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How the re-entry casualty risk could be impacted by future launch traffic?

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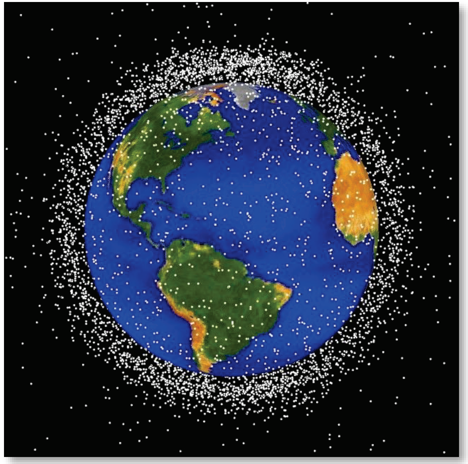
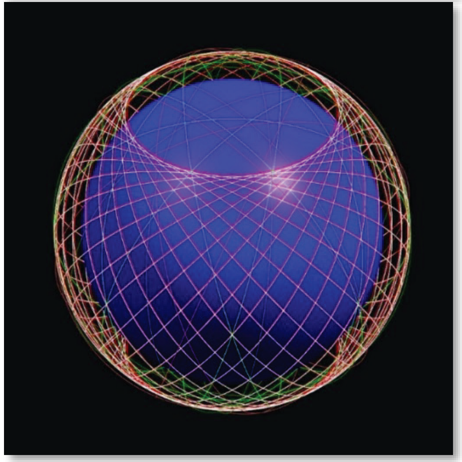
Space Debris Risk Assessment and Mitigation Analysis Workshop, ESA/ESOC, 23-24 June 2022

Introduction





- **Space activities are in the midst of an epochal transformation**
- The number of uncontrolled re-entries could increase significantly in the coming years, due to the launch of mega-constellations in low LEO (Low Earth Orbit) and the disposal of satellites from higher orbits in compliance with debris mitigation guidelines
- **Even if still relatively small, compared to all other risks faced in everyday life, the risk related to uncontrolled re-entries could substantially increase over the next few years**
- To date the re-entry risk has been assessed and managed on an object-by-object basis, such as assessing whether or not a single event might exceed a certain casualty expectancy threshold, typically set equal to 10^{-4}
- However, in view of future developments in space activities, it may be necessary to shift to a more holistic approach to the problem, at the very least more system-oriented than object-oriented

Outline

- Introduction of metrics to characterize the risk associated with uncontrolled re-entries
- Application of these metrics to uncontrolled re-entries of large intact objects, occurred during the transition phase between the so-called old and new space economy – or roughly the last decade – to evaluate the percentage of events exceeding the casualty expectancy threshold of 10^{-4}
- Application of one of these metrics to all re-entries considered, in order to assess their casualty expectancy and casualty probability on an annual basis and over the entire period analyzed
- Projections of the re-entry risk through the simulation of possible launch traffic scenarios, in the attempt to assess how the re-entry casualty risk could increase in consequence of the evolution of space activities
- Reflections on the need to establish a system-oriented cumulative risk threshold on an annual basis, in order to manage uncontrolled re-entries before their associated risk becomes too high to be controlled

Re-entry risk evaluation

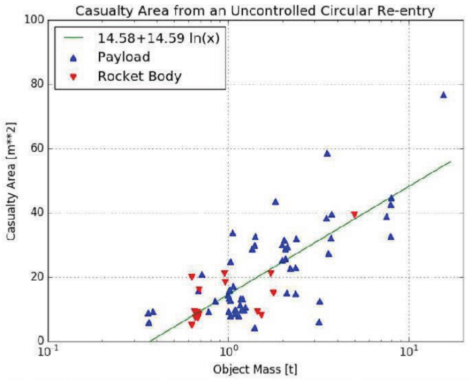
- A crucial metric to represent and to evaluate the potential risk from re-entering debris is the so-called **total debris casualty area (A_C)**
- The human casualty expectation, better known as the **casualty expectancy (E_C)**, is obtained as the product of the total debris casualty area (A_C) and the average population density (P_D) in the latitude band overflown by the re-entering object

