 km. However, due to a failure, the control of the satellite was lost and its orbit decayed down to an uncontrolled re-entry over a sparsely inhabited area of Canada's Northwest Territories (Figures 3 and 4). Several large and highly radioactive fragments were scattered over a 600 km long strip, but a much wider area was contaminated by radioactive particulate [9]. The reactor is thought to have had at least 500,000 curies of fission product activity at shutdown [11], resulting in the event of far more serious radioactive contamination from a satellite re-entry recorded so far.

Spacecraft of the same type encountered similar problems again in 1982 and 1988. In the case of Cosmos 1402, the reactor core separated from the satellite, to improve the probability of a full disintegration at high altitude during the re-entry, but both objects plunged in the atmosphere uncontrolled. The satellite re-entered on 23 January 1983, the nuclear reactor fuel core on 7 February 1983, yet the re-entries occurred over oceanic areas and no significant change of the radioactivity levels was detected [12,13]. Concerning Cosmos 1900, a new automatic safety system was able to propel the nuclear reactor and the fuel core into a higher graveyard orbit just a few days before the uncontrolled re-entry, while the main instrument module of the satellite re-entered over the Indian Ocean on 1 October 1988, again with no consequences [14].

After these failures, this satellite program was suspended and no further nuclear reactor was launched in space after 1988. On the other hand, the use of radioisotope thermoelectric generators (RTG), i.e. of electric generators with no moving parts using an array of thermocouples to convert the heat released by the decay of radioactive isotopes, continued, even though restricted to space missions leaving the Earth's sphere of gravitational influence. These devices, more compact and less radioactive than activated nuclear reactors, were considered quite safer in case of launch or mission failures, as demonstrated by a series of accidental events.

The first occurred on 21 April 1964, when the American Transit-5BN-3 satellite (Figure 5) failed to achieve orbit. The RTG on board performed however as designed, completely spreading 17,000 curies of plutonium-238 fuel [15] during re-entry over the west Indian Ocean north of Madagascar, at an altitude between 60 and 45 km. This was confirmed four months later, when airborne sampling detected plutonium dioxide at an altitude of 33 km in the Southern Hemisphere [9].

The second American RTG accidental re-entry occurred on 18 May 1968, following the failed launch of the Nimbus B-1 satellite (Figure 5). This time the RTG, with an activity of 34,400 curies [15], was designed to survive the re-entry and to withstand the marine environment. Having impacted in the Santa Barbara Channel about 5 km north of San Miguel Island off the California coast, in waters with a depth of just 90 m, the RTG was therefore recovered intact five months later [9] and recycled [15].

The third and last American accident involved the aborted Apollo 13 mission to the Moon, on 17 April 1970. The RTG, intended to power for years the instruments to be deployed on the lunar surface, contained 44,500 curies of plutonium-238 and was stored in the Lunar Module Aquarius (Figure 5), which had served as a lifeboat for the stranded crew during the translunar trajectory. Discarded just before re-entry, the Lunar Module disintegrated in the atmosphere, but the RTG, encapsulated in a graphite container and designed to maintain its structural integrity, probably survived, plunging in the Pacific Ocean near the Tonga Trench, at a water depth between 6 and 9 km. No release of radioactivity was subsequently detected [9].

The last accident of this kind occurred on 17 November 1996 and involved a Russian probe for the exploration of Mars. The spacecraft, Mars 96, reached a parking orbit around the Earth, but the Proton Block D-2 fourth stage re-ignition, intended to place the probe into the planned interplanetary trajectory, failed, followed by the spacecraft separation and an automatic burn which caused its re-entry in the Earth's atmosphere. Mars 96 carried two Mars landers and two penetrators, equipped with a total of 6 RTGs for power generation using 200 g of plutonium-238, encapsulated in small pellets and casings designed to withstand heat and impact, and to survive re-entry. Based on a number of eyewitness accounts of the re-entry, it is believed that the remains of the probe actually fell in the mountainous region of the Andes between Chile and Bolivia, but no debris has been found or reported so far [6,16].

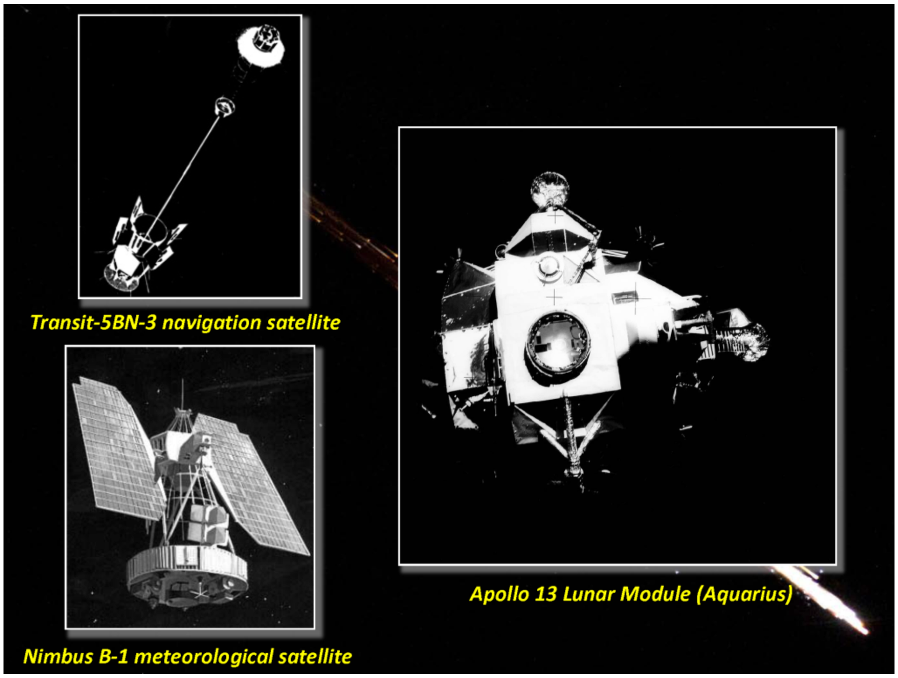

Fig. 5. US spacecraft equipped with RTGs experiencing accidental re-entries (not in scale; courtesy of NASA): Transit-5BN-3 navigation satellite; Nimbus B-1 meteorological satellite; Apollo 13 Lunar Module (Aquarius) after being jettisoned, just over an hour prior to splashdown of the Command Module (Odyssey) in the south Pacific Ocean. The explosion of oxygen tank number two in the Apollo 13 Service Module caused the crew members to rely on Aquarius as a lifeboat until re-entry.

It should also be recalled that on 23 September and 22 October 1969 two Soviet spacecraft, Cosmos 300 and Cosmos 305, probably destined to land on the Moon with Lunokhod rovers, failed the trans-lunar injection and re-entered in the Earth's atmosphere a few days after the launch [10]. If this identification is correct, each Lunokhod carried on board polonium-210 to keep their internal components warm during the two-week long lunar nights. In fact, 1 mg of polonium-210 emits as many alpha particles as 5 g of radium, and a single gram of the isotope generates 140 W of thermal power. In any case, following the two accidental re-entries, the US Department of Energy detected the release of high-altitude radiation [11].

In addition to the accidental re-entry of significant amounts of radioactive materials, other substances with high chemical toxicity may represent a non-negligible risk on the ground. This is the case, for instance, of hypergolic propellants, e.g. hydrazine, monomethylhydrazine (MMH), unsymmetrical dimethylhydrazine (UDMH) and dinitrogen tetroxide. Generally, during re-entry, these substances disperse and/or ignite at high altitudes, but in failed spacecraft they may also freeze in their heat resistant tanks, reaching the ground in significant amounts, to be later released as toxic clouds around the impact point.

A paradigmatic case was that of the American USA-193 satellite, launched at the end of 2006. Its mission, payload and characteristics were classified, but it was probably the first of a new type of high resolution radar imaging spacecraft, developed by the National Reconnaissance Office (NRO). Even though the launch was successful, the spacecraft immediately encountered a fatal failure, preventing the deployment of the solar arrays and any contact with the ground controllers [17].

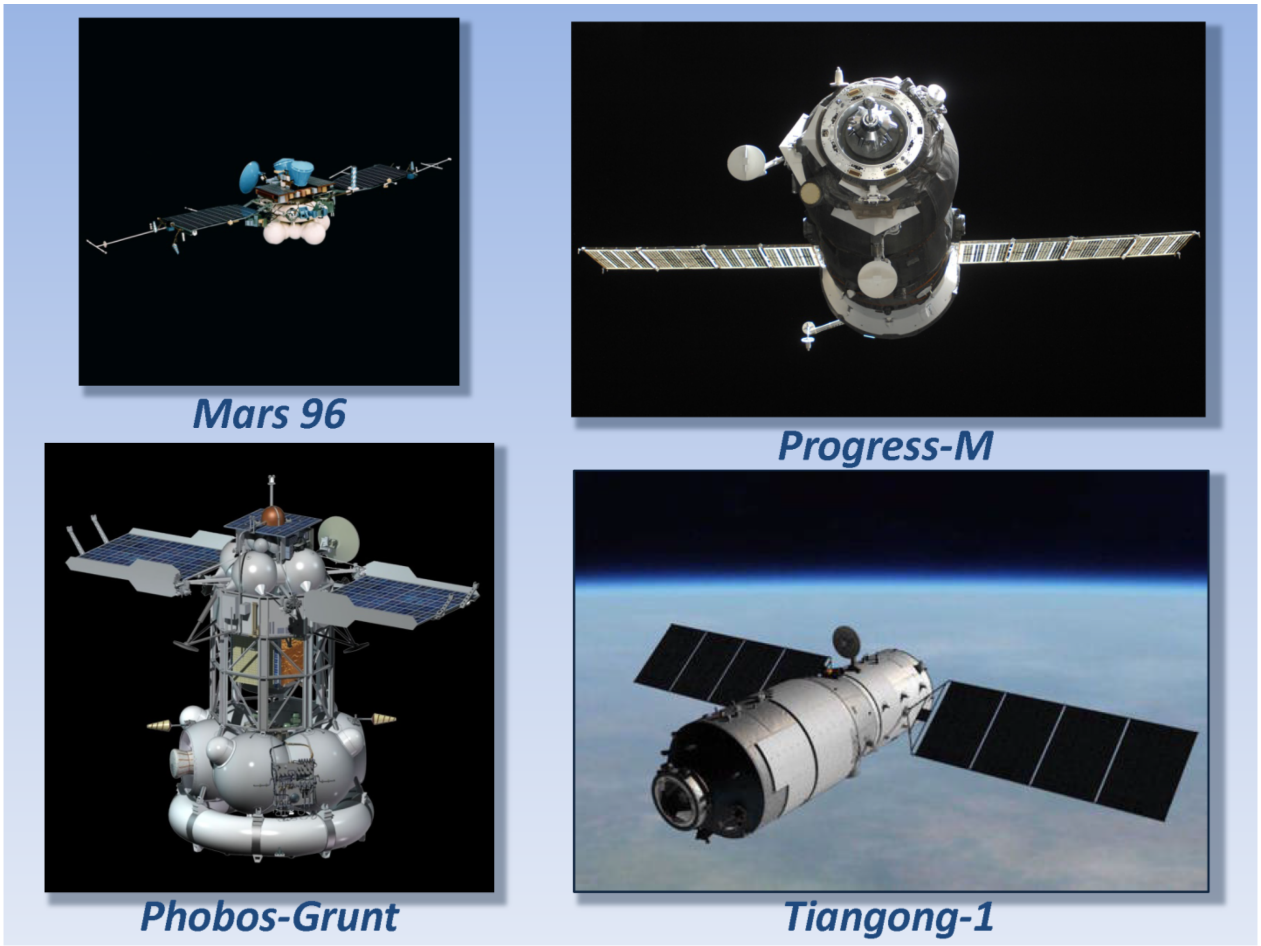

Fig. 6. A sample of spacecraft carrying on board a considerable amount of hypergolic propellants before re-entry (not in scale): Mars 96 (courtesy of NASA); Phobos-Grunt (courtesy of ESA); Progress-M cargo vessel (courtesy of NASA); Tiangong-1 (courtesy of Chinese Manned Space Agency).