$$A_c = \sum_{i=1}^{n} \left(\sqrt{A_h} + \sqrt{A_i} \right)^2$$

$$E_C = A_C \times P_D$$

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
- **In all cases where this information is not available, it is necessary to resort to alternative, albeit coarser, methods to assess the casualty area**
- One possible approach consists in deriving A_C from a sample of historical re-entry assessments – carried out with specific software tools for re-entries, such as ORSAT or SCARAB – and then in fitting the results with simple mathematical functions in terms of the re-entering dry mass



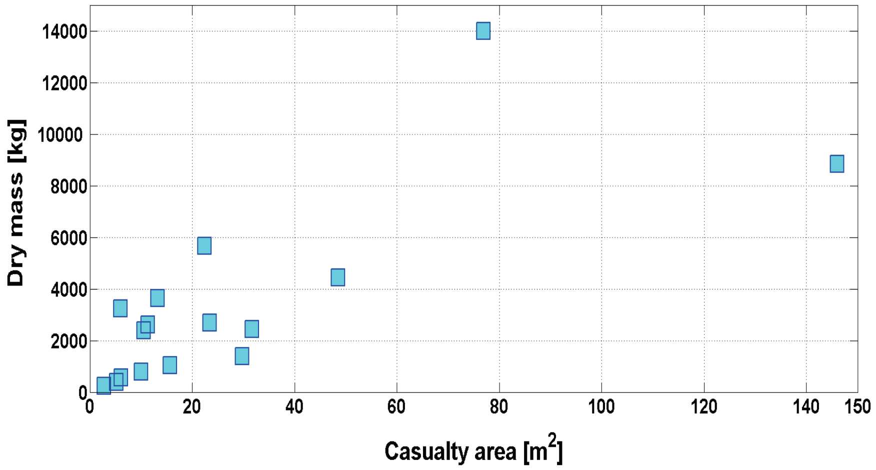
Credit: ESA/ESOC

$$A_C = 14.58 + 14.49 \times \ln(M)$$

Casualty area

Satellite name	Satellite mass [kg]	Model	Casualty area [m²]
BeppoSAX	1385.63	SCARAB	29.816
CGRO	14000	ORSAT	76.9
Delta 2nd Stage	800	based on recovered fragments	10
EUVE	3243	ORSAT	5.95
HST	8844	ORSAT	146
EOS-Aura	2400	ORSAT	10.49
GPM	2676	ORSAT	23.38
GLAST/Fermi	3639	ORSAT	13.24
GOCE	1034.363	SCARAB	15.675
Iridium (1st generation)	560	ORSAT	6.1
PAM-D/STAR-48B	230	based on recovered fragments	2.8
ROSAT	2426	SCARAB	31.68
Terra	4427	ORSAT	48.5
Test-sat	400	SCARAB	5.226
TRMM	2621	ORSAT	11.3
UARS	5668	ORSAT	22.38

Sample of objects considered at ISTI-CNR

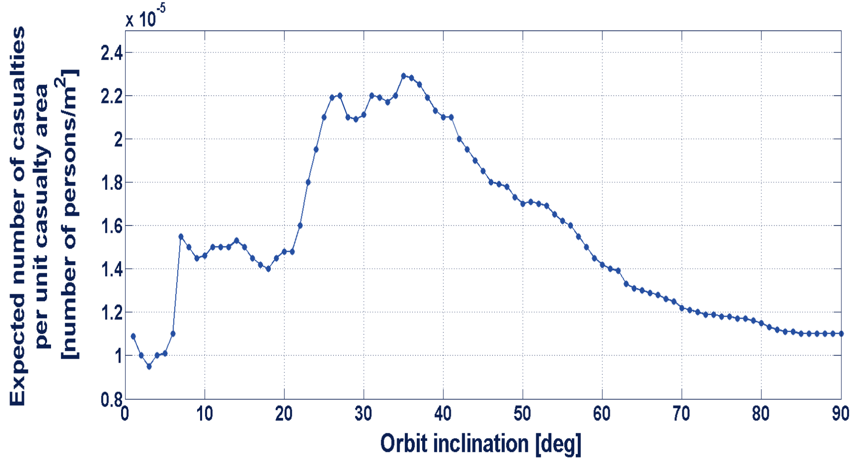


- The results were fitted using the following mathematical functions, where A_C is given in m² and M in kg