At the beginning of 2008 it was finally clear that the imminent uncontrolled re-entry of USA-193 was unavoidable. Moreover, the US Government publicly announced its intention to destroy the dead satellite in space. The unprecedented move was justified by the need to destroy a 1-meter spherical propellant tank filled with about 450 kg of toxic hydrazine. The hydrazine, needed for orbit maintenance, had been never used, due to the premature spacecraft failure, and was now frozen inside the tank. The simulations carried out had shown, according to the US Government, that the tank was able to survive the re-entry conditions with most of the frozen propellant inside, with the concrete perspective of dispersing the sublimating hydrazine on the ground, over an area roughly the size of two football fields [18]. So, even though the probability of hitting a populated area was remote, the decision to destroy the satellite was considered the safest option, assuming a casualty expectancy of ~1:50.

At last, USA-193 was destroyed in the first hours of 21 February 2008. A modified SM-3 missile, carrying a lightweight exo-atmospheric projectile kinetic warhead, was fired from the Aegis cruiser USS Lake Erie, stationed west of the Hawaii Islands. The satellite was hit by the homing kill vehicle at a geodetic altitude of 249 km, with a relative impact velocity of about 9.8 km/s, and a catastrophic breakup occurred. More than 50% of the fragments re-entered within 45 minutes of the intercept. All the others did so in the following several months [17].

Sizable amounts of hypergolic propellants had already re-entered uncontrolled in the past (see Figure 6 for recent events), for instance in the case of Mars 96, on 17 November 1996, already remembered for the plutonium-238 carried on board. In that case, the unused propellant amounted to about 3000 kg. More recent remarkable cases involved Phobos-Grunt, on 15 January 2012, with 11,150 kg of hypergolic propellants [19], Progress-M 27M, on 8 May 2015, with 1373 kg [20], and Tiangong-1, on 2 April 2018, with 350 kg [3,4,21]. In none of these latter cases, all occurring over oceanic areas, as well as for Mars 96, re-entered on land, has environmental pollution been reported. However, all the events affected very remote areas, so the lack of evidence does not imply that no pollution occurred. Moreover, the aggregation status of the propellants before re-entry, either liquid or frozen, was unknown.

3. Uncontrolled re-entries of large intact objects from 2008 to 2017

A data file of large intact objects, re-entered without control during the 10 years from 2008 to 2017, was built by sorting out all the known controlled re-entries from the "Satellite Decay & Re-Entry Data" provided by the US Space-Track Organization. Large debris were excluded from the analysis, while only large payloads and rockets bodies, i.e. with RCS > 1 m^2, were considered. The data file obtained at last included 448 large intact objects, of which 366 (~82%) were represented by rocket bodies and 82 (~18%) by payloads.

A further massive effort was dedicated to assign a reasonable value for the mass to each of the 448 objects. Different sources of data were considered for this task. The main help came from the DISCOS Database of the European Space Agency (ESA) [22]. Others were the Mark Wade's Encyclopedia Astronautica [23], the NASA Space Science Data Coordinated Archive [24] and the Jane's Space Directory book [25]. The dry mass was generally considered for each object, with the only exceptions of the Phobos-Grunt and Progress-M 27M spacecraft, which included instead considerable amounts of fluids before re-entry. In the first case the returning mass was 13,525 kg, but it consisted of 11,150 kg of very toxic liquid hypergolic propellants and just 2375 kg of inert mass [19]. In the second case, having the spacecraft never fired its engines after the anomalous separation from the upper stage of the Soyuz-2-1a launcher [26], 1373 kg of propellants were still on board of Progress-M 27M before re-entry [20], accounting for nearly 19% of the launch mass (7289 kg), plus 420 kg of water, 50 kg of compressed oxygen and 1393 kg of dry cargo for the resupply of the International Space Station.

At the end, among all the large intact objects re-entered without control in the 10 years considered, it was found that only one was lighter than 50 kg, 55 out of 448 objects, i.e. 12% (14 spacecraft and 41 upper stages) had masses from 50 to 500 kg, 376, i.e. 84% (66 spacecraft and 310 upper stages) were between

500 and 5000 kg, and only 17, i.e. 4% (3 spacecraft and 14 upper stages) exceeded 5 metric tons (Table 1). The total returning mass associated with the 448 uncontrolled re-entries was approximately 911 metric tons, of which 83% belonging to spent upper stages and the remaining 17% to spacecraft. Most of the mass (98.5%) was concentrated in 392 objects (324 rocket bodies and 68 spacecraft) heavier than 500 kg, while 13.2% in 17 objects (14 rocket bodies and 3 spacecraft) heavier than 5000 kg (Table 2).

Table 1. Number of large intact objects re-entered without control from 2008 to 2017, in terms of the mass (*M*) of the objects.

Object Mass [kg]	**Number of large intact objects re-entered without control from 2008 to 2017**		
	Intact Objects	**Spacecraft**	**Upper Stages**
$M \leq 50$	1	0	1
$50 < M \leq 500$	55	14	41
$500 < M \leq 5000$	376	66	310
$M > 5000$	17	3	14
Total re-entries	**448**	**82**	**366**

Table 2. Total returning mass associated with upper stages, spacecraft, and intact objects heavier than 50, 500 and 5000 kg.

	Number and cumulative mass of the intact objects re-entered without control from 2008 and 2017					
	$M > 50$ kg		**$M > 500$ kg**		**$M > 5000$ kg**	
	No.	**Mass [kg]**	**No.**	**Mass [kg]**	**No.**	**Mass [kg]**
Upper Stages	366	754,142	324	744,637	14	93,808
Spacecraft	82	157,098	68	153,254	3	26,482
Intact Objects	448	911,240	392	897,891	17	120,290

3.1 Relevance of uncontrolled re-entries

At international level, an uncontrolled re-entry is generally considered at risk by several guidelines, standards or national laws if the global casualty expectancy exceeds 10^{-4} or, in other words, if the chance for anybody anywhere in the world of being injured by a piece of falling debris from a single uncontrolled re-entering object is greater than 1:10,000. Unfortunately, detailed and reliable estimates of the casualty expectancy are publicly available only for very few objects, typically ~1% of the relevant ones. Therefore, other rough evaluation criteria must be used, based on size, mass or supplementary noteworthy information, like the presence on board of significant amounts of toxic or radioactive substances, or of sizable components made of materials able to survive the harsh conditions of the re-entry. In order to roughly characterize in a synthetic way the relevance of uncontrolled re-entries when detailed information is not available, a magnitude scale was introduced at CNR, in Pisa, in 1995 [27]. This uncontrolled re-entry magnitude M_R was slightly modified in 2017 [3,4] and is currently defined as follows:

$$M_R = \log_{10} [(\text{dry mass of re-entering object in kg}) / 100] + 0.3 \tag{1}$$

Table 3 shows how this magnitude is related to the mass and the associated alert colour code adopted by ISTI/CNR. A rough order of magnitude matching with the expected global casualty expectancy, when the re-entering dry mass is the dominant source of (mechanical) risk, the final orbit is nearly circular, the inclination is greater than 30° and the world population is that of 2018, was estimated as well. For re-entering masses lesser than 10 metric tons this guess is in good agreement with the logarithmic debris casualty area vs. re-entering dry mass distribution found in [28]. However, for higher masses, tacking also into account the modular structure of large space objects, a linear casualty area vs. re-entering dry mass distribution was assumed.

Table 3. ISTI/CNR uncontrolled re-entry magnitude scale definition when the re-entering dry mass is the dominant source of (mechanical) risk. For nearly circular orbits with inclination greater than 30° and the world population of 2018, a rough order of magnitude matching with the expected global casualty expectancy is provided as well.

Dry mass M_0 of the re-entering object [kg]	**Uncontrolled re-entry magnitude M_R**	**Casualty expectancy E_C (order of magnitude)**	**ISTI/CNR alert colour code**
$M_0 \leq 50$	$M_R < 0$	$E_C < \sim10^{-5}$	White
$50 < M_0 \leq 500$	$0 \leq M_R < 1$	$\sim10^{-5} < E_C < \sim10^{-4}$	Light blue
$500 < M_0 \leq 5000$	$1 \leq M_R < 2$	$\sim10^{-4} < E_C < \sim10^{-3}$	Green
$5000 < M_0 \leq 50,000$	$2 \leq M_R < 3$	$\sim10^{-3} < E_C < \sim10^{-2}$	Yellow
$50,000 < M_0 \leq 500,000$	$3 \leq M_R < 4$	$\sim10^{-2} < E_C < \sim10^{-1}$	Orange
$500,000 < M_0 \leq 5,000,000$	$4 \leq M_R < 5$	$\sim10^{-1} < E_C < \sim1$	Red

Therefore, by comparing and merging Tables 1 and 3, it resulted that 16 uncontrolled re-entries (herein Phobos-Grunt was not part of the tally because its dry mass was lesser than 5000 kg), occurred from 2008 to 2017, had a casualty expectancy probably exceeding by one order of magnitude the acceptable upper limit of 10^{-4}. Such potentially risky events had an associated re-entry magnitude between 2 and 3 (Table 3), and a casualty expectancy of the order $\sim10^{-3}$ (Figure 7). 376 objects (84%) had a re-entry magnitude in between 1 and 2, and a casualty expectancy from approximately $\sim10^{-4}$ to $\sim10^{-3}$ (Figure 7). Finally, 23 (12%) objects had a re-entry magnitude lesser than 1, roughly related to a casualty expectancy below the accepted threshold for the risk, i.e. $< 10^{-4}$, while only 1 had a casualty expectancy lesser than $\sim10^{-5}$.

With reference to the past uncontrolled re-entries of sizable space objects (Section 2.1), only two would have had so far, on the basis of the ISTI/CNR classification, a magnitude $M_R > 3$ (orange colour code), roughly corresponding to a casualty expectancy exceeding $\sim10^{-2}$. They were the disastrous return of the Columbia space shuttle orbiter (M_0 = 82,000 kg), in 2003, and the decay of the Skylab space station (M_0 = 74,000 kg), in 1979. In the first case, the ground casualty expectancy was estimated to exceed 10^{-1} over the specific re-entry ground track in the contiguous United States where the accidental breakup occurred [5]. Also the largest manmade space object ever re-entered into the Earth's atmosphere, i.e. the Russian space station Mir, with a mass of about 135 metric tons, would have posed a substantial risk (orange colour code) if its re-entry had not been successfully controlled up to the splashdown of the largest fragments on the planned disposal area in the southern Pacific Ocean, on 23 March 2001. An orange colour code would be also associated with the International Space Station, with a mass exceeding 400 metric tons, if it were to be abandoned and its uncontrolled re-entry could not be avoided. A yellow colour code, with $2 \leq M_R < 3$ and an associated casualty expectancy ranging from $\sim10^{-3}$ to $\sim10^{-2}$, would have on the other hand characterized, among others, the re-entries of the second stage of the Saturn V used to launch Skylab (M_0 = 45,100 kg), the complex Salyut 7/Cosmos 1686 (M_0 = 40,000 kg), the space stations Cosmos 557 and Salyut 2 (M_0 = 18,300 kg), and several Zenit-3F (SL-23, according to the US Department of Defense designation) upper stages (M_0 = 9300 kg).

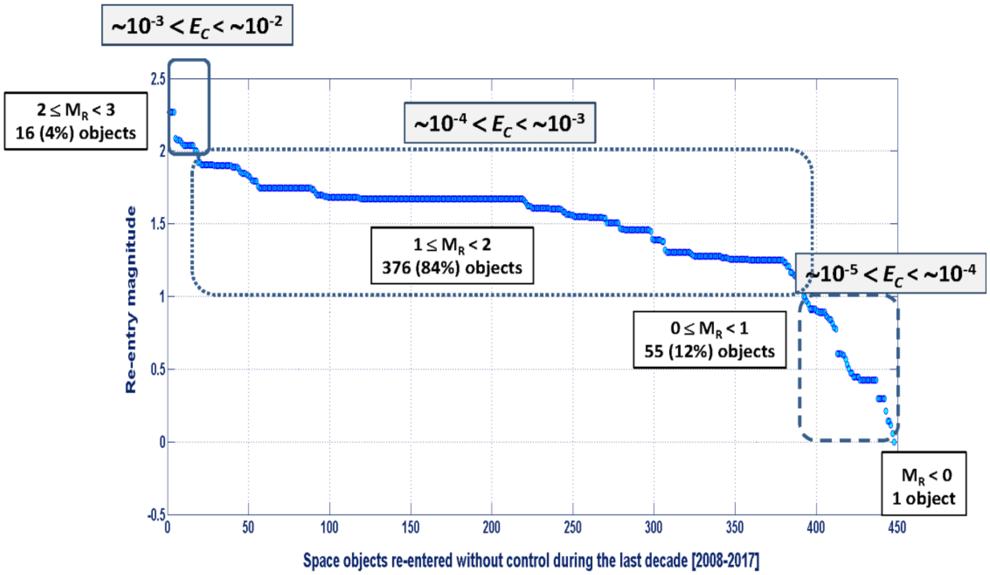

Fig. 7. Re-entry magnitude, with the associated order of magnitude of global casualty expectancy, for the 448 large intact objects re-entered without control in the 10 years between 2008 and 2017.

3.2 Frequency of uncontrolled re-entries

Taking into account that spacecraft and upper stages lighter than 500 kg would have probably posed a relatively small risk during re-entry (see Table 3 and Figure 7), from now on the attention will be focused on objects heavier than one half metric ton. That said, between 2008 and 2017 re-entered uncontrolled into the Earth's atmosphere 392 intact objects with $M > 500$ kg (Table 2). Of these, 324 were rockets bodies, corresponding to about 88% of those with $M > 50$ kg, and 68 were spacecraft, accounting for approximately 83% of those heavier than 50 kg. Figure 8 shows the yearly re-entry rate for these objects. Over the decade 2008-2017, 32 rocket bodies and 7 spacecraft with $M > 500$ kg re-entered, on average each year, corresponding to the re-entry of one intact object every about 9 days.

Concerning the objects with a mass above 5000 kg, from 2008 to 2017 re-entered uncontrolled 14 rocket bodies, i.e. approximately 4% of those with $M > 50$ kg, and 3 spacecraft, still representing about 4% of those with $M > 50$ kg (Figure 9). Therefore, the re-entry of one intact object with $M > 5000$ kg occurred, on average, every 215 days. The 3 sizable re-entered spacecraft were the NASA's Upper Atmosphere Research Satellite (UARS), on 24 September 2011, with a mass of 5668 kg [19], the Phobos-Grunt failed Mars exploration probe, on 15 January 2012, with a mass of 13,525 kg (including 11,150 kg of very toxic liquid hypergolic propellants) [19], and the not working Progress-M 27M cargo ship, on 8 May 2015, with a mass of 7289 kg (including 1373 kg of highly toxic propellants) [20]. The 14 re-entered rocket bodies included 4 Russian-Ukrainian Zenit upper stages (1 SL-16 and 3 SL-23), 9 upper stages of the Long March Chinese launcher (2 CZ-7 and 7 CZ-2F) and the complex Dragon/Falcon 9. The latest was, to be exact, a Dragon qualification unit, structurally identical to the Dragon capsule, but lacking the instrumentation and the equipment. For the purposes of the experiment, it was intended to remain attached to the Falcon 9 final stage and to return to Earth without control.

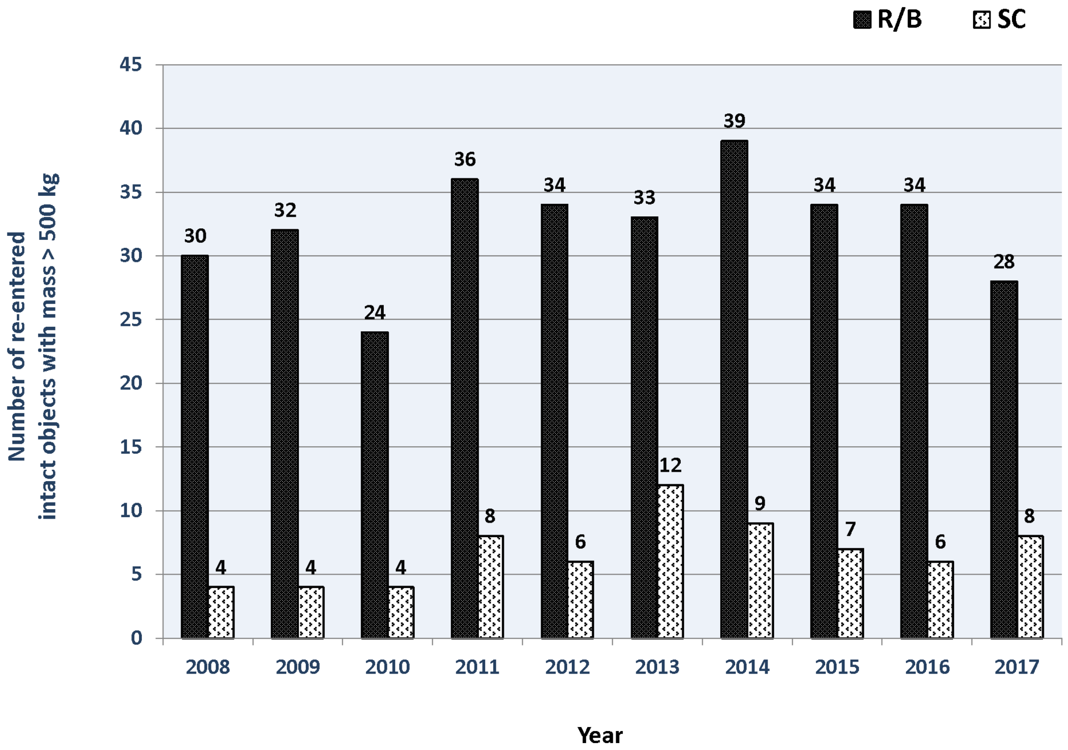

Fig. 8. Uncontrolled re-entry frequency for rocket bodies (R/B) and spacecraft (SC) with M > 500 kg in the 10 years from 2008 to 2017.

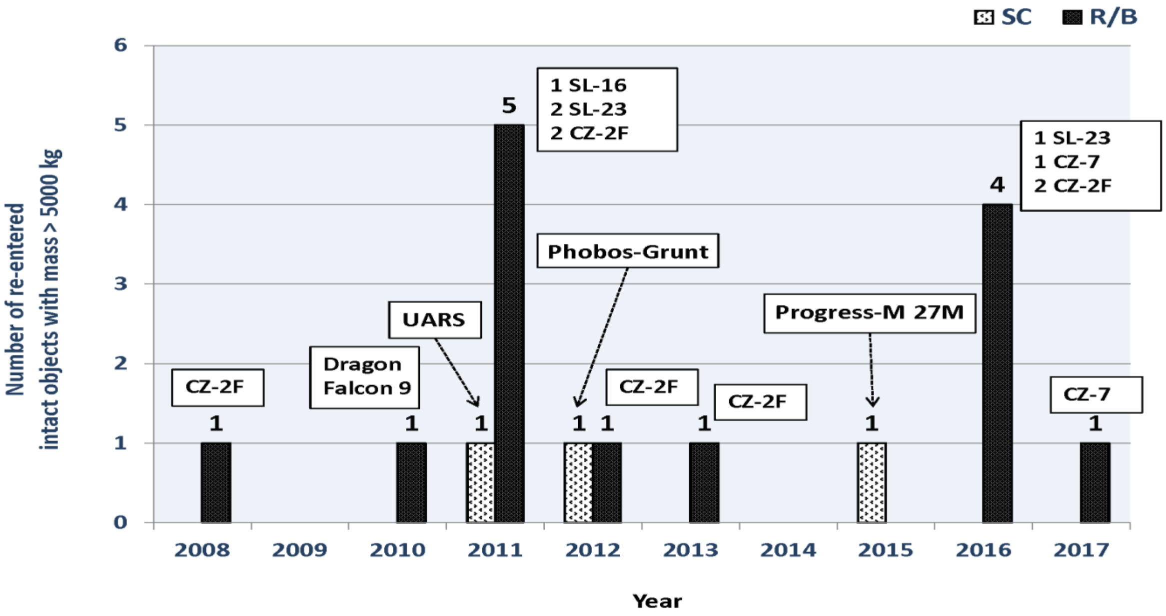

Fig. 9. Uncontrolled re-entry frequency for rocket bodies (R/B) and spacecraft (SC) with M > 5000 kg in the 10 years from 2008 to 2017.