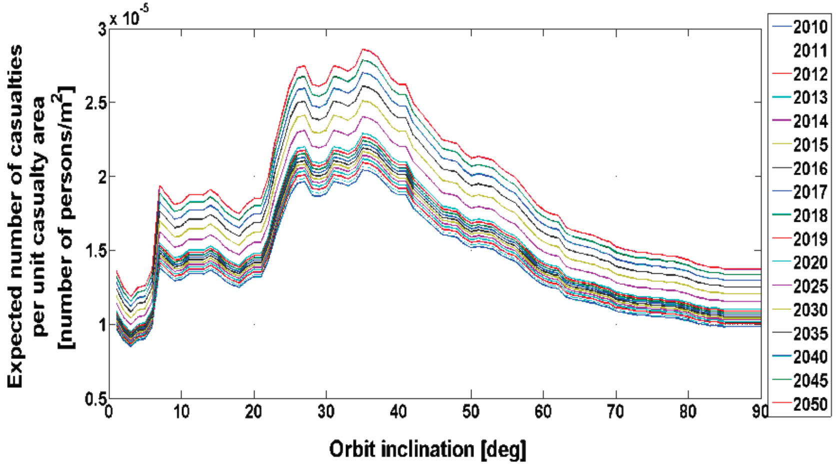
- Linear (least-squares fitting)
  $A_C = 0.007604\ M + 2.882$
- Linear (least absolute residuals)
  $A_C = 0.005268\ M + 3.15$
- Power (least-squares fitting)
  $A_C = 0.02308\ M^{0.8834}$
- Power (least absolute residuals)
  $A_C = 0.05627\ M^{0.7563}$
- Power (bisquare weights)
  $A_C = 0.03351\ M^{0.8053}$

Casualty expectancy

- Considering the world population by year and the population projections, the historical expected number of casualties from 2010 to 2020, as well as the projections up to 2050, were assessed



Expected number of casualties per unit casualty area versus inclination for the year 2020



Expected number of casualties per unit casualty area versus inclination from 2010 to 2050

- **The casualty expectancy E_C** for each re-entering object was obtained by multiplying the object's casualty area 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

Casualty expectancy – an alternative ISTI-CNR approach

- Another approach to assess the relevance of uncontrolled re-entries was introduced at ISTI-CNR (formerly CNUCE-CNR) since 1995
- It defines the **magnitude M_R of uncontrolled re-entries** as a function of the dry mass M, in kg, of a re-entering object

$$M_R = \log_{10}(M/100)$$

- This definition was subsequently slightly modified in 2017

$$M_R = \log_{10}(M/100) + 0.3$$

- The **order of magnitude of the global casualty expectancy E_C** may be then evaluated as