3.3 Yearly returned mass

Regarding the returning mass associated with the objects heavier than 500 kg decayed from 2008 to 2017, it was found that the average re-entered mass per year was almost 90 metric tons, of which nearly 75 tons (83%) were concentrated in rocket bodies and about 15 tons (17%) belonged to spacecraft (Table 2). The returned mass per year, both for spacecraft and rocket bodies, is plotted in Figure 10.

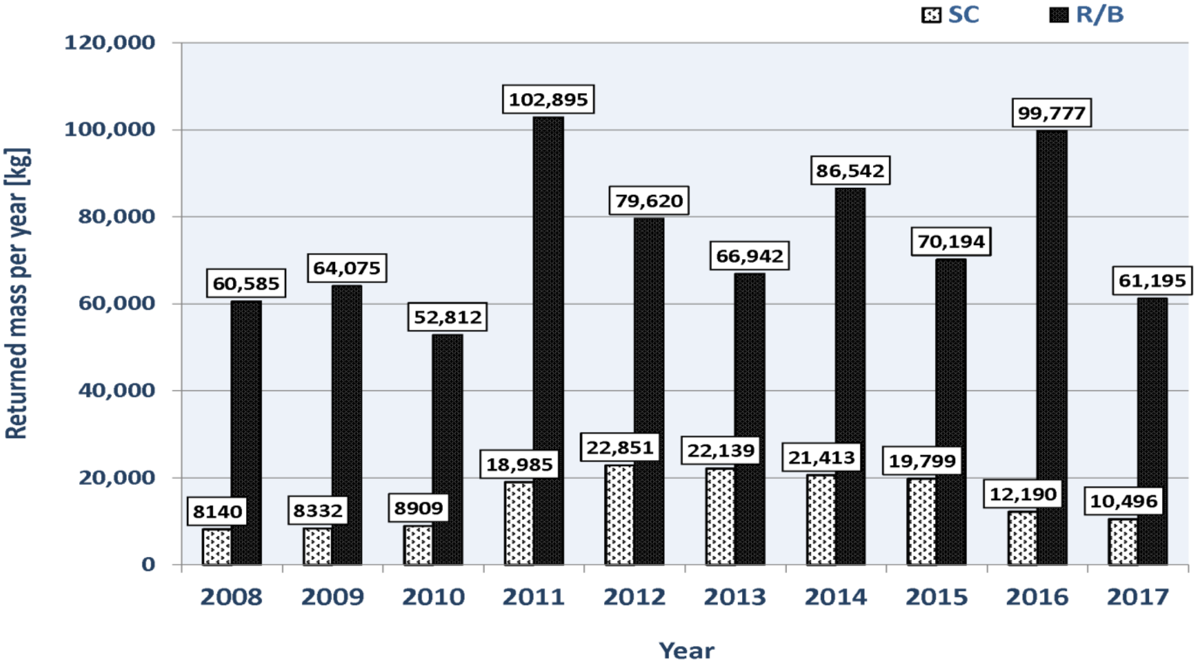

Fig. 10. Yearly returned mass (in kg) associated with the uncontrolled re-entry of rocket bodies (R/B) and spacecraft (SC) heavier than 500 kg in the 10 years from 2008 to 2017.

According to the values reported in Table 2, the total returned mass concentrated in objects heavier than 5000 kg was 120,290 kg, corresponding, on average, to the re-entry of approximately 12 metric tons per year. Table 4 lists the 17 objects with $M > 5000$ kg re-entered without control from 2008 to 2017. It is worth noting that in addition to the three above mentioned spacecraft, there were also two upper stages of the Chinese Long March rocket (CZ-2F) used to launch the space stations Tiangong-1 (international designator: 2011-053B) and Tiangong-2 (international designator: 2016-057B). Both stages had a mass of nearly 5500 kg. Except for the Dragon/Falcon 9 complex, with an inclination of 34.48°, all the other 16 objects overflew the Italian territory.

3.4 Distribution in inclination

Still focusing the attention on the 392 objects with $M > 500$ kg (Table 2), it was found that nearly 18% came from retrograde orbits (i.e. with inclination > 90°), 25% had an orbit inclination > 70°, 47% between 50° and 70°, 8% between 30° and 50°, and 20% below 30° (see Figure 11). Taking into account the overall distribution in inclination of the 392 re-entries analysed, it resulted that the Italian territory would not have been affected in 23% of the cases, i.e. by all the objects with an inclination below around 36°.

The number of re-entered objects per inclination range, with the associated percentage, is reported in Table 5. The highest concentration (108 re-entries) corresponded to the inclination range between 50° and 60°, followed by the objects in the inclination range between 60° and 70° (76 re-entries), and by those decayed from retrograde orbits (70 re-entries).

Table 4. Objects with $M > 5000$ kg re-entered without control into the Earth's atmosphere from 2008 to 2017.

Space object	International Designator	Re-entry epoch	Mass [kg]	Inclination [deg]
CZ-2F R/B	2008-047B	17/10/2008	5502	42.39
DRAGON/FALCON 9	2010-026A	27/06/2010	6100	34.48
SL-23 R/B	2011-001C	19/03/2011	9300	51.39
SL-23 R/B	2011-037D	08/08/2011	9300	51.38
UARS	1991-063B	24/09/2011	5668	60.35
CZ-2F R/B	2011-053B	10/10/2011	5500	42.78
CZ-2F R/B	2011-063B	08/11/2011	5502	42.77
SL-16 R/B	2011-065B	22/11/2011	9300	51.42
PHOBOS-GRUNT	2011-065A	15/01/2012	13,525	61.73
CZ-2F R/B	2012-032B	26/01/2012	5502	42.77
CZ-2F R/B	2013-029B	21/06/2013	5502	42.77
PROGRESS-M 27M	2015-024A	08/05/2015	7289	64.76
SL-23 R/B	2015-074C	02/01/2016	9300	51.36
CZ-7 R/B	2016-042E	28/07/2016	6000	40.79
CZ-2F R/B	2016-057B	29/09/2016	5500	42.78
CZ-2F R/B	2016-061B	04/11/2016	5500	42.77
CZ-7 R/B	2017-021B	18/05/2017	6000	42.76

Table 5. Number and percentage of re-entered intact objects with $M > 500$ kg per inclination range.

Inclination range	Number of re-entered intact objects	Percentage of re-entered intact objects [%]
> 90°	70	18
80° – 90°	29	7
70° – 80°	0	0
60° – 70°	76	19
50° – 60°	108	28
40° – 50°	19	5
30° – 40°	11	3
20° – 30°	45	11
10° – 20°	14	4
0° – 10°	20	5

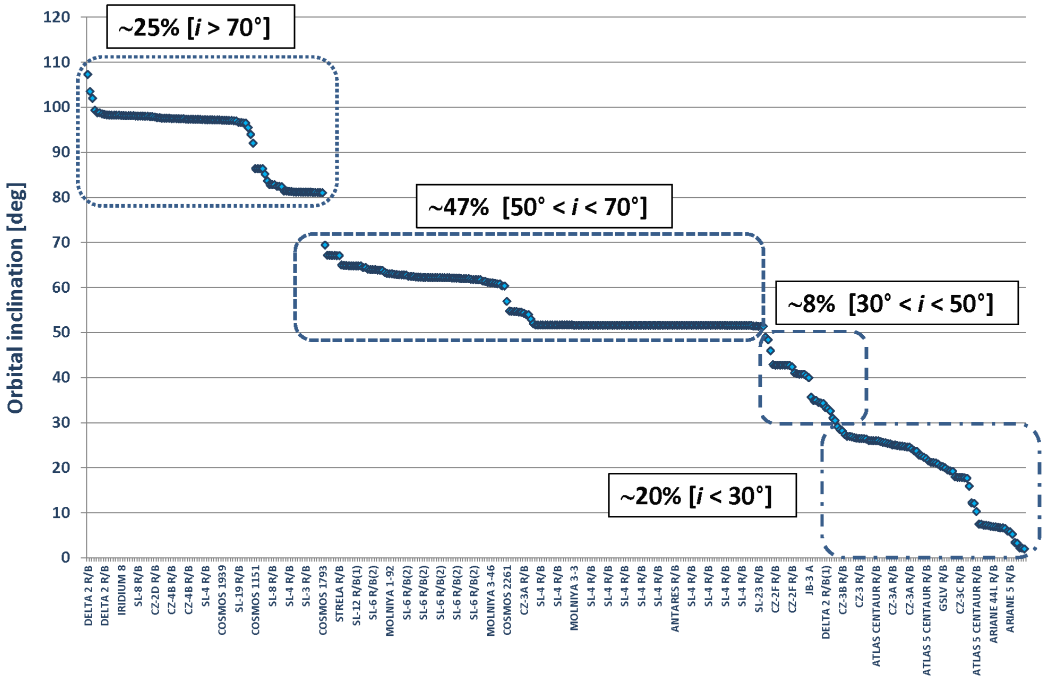

Fig. 11. Distribution in inclination (i) of the intact objects with $M > 500$ kg re-entered uncontrolled from 2008 to 2017.

3.5 Latitude bands overflown

The latitude belt potentially affected by the impact of the surviving fragments of a re-entering object results from the following relationships [29]:

$$L_{max} = i + \delta + \Lambda \text{ [for direct orbits]} \tag{2}$$

$$L_{max} = 180° - i + \delta + \Lambda \text{ [for retrograde orbits]} \tag{3}$$

where L_{max} is the limiting latitude, north or south, of the latitude belt, i is the satellite orbit inclination, δ is a small corrective term, to convert from geocentric to geodetic coordinates, and Λ is the maximum cross-track dispersion of the fragments with respect to the nominal trajectory (herein expressed in terms of the angle with respect to the centre of the Earth and typically < 1°). The term δ reaches its maximum (~0.2°) at intermediate latitudes, but vanishes at the poles and the equator. The re-entry probability is latitude dependent, minimum on the equator and maximum close to the extreme latitudes for a near circular orbit [30]. The satellite surviving fragments might hit the surface of the Earth anywhere in between $-L_{max}$ and $+L_{max}$.

On the basis of the distribution in inclination of the 392 objects with $M > 500$ kg, re-entered without control between 2008 and 2017, and neglecting the small contribution of δ, the overflown latitude bands were found. It resulted that nearly 95% of the re-entered objects overflew regions of the planet with latitudes, north or south, > 10°, 91% with latitudes > 20°, 80% with latitudes > 30°, 77% with latitudes > 40°, 72% with latitudes > 50°, 45% with latitudes > 60°, 25% with latitudes > 70°, and 24% with latitudes > 80° (Figure 12).