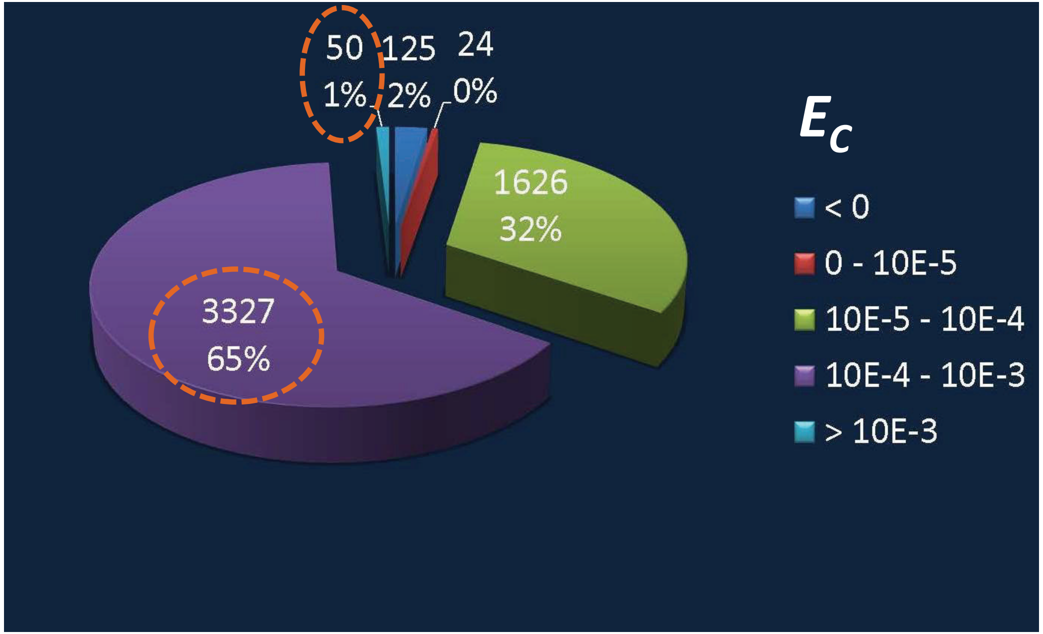
$$E_C \sim 10^{M_R - 5}$$

Dry mass M_0 of the re-entering object [kg]	Uncontrolled re-entry magnitude	Order of magnitude of the casualty expectancy E_C	ISTI-CNR alert color code
$M_0 \leq 50$	$M_R < 0$	$E_C < \sim 10^{-5}$	White
$50 < M_0 \leq 500$	$0 \leq M_R < 1$	$\sim 10^{-5} < E_C < \sim 10^{-4}$	Light blue
$500 < M_0 \leq 5000$	$1 \leq M_R < 2$	$\sim 10^{-4} < E_C < \sim 10^{-3}$	Green
$5000 < M_0 \leq 50{,}000$	$2 \leq M_R < 3$	$\sim 10^{-3} < E_C < \sim 10^{-2}$	Yellow
$50{,}000 < M_0 \leq 500{,}000$	$3 \leq M_R < 4$	$\sim 10^{-2} < E_C < \sim 10^{-1}$	Orange
$500{,}000 < M_0 \leq 5{,}000{,}000$	$4 \leq M_R < 5$	$\sim 10^{-1} < E_C < \sim 1$	Red

Re-entry casualty risk between 2010 and 2020

- The different approaches (8 in total) for estimating the casualty expectancy were applied to large intact objects (RCS > 1 m^2): 214 payloads and 417 rocket bodies, re-entered without control from 1 January 2010 to 31 December 2020
- For each approach, the number of re-entries was classified per interval of casualty expectancy. Then, by summing for each E_C interval, the number of re-entries occurred in all 8 cases, it was found that