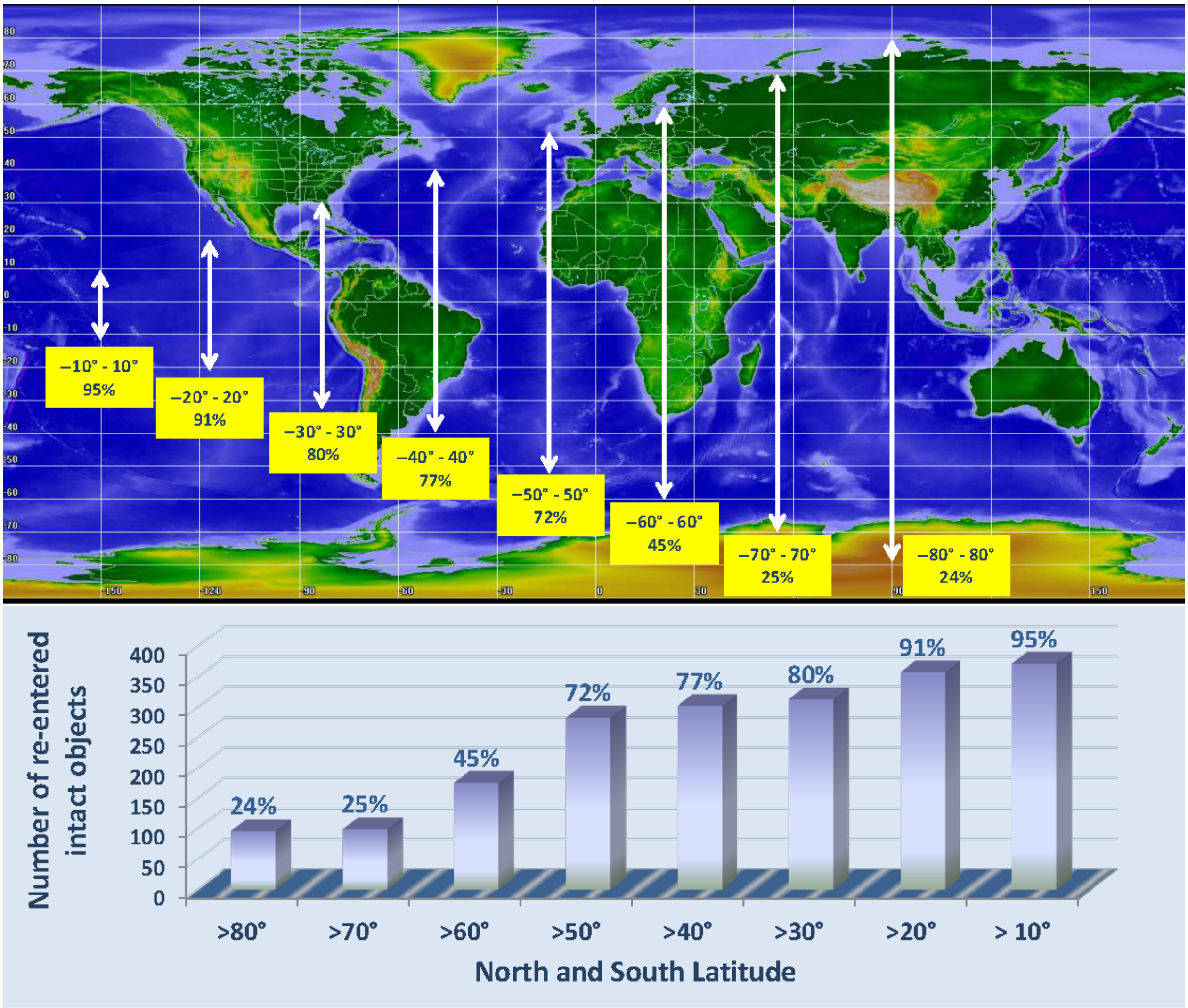

Fig. 12. Latitude bands overflown by the objects with $M > 500$ kg re-entered uncontrolled from 2008 to 2017. The percentage of the objects overflying latitude bands of assigned amplitude is shown.

3.6 Eccentricity and perigee/apogee distributions before re-entry

Information on the eccentricity (e) and perigee/apogee altitude of objects before re-entry was attained using their last orbit available in the US Space-Track Organization website. All the 448 large intact objects re-entered uncontrolled from 2008 to 2017, i.e. also those with $M < 500$ kg, were considered. It was found that approximately 45% of the objects were in almost circular orbits ($0 < e < 0.001$) before re-entry, about 28% had very low eccentricity orbits ($0.001 < e < 0.01$), nearly 24% came from low to moderate eccentricity orbits ($0.01 < e < 0.1$), and only 3% were in highly elliptic trajectories ($e > 0.1$). Therefore, most (~73%) of the large intact objects approached the re-entry from nearly circular orbits ($0 < e < 0.01$), while the remaining 27% came from low to moderate (24%) and high (3%) eccentricity orbits (Figure 13). The perigee/apogee altitudes of objects before re-entry, still inferred from the last orbits available, are represented in Figure 14.

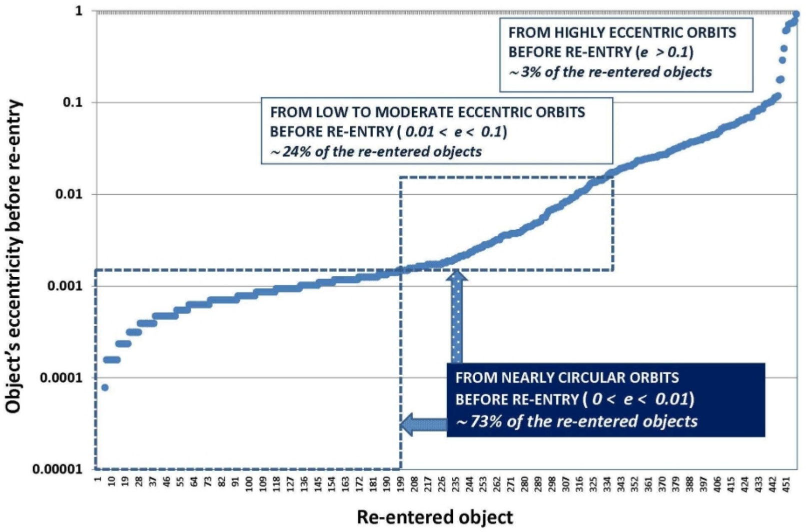

Fig. 13. Distribution of the orbit eccentricity before re-entry for the large intact objects decayed without control from 2008 to 2017.

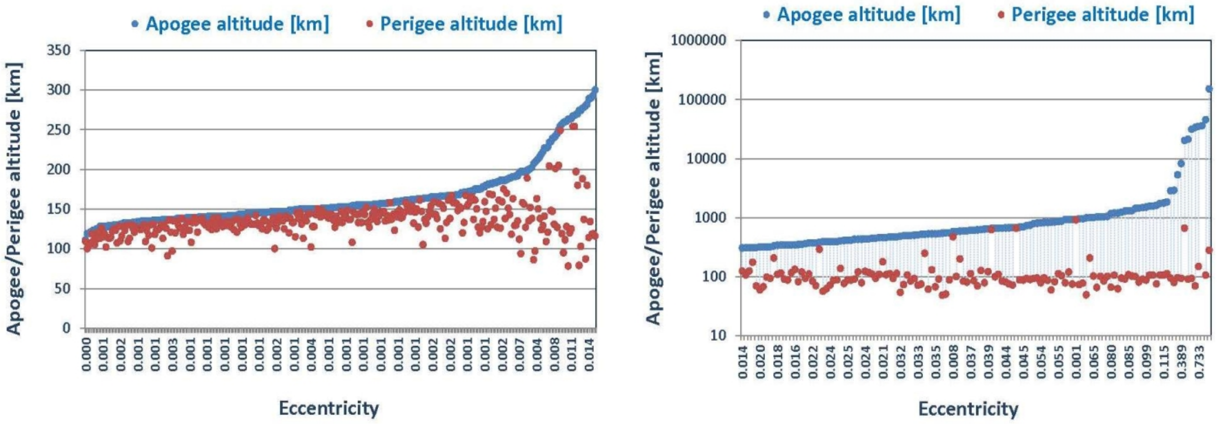

Fig. 14. Distribution of the perigee/apogee altitudes before re-entry for objects decayed without control from 2008 to 2017 (Left panel: $0 < e \leq 0.014$; Right panel: $0.014 < e < 0.963$). The highest eccentricity was 0.92, corresponding to the last orbit of the Proton (SL-12) upper stage with international designator 2002-048C, re-entered on 3 November 2010, with a perigee/apogee altitude of 280 × 151,116 km.

3.7 Eyewitness sightings and recovered debris

For a number of re-entry events eyewitness sightings were reported and/or pieces of debris were recovered. Recorded sightings were available in the Aerospace Corporation website since 2010 [31]. Therefore, considering the period of time between 2010 and 2017, the large re-entered intact objects were 373 (instead of the 448 objects re-entered from 2008 to 2017), including 299 rocket bodies and 74 spacecraft. Among these, sightings were reported for 34 re-entry events, i.e. in nearly 9% of the cases. Figure 15 shows the 34 uncontrolled re-entries, from 2010 to 2017, for which sightings were reported: 27 were for rocket bodies and 7 for spacecraft. The satellites, identified by boxed re-entry years in the figure, were: Cosmos 1484 and GOCE, re-entered in 2013; Cosmos 1220 and Cosmos 1400, re-entered in 2014; Cosmos 1315 and NFIRE, re-entered in 2015, and JB-3A, plunged into the Earth's atmosphere in 2016.

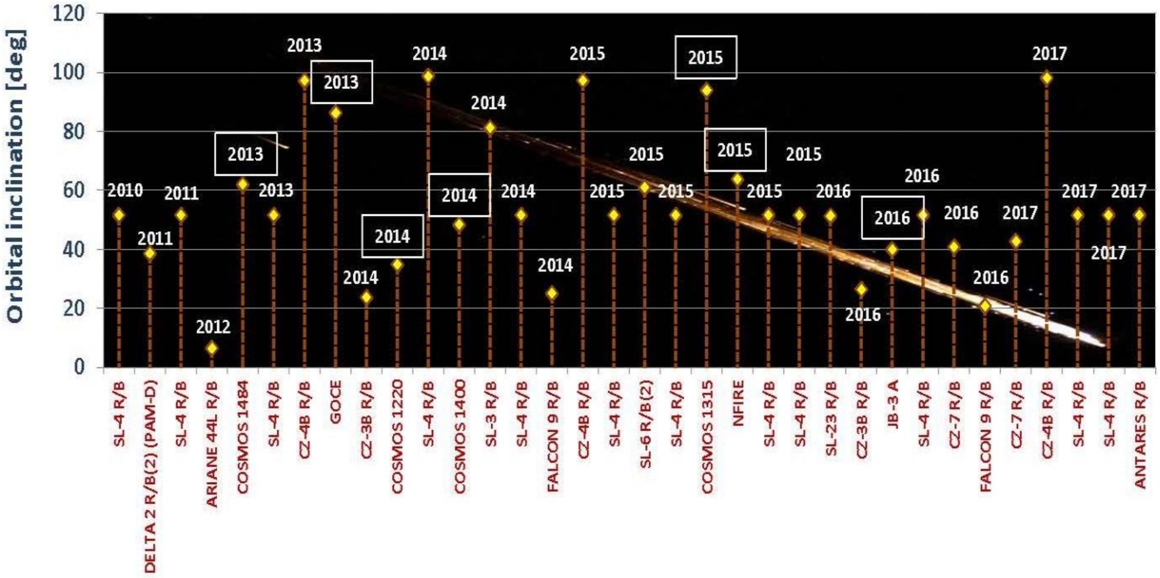

Fig. 15. Uncontrolled re-entries occurred between 2010 and 2017 for which eyewitness sightings were reported [31]. These included 27 rocket bodies and 7 spacecraft. For each object (in abscissa), and its corresponding orbit inclination (in ordinate), the year of the re-entry sighting is shown as well, boxed for spacecraft.

In addition to the sightings recorded from 2010 to 2017, 3 rocket bodies and 1 spacecraft were sighted re-entering during 2018, up to the end of November [31]. The rocket bodies were: the Zenit-3F (SL-23) upper stage with international designator 2017-086D, on 27 January 2018 at 23:32 UTC over Pucallpa, in Peru (observed also beyond the border from Brazil); the CZ-3B upper stage with international designator 2017-078B, on 10 March 2018, around 05:30 UTC, from various locations in Paraguay, as well as from Chile, Argentina and Brazil [32]; and the Soyuz (SL-4) upper stage with international designator 2018-026B, on 25 March 2018 at 01:28 UTC over Pozzuoli, and from other locations in Italy [31]. The spacecraft was Iridium 70, disposed at the end-of-life and seen re-entering from various locations near Orange County, in California, on 11 October 2018 at 08:15 UTC [31].

In terms of re-entry dry mass, number of uncontrolled re-entries, and survivability of large and recognizable pieces, spent upper stages seem to prevail compared with spacecraft. In fact, apart from uncommon accidental cases, as the tragic loss of the Columbia space shuttle orbiter (2003), or the decay of Skylab (1979), the bulk of the re-entry fragments recovered so far on the ground comes from rocket bodies. Still according to the database maintained by the Aerospace Corporation [31], major pieces of debris from space hardware re-entries were recovered in at least 77 events, from 1960 to 2018, with masses varying from a few kilograms to nearly 290 kg. For re-entries occurred without control from 1 January 2008 to 30 November 2018, pieces of debris were retrieved in at least 14 events (see Table 6). Of these, only one piece was identified as belonging to a spacecraft (a fuel tank from Iridium 70), while the others probably were all part of decayed spent upper stages.

Table 6. Recovered debris related to 14 uncontrolled re-entries occurred from 1 January 2008 to 30 November 2018. The information was collected from the database maintained by the Center for Orbital and Reentry Debris Studies (CORDS) of The Aerospace Corporation [31].

Re-entry year	Probable source of the recovered debris	International designator	Recovered debris	Recovered debris location
2010	2nd stage of **Delta II**	2009-052C	A steel propellant tank 2 titanium pressure spheres	Mongolia, Asia
2011	3rd stage of **GSLV**	2007-037B	Several metallic objects	Malawi, Africa
2011	3rd stage of **Delta II**	2003-058C	A titanium rocket motor casing	near Artigas, Uruguay
2011	2nd stage of **Zenit-3F**	2011-001C	A metallic sphere	near Baggs, Wyoming
2012	3rd stage of **Ariane 4**	1997-016C	A metallic sphere	near Mata Roma, Brazil
2013	3rd stage of **CZ-4B**	2012-021C	2 metallic spheres	near Buna, Texas
2013	2nd stage of **Delta**	1975-077B	A propellant tank	near Ngezi, Zimbabwe
2014	2nd stage of **Falcon 9**	2014-052B	3 small cylindrical tanks A metal ring	near Santa Rita do Pardo, Brazil
2016	2nd stage of **Zenit-3F**	2015-074C	2 small spherical tanks	Tuyen Quang Province, Vietnam
2016	2nd stage of **Falcon 9**	2016-050B	A pressure vessel	Giliraja, East Java, Indonesia
2016	AVUM stage of **Vega**	2012-006K	A pressure vessel	near Oddanchatram, India
2018	2nd stage of **Zenit-3F**	2017-086D	Several fuel tanks	near the Puno region, Peru
2018	3rd stage of **CZ-3B**	2017-078B	Fuel tank	City of Canindeyú, Paraguay
2018	**Iridium 70**	1998-032A	Fuel tank	near Hanford, California

4. Uncontrolled re-entries in 2018

During 2018, up to mid-November, 65 large intact objects had re-entered without control into the Earth's atmosphere. These included 22 spent upper stages, accounting for a returning mass of nearly 47 metric tons (Figure 16), and 43 spacecraft, with a re-entering mass of about 39 metric tons (Figure 17). Therefore, the total re-entered mass concentrated in large intact objects (86 metric tons) was already close to the average mass returned per year during the decade 2008-2017, i.e. 90 metric tons. Three objects heavier than 5000 kg had re-entered without control in 2018: two spent upper stages, i.e. the Zenit-3F (SL-23) second stage with international designator 2017-086D and the GSLV CZ-5 cryogenic upper stage with international designator 2017-031B (Figure 16), and the Chinese space station Tiangong-1 (Figure 17). Further details for these re-entries are provided in the following.

4.1 The uncontrolled re-entry of the Zenit-3F second stage 2017-086D

Among the large rocket bodies re-entered in 2018, the most massive was the second stage of the Zenit-3F (SL-23) rocket with international designator 2017-086D. It was used in the fourth launch, on 26 December 2017, of the Russian-Ukrainian expendable carrier rocket Zenit-3F to put into orbit the Angola's first geostationary communication satellite AngoSat-1, which unfortunately failed in drift orbit. After separating from the Fregat-SB upper stage, the Zenit-3F second stage, with a mass of about 8360 kg, began its orbital decay, only subject to natural orbit perturbations, from an initial orbit of 162 × 566 km in altitude and inclination of 51.37°. Figure 18 shows the observed evolution of the perigee and apogee altitude of the stage, as inferred from the US Two-Line Elements (TLEs).

According to the post-event assessment of the US Joint Space Operations Center (JSpOC), the object 2017-086D would have reached the re-entry altitude of 80 km on 27 January 2018 at 23:32 UTC, with an uncertainty of ±1 minute. It was sighted re-entering over Pucallpa, in Peru, while several fuel tanks were recovered by the Peruvian Air Force near the Puno region of Peru after notification by local residents (see

Figure 19).

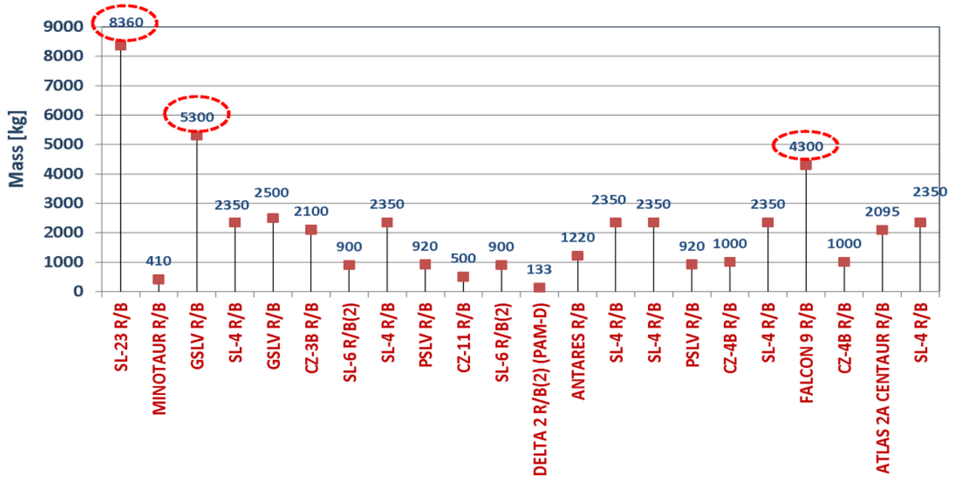

Fig. 16. Spent upper stages re-entered without control during 2018, up to mid-November. The associated mass, from the ESA's DISCOS Database [22], is reported over each object. The heaviest returned objects were: the SL-23 R/B (Zenit-3F 2nd stage with a mass around 8360 kg), the GSLV R/B (C-25 cryogenic upper stage with a mass of about 5300 kg) and the Falcon 9 R/B (M ~ 4300 kg).

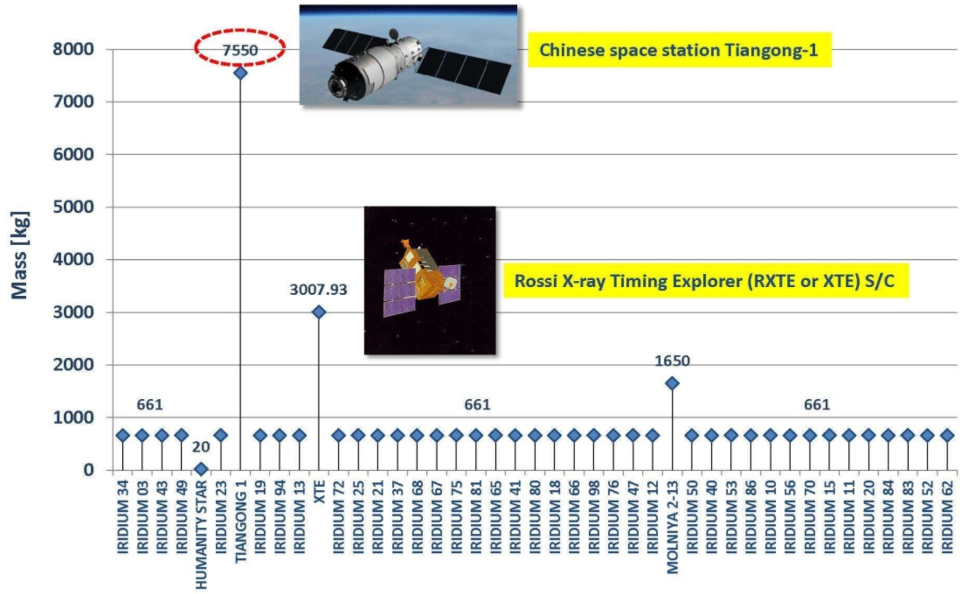

Fig. 17. Spacecraft re-entered without control during 2018, up to mid-November. The associated mass, from the ESA's DISCOS Database [22], is reported over each object. The heaviest spacecraft re-entered were the Chinese space station Tiangong-1, with an estimated mass before re-entry of about 7550 kg [21], and the Rossi X-ray Timing Explorer, with a mass of 3007.93 kg [22] (spacecraft images courtesy of Chinese Manned Space Agency and NASA, respectively).