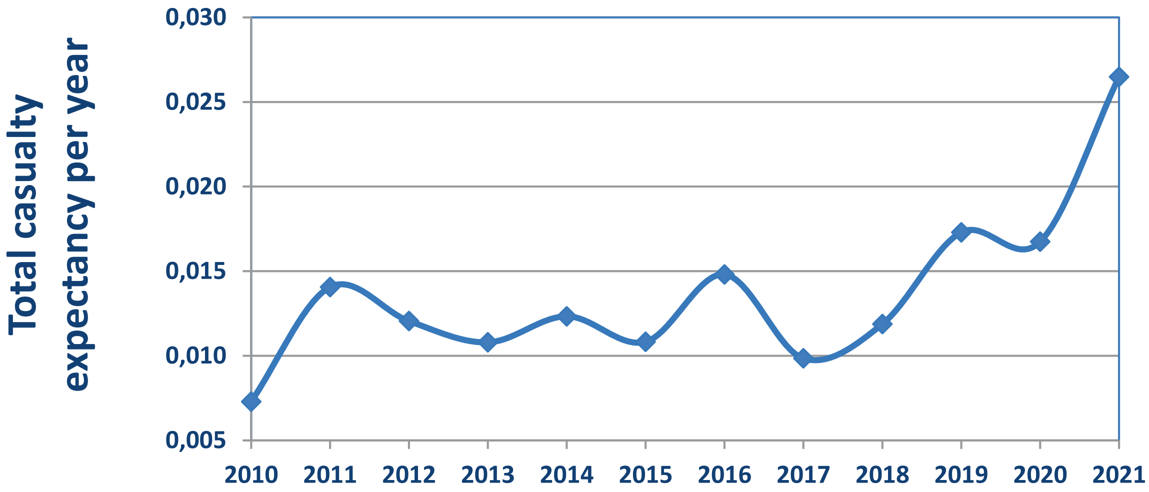
> - Nearly 66% of the re-entries of large intact objects were characterized by a casualty expectancy larger than the alert threshold of 10^{-4}
> - Almost 81% of the rocket bodies had $E_C > 10^{-4}$, against 36% of the payloads



Distribution, per casualty expectancy interval, of the re-entries of large intact objects occurred from 1 January 2010 to 31 December 2020

Casualty expectancy & casualty probability for uncontrolled re-entries of large intact objects occurred between 2010 and 2021

- Herein A_C was obtained using the «Power LAR» relationship: $A_C = 0.05627\ M^{0.7563}$



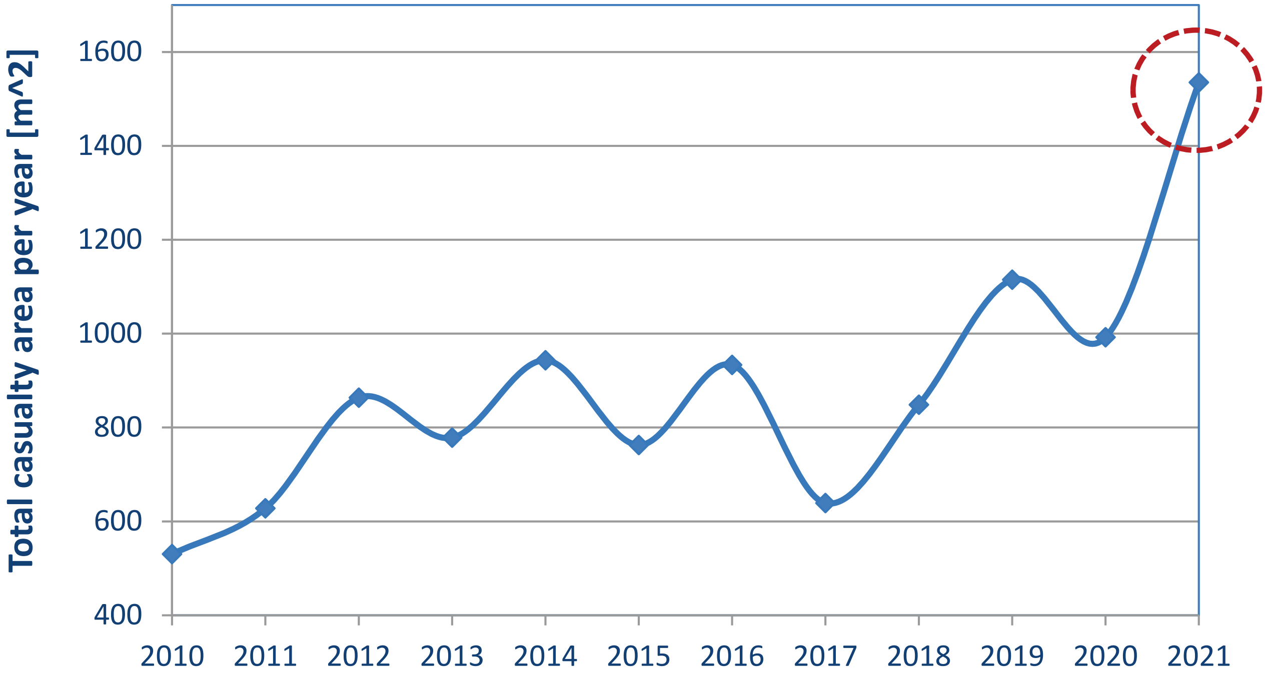
Total casualty expectancy per year and probability of having no victims for uncontrolled re-entries of large intact objects occurred between 2010 and 2021