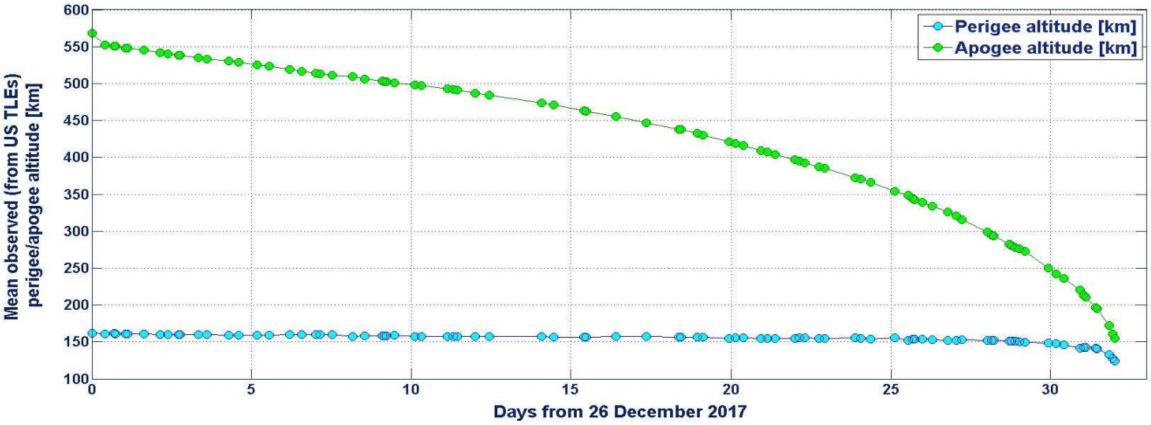

Fig. 18. Observed mean perigee/apogee altitude of the Zenit-3F second stage 2017-086D from the launch, on 26 December 2017, to the plunge into the Earth's atmosphere, on 27 January 2018.

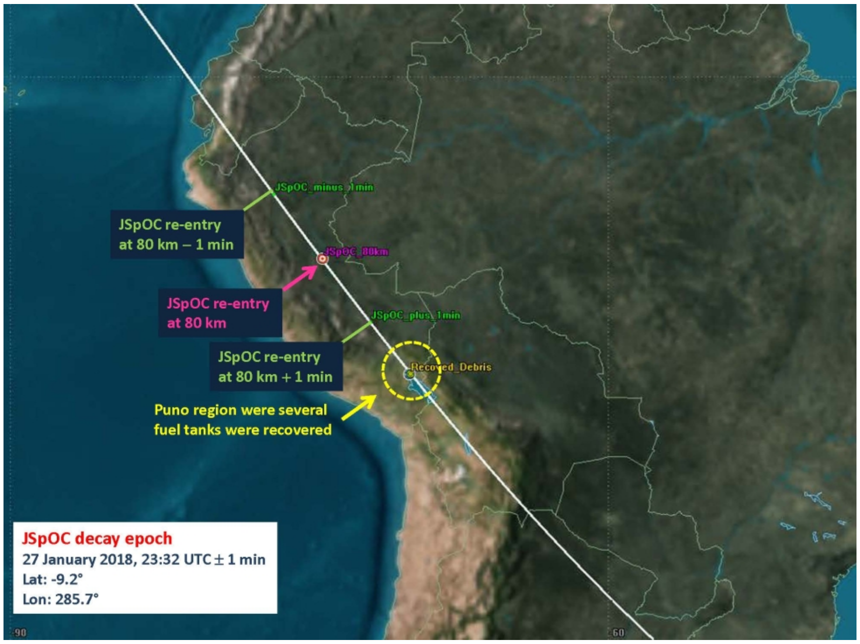

Fig. 19. Re-entry ground track over Peru of the Zenit-3F second stage 2017-086D. The post-event JSpOC decay at 80 km, with the uncertainty window of ±1 minute, and the location (near the Puno region) where several fuel tanks were recovered, are highlighted.

4.2 The uncontrolled re-entry of the C-25 cryogenic upper stage 2017-031B

After the 2nd stage of the Zenit-3F booster with international designator 2017-086D, the second most massive rocket body re-entered without control in 2018 was the Indian C-25 cryogenic upper stage with international designator 2017-031B, which had an inert mass of about 5300 kg. It was the upper stage of the Indian Geosynchronous Satellite Launch Vehicle Mark III D1 (GSLV-MK3-D1), used to launch the experimental Indian geostationary communication satellite GSAT-19, on 5 June 2017. After releasing the spacecraft, the C-25 upper stage remained passive in a geosynchronous transfer orbit of nearly 160 × 34918 km in altitude and inclination of 21.55° (as resulting from the first US TLE available for this object on 5 June 2017, at 07:18 UTC). It then began its orbital decay towards the Earth (Figure 20), where it re-entered just more than eight months after the launch, on 8 February 2018. The orbit of this stage was highly eccentric (initial eccentricity = 0.727), with an eccentricity just before re-entry (obtained from the last available US TLE on 7 February 2018, at 19:17 UTC) of 0.096, corresponding to a final altitude of 101 × 1484 km.

Based on the JSpOC post-event assessment, the stage would have reached the re-entry altitude of 80 km over the North Atlantic Ocean at 11:30 UTC on 8 February 2018. However, the re-entry uncertainty window was ±180 minutes. The sub-satellite ground tracks within this quite large uncertainty window, together with the vast area of the planet which might have been affected by the falling debris, is shown in Figure 21. No sighting was reported for this re-entry, and no fragment was recovered.

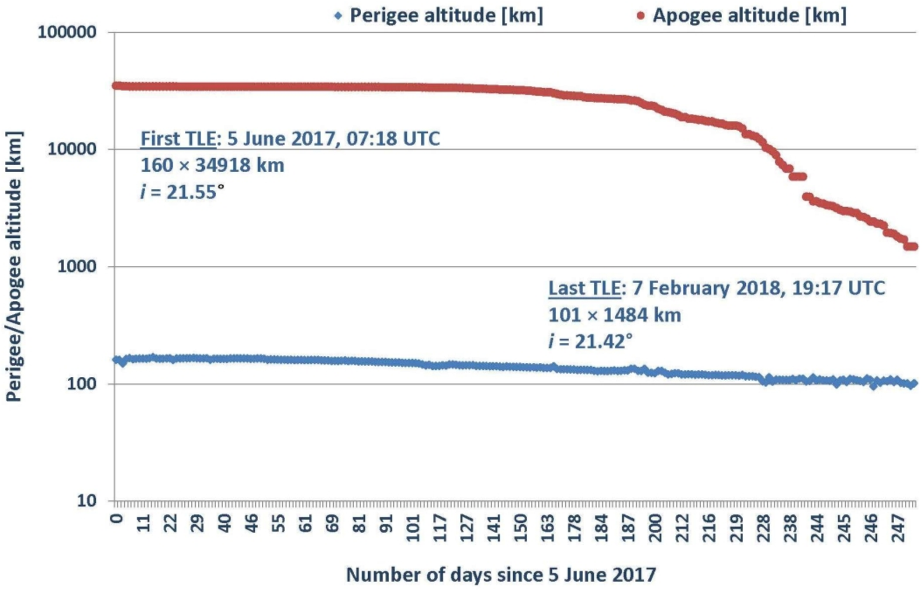

Fig. 20. Observed mean perigee/apogee altitude of the C-25 cryogenic upper stage 2017-031B from the launch, on 5 June 2017, to the plunge of the stage into the Earth's atmosphere, on 8 February 2018.

4.3 The uncontrolled re-entry of the Chinese space station Tiangong-1

Launched on 29 September 2011, the first Chinese space station Tiangong-1 (2011-053A) was originally intended for a controlled re-entry in the South Pacific Ocean Uninhabited Area (SPOUA) at the end of its planned operational lifetime in 2013. Nevertheless, the evolution of the average altitude of Tiangong-1 displayed regular orbital maintenance manoeuvres, executed between 2011 and 2013, followed by less frequent orbit raising manoeuvres during an extended mission phase, until December 2015. On 16 March 2016, the control of the space station was lost, due to an on board fatal power failure, preventing a targeted re-entry of the spacecraft in the SPOUA.

Given its large size (a cylindrical body with a length of 10.4 m and an overall diameter of up to 3.4 m, with two 7 × 3 m rectangular solar panels attached), the lift off mass (8506 kg, including 1000 kg of propellant), and the design properties, a complete demise of the space station upon re-entry would have been practically impossible. A not negligible fraction of the re-entering mass was therefore expected to survive and hit the ground anywhere in between approximately 44° of latitude north and south. Moreover, a possible contamination on the ground from the extremely toxic propellants still on board before re-entry (nearly 350 kg of mono-methyl hydrazine and nitrogen tetroxide, combined [21]) was not a priori excluded. For all of these reasons, even if no reliable information was available on the possible risk associated with the re-entry of Tiangong-1, the global casualty expectancy for this event was expected to exceed the internationally accepted threshold of 10^{-4} by at least one order of magnitude (see Section 3.1).

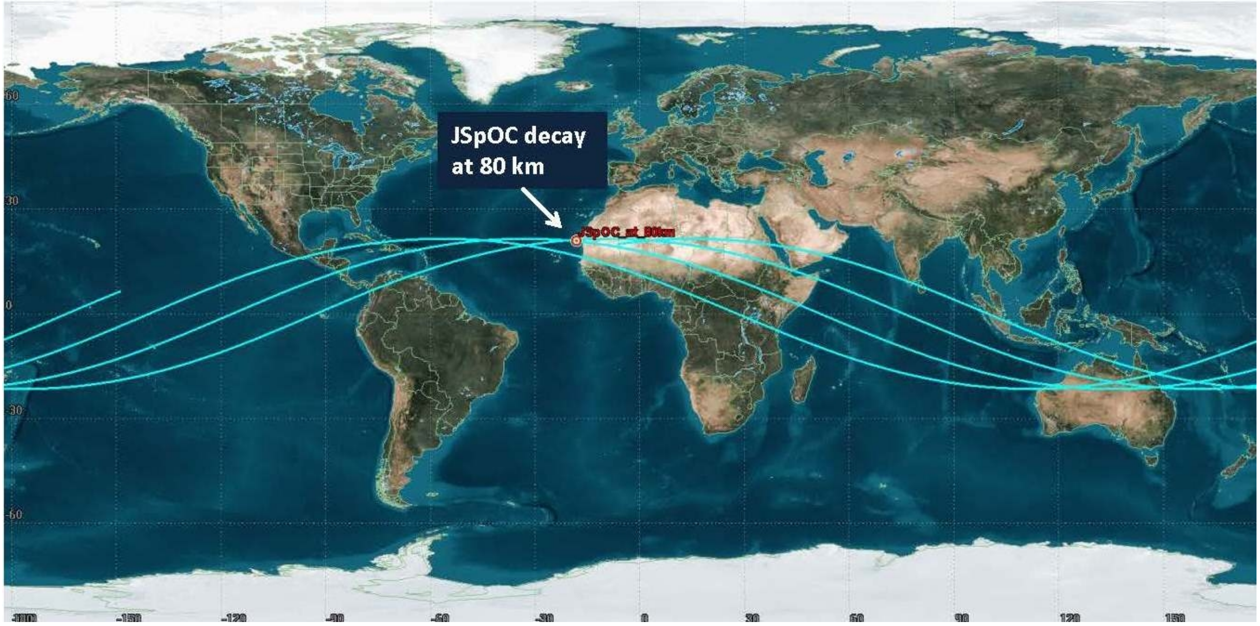

Fig. 21. Sub-satellite ground tracks corresponding to the last JSpOC re-entry uncertainty window (±180 minutes) for the C-25 upper stage 2017-021B re-entered on 8 February 2018, around 11:30 UTC. No sighting was reported and no fragment was recovered.