Year	Total casualty expectancy per year	No casualty probability (%)
2010	0.007286	99.27
2011	0.014057	98.60
2012	0.012048	98.80
2013	0.010791	98.93
2014	0.012330	98.77
2015	0.010826	98.92
2016	0.014806	98.53
2017	0.009844	99.02
2018	0.011867	98.82
2019	0.017293	98.29
2020	0.016738	98.34
2021	0.026478	97.39

- The total casualty expectancy in 2021 (0.0265) was roughly double the average E_C recorded between 2010 and 2020 (0.0125), and about 58% higher than in 2020 (0.0167)
- The **global casualty probability** is still quite low, of the order, or less, than 2% per year. However, an increase up to about 3% has been observed in 2021
- The **total casualty expectancy over the last 12 years was 0.1644**, corresponding to a global casualty probability of about 15%

Casualty area for uncontrolled re-entries of large intact objects occurred between 2010 and 2021

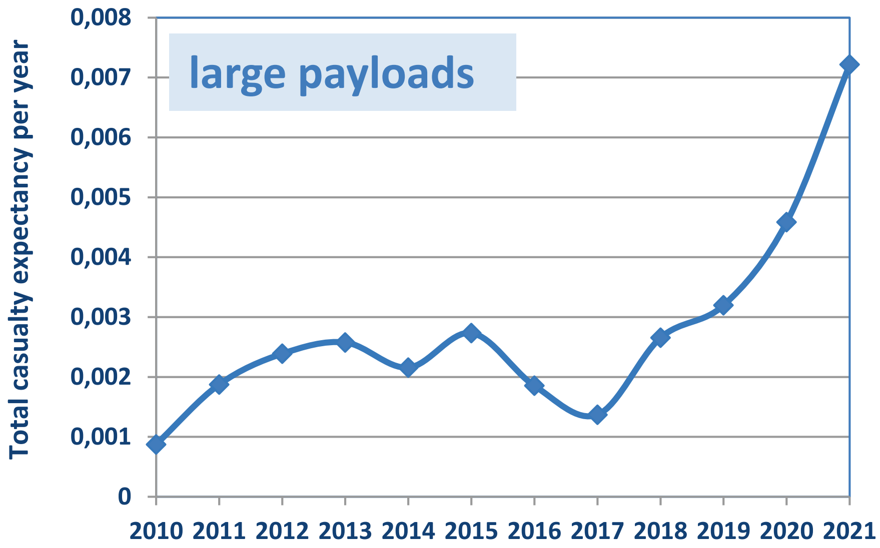
$A_C = 0.05627\ M^{0.7563}$



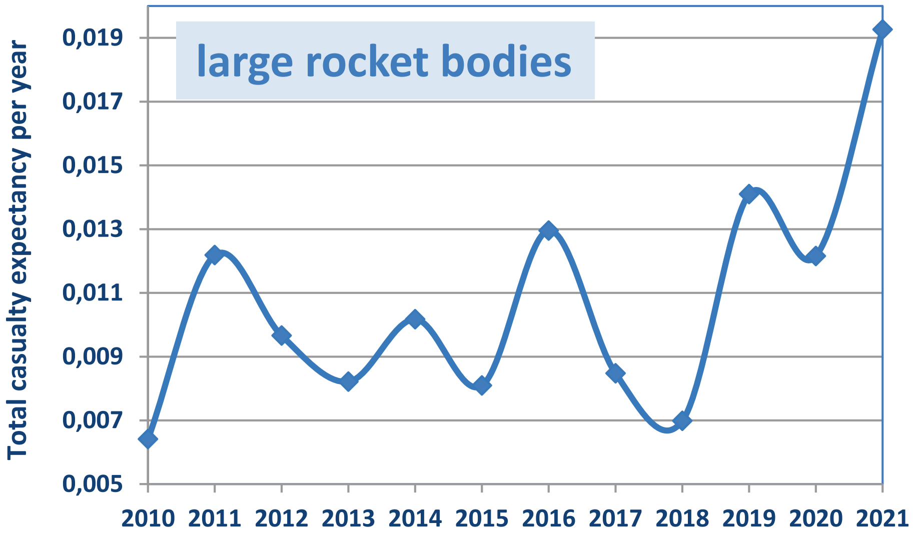
- The **total casualty area in 2021** (1535 m^2) increased by approximately 87% with respect to the average A_C (821 m^2) between 2010 and 2020
- The **total casualty area** from 2010 to 2021 was more than 10,000 m^2

Casualty expectancy for large payloads and rocket bodies re-entered without control between 2010 and 2021

- In the 12 years between 2010 and 2021, 316 **large payloads** have re-entered without control into the Earth's atmosphere, 102 of them in 2021
- The casualty expectancy in 2021 (0.0072) was 3 times higher than the average E_C between 2010 and 2020 (0.0024)
- However, the global casualty probability was still below 1% in 2021