As in past events in which the uncontrolled re-entry of a manmade space object could have represented a potential threat to people and properties on the Italian territory, the Space Flight Dynamics Laboratory of ISTI/CNR provided support to the Italian Space Agency (ASI) for the National Department of Civil Protection (DCP). It also participated to the re-entry campaign of Tiangong-1 promoted by the Inter-Agency Space Debris Coordination Committee (IADC) (see [33] for information on the IADC re-entry campaigns). Even if the decay of the object was monitored at ISTI/CNR since mid-2017, the re-entry prediction campaign was started in January 2018 [8]. An extremely low solar activity was observed during the campaign, together with slowly perturbed geomagnetic conditions. The effect of numerous minor geomagnetic storms, combined with very low solar activity levels, probably played an appreciable role on driving the orbit evolution and the nominal re-entry time of the spacecraft, in consequence of some significant variations induced by the space environment on the local atmospheric density [3,4,8].

Tiangong-1 would have reached the altitude interface of 80 km at 00:10 UTC ±1 minute on 2 April 2018, according to the post-event assessment released by JSpOC. This re-entry epoch was just 33 minutes earlier than their last prediction (00:43 UTC ±120 minutes), issued about one hour before re-entry. Nevertheless, during the 8 hours preceding the re-entry, the US Space Surveillance Network was not able to produce any new orbit determination, so the post-re-entry estimate seems to be likely the result of further adjustments of the last determination/prediction, in which the ballistic parameter increased at the end, causing an earlier re-entry time.

However, after the re-entry, the Russian Space Agency, Roscosmos, uploaded in the IADC Re-Entry Database [34] further orbital elements based on the last pass of Tiangong-1 over the Russian sensors. Such orbit data were acquired during the last orbit, when the space station had a geodetic altitude of just 125 km. Using the last Russian orbit, it was impossible to obtain the decay time reported by JSpOC, unless assuming a fully unrealistic scenario, as increasing the atmospheric density by 5 times or more. Instead, the re-entry epoch at 80 km obtained at ISTI/CNR by propagating the last Russian orbit was 00:37 UTC on 2 April 2018, corresponding to 00:43 UTC at the IADC "conventional" re-entry altitude of 10 km for the "fictitious" intact object. This estimate was in reasonable agreement with the post-re-entry assessment of Roscosmos, which was 00:50 UTC, still at the IADC "conventional" altitude of 10 km (see Figure 22). It is worth mentioning that the solution obtained by Roscosmos was also compatible with the fact that no pass was acquired by the Ascension Island radar facility, because the object would have been too low anyway.

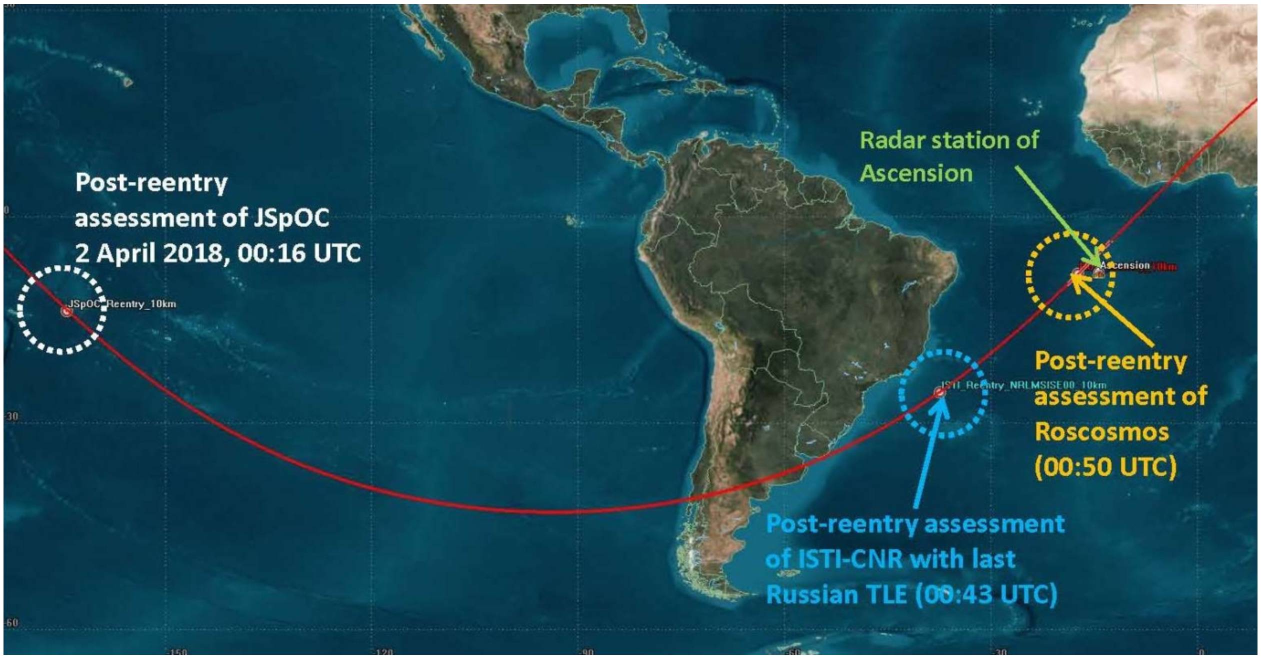

Fig. 22. Post-re-entry assessments of Roscosmos and ISTI/CNR, at the "conventional" altitude of 10 km (IADC), based on the last Russian orbit, compared with that of JSpOC, based on the last US TLE.

5. Conclusions

After an overview of the most relevant past uncontrolled re-entries, involving both massive space objects or satellites carrying hazardous substances on board before decay, the re-entries of large intact objects occurred without control from 2008 to mid-November 2018 were analysed. During the 10 years from

2008 to 2017, a statistical survey was performed to characterise the re-entry events in terms of frequency, returned mass, relevance, distribution in inclination, latitude bands overflown, eccentricity and perigee/apogee altitudes before re-entry, eyewitness sightings during the final decay phase and pieces of debris recovered on the ground. Moreover, the major uncontrolled re-entries occurred in 2018 were shortly described.

Concerning the statistics over the 2008-2017 decade, the main results are the following:

- In the 10 years considered, 448 large (RCS > 1 m^2) intact objects, represented by 366 rocket bodies (~82%), and 82 spacecraft (~18%), re-entered uncontrolled into the Earth's atmosphere;
- The total returned mass was approximately 911 metric tons, 83% concentrated in upper stages and the remaining 17% in spacecraft;
- The average re-entered mass per year was approximately 90 metric tons;
- Objects heavier than 500 kg re-entered, on average, every 9 days, while those with mass above 5000 kg every 215 days;
- In about 4% of the re-entries the casualty expectancy was expected to exceed, by approximately one order of magnitude, the threshold of 10^{-4}. In almost 84% of the events the casualty expectancy could have been of the order of 10^{-4}. Only in approximately 12% of the cases the casualty expectancy was probably significantly lower than 10^{-4};
- In consequence of the distribution in inclination and latitudes overflown, it was found that the Italian territory would have been affected in about 77% of the cases, while continental Europe in approximately 80% of the events;
- About 73% of the objects had a nearly circular orbit just before re-entry, while only 3% re-entered from highly eccentric orbits;
- 34 objects were sighted re-entering from 2010 to 2017 by eyewitnesses, i.e. in nearly 9% of the cases. As of mid-November, four additional sightings were reported in 2018;
- Pieces of debris were retrieved in at least 14 events from 2008 to mid-November 2018. Among them, only one was expected to belong to a spacecraft (Iridium 70), re-entered on 11 October 2018, while all the others were probably components of upper stages.

During 2018, up to mid-November, almost 86 metric tons of manmade materials had already re-entered into the Earth's atmosphere. The relevant uncontrolled re-entries of 2018 involved two spent upper stages, both heavier than 5 metric tons, and the Chinese space station Tiangong-1, with a re-entering mass of more than 7 metric tons.

Finally, the lessons learned from the analysed uncontrolled re-entries are:

- The uncontrolled re-entries probably violating the casualty upper limit of 10^{-4} can be relatively frequent, even if generally unknown to governments and the public at large;
- Typically, the re-entry of sizable spacecraft, like UARS, Phobos-Grunt, Progress-M 27 and Tiangong-1, catches more media and people attention than the re-entry of an equally, or even more massive, upper stage. For instance, the spent second stage of the Zenit-2SB launcher (SL-16 R/B 2011-065B, Table 4) which put into orbit Phobos-Grunt had a mass close to 9300 kg, but its uncontrolled re-entry, on 22 November 2011, did not receive any media attention at all [19]. The same can be said of all the large rocket bodies listed in Table 4, in particular of the three massive ($M \approx 9300$ kg) second stages of the Zenit-3F (SL-23) launcher. Added to these, there was also the uncontrolled re-entry of the Zenit-3F second stage, on 27 January 2018, almost unbeknown to all. Moreover, debris were recovered on the ground for three of the re-entered SL-23 second stages (see Table 6);
- There are several sizable upper stages, heavier than 4 metric tons, which still mostly re-enter without control;

- Also space vehicles intended for a controlled re-entry may sometime suffer failures, compromising the success of the planned targeted de-orbiting strategy, as was recently the case for the space station Tiangong-1, in 2018, or the cargo ship Progress-M 27 M, in 2015;
- The recovery, in 2018, of a fuel tank probably belonging to the re-entered spacecraft Iridium 70 might indicate that also components from not sizable payloads may survive re-entry and hit the ground. Another noteworthy fact is that the decay of the Iridium satellites, whose mass is around 661 kg, accounted for most (~91%) of the uncontrolled re-entries of spacecraft occurred in 2018, up to mid-November;
- Therefore, the uncontrolled re-entries of manmade space objects might become of greater concern in the future, due to the launch of hundreds or thousands of satellites for large constellations, and/or to a better compliance with the end-of-life guidelines for orbital debris mitigation, requiring the disposal of satellites to graveyard orbits with a residual lifetime of less than 25 years;
- As a consequence, if not designed for a complete or substantial demise at the re-entry in the atmosphere, also small satellites might represent a risk in the future, because the number of re-entries without control will inevitably be destined to increase;
- Also considering that a growth of the Earth's population and the commercial air traffic is expected in the coming years, the risk of being hit by falling orbital debris for people and property on the ground, or aircraft in flight, even if still small can no longer be neglected.

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