- In the 12 years between 2010 and 2021, 467 **large rocket bodies** have re-entered without control into the Earth's atmosphere, 50 of them in 2021
- The casualty expectancy in 2021 (0.0193) was nearly 2 times higher than the average E_C between 2010 and 2020 (0.0099)
- The global casualty probability is currently on the order of 2%



Projections of the re-entry casualty risk

- A noticeable increase of uncontrolled re-entries of small satellites has to be expected in the coming years
- Making an accurate forecast of what will happen in the near future is practically impossible, due to frequent and sudden changes in the planning of new space activities
- However, **by simulating possible scenarios, it was roughly estimated how much the current re-entry risk could increase in the near future**

Simulated scenarios

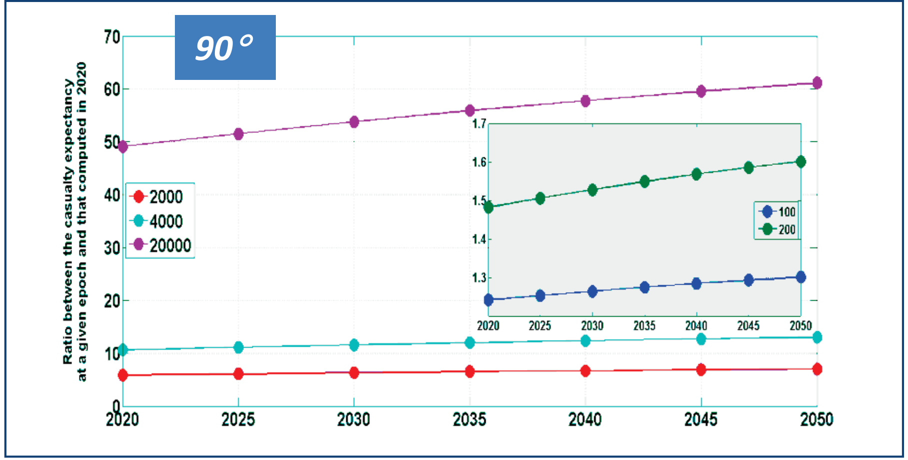
- Small constellation satellites with a mass of 250 kg were considered
- Their individual casualty area, computed with the «Power LAR» relationship, was approximately 3.66 m^2
- These satellites were supposed to decay from different orbit inclinations, nearly corresponding to the maximum (35°), medium (50°) and minimum (90°) of the world population density distribution
- The number of re-entering satellites per year was assumed to be: 100, 200, 2000, 4000 and 20,000
- The reference value of the casualty expectancy was that associated with the uncontrolled re-entries of large intact objects in 2020, which was 0.0167
- Successively, by taking into account the increase of the world population in the next three decades, projections of the re-entry risk up to 2050 were carried out

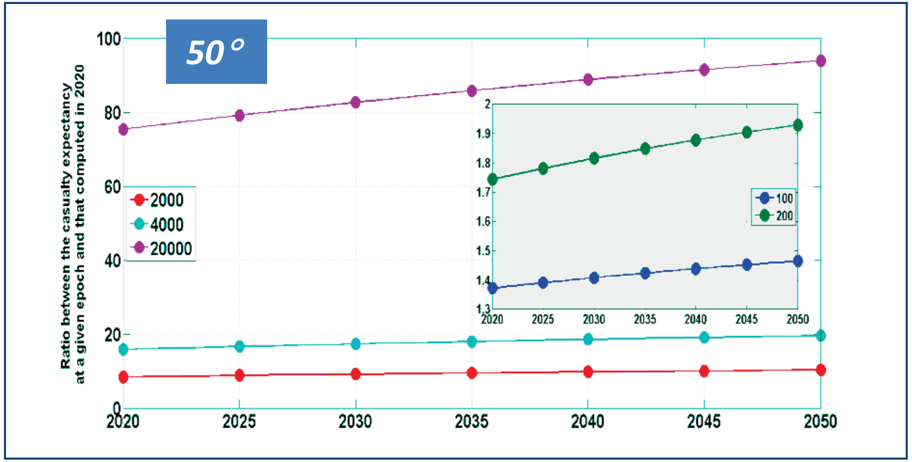
Projections of the re-entry casualty risk

- The casualty expectancy obtained for each single satellite was multiplied by the number of constellation satellites re-entering annually and added to the unrelated re-entry background (assumed to remain constant since 2020) to obtain the corresponding total casualty expectancy for each case
- The ratio between the total casualty expectancy obtained in each case and the reference value in 2020 was computed

Casualty expectancy for each single satellite as a function of the orbit inclination and epoch

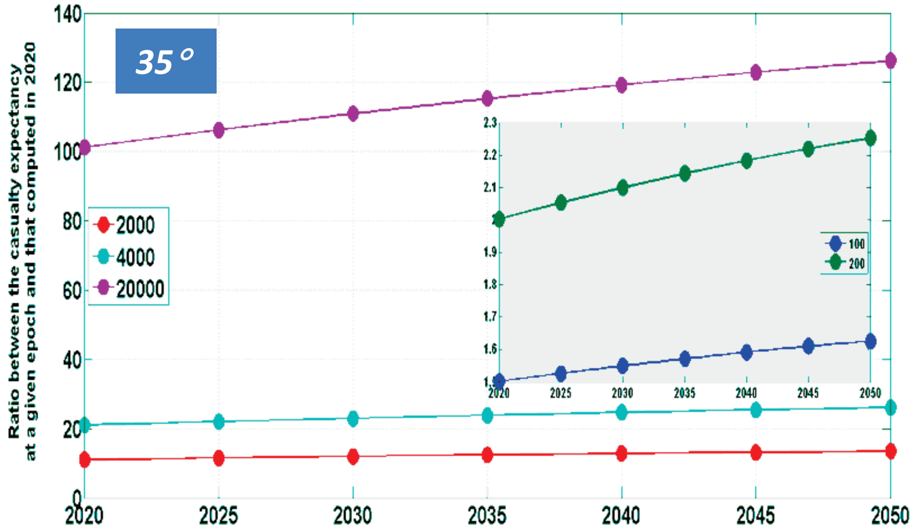
Epoch	Orbit inclination		
	35°	50°	90°
2020	8.39E-05	6.23E-05	4.03E-05
2025	8.81E-05	6.54E-05	4.23E-05
2030	9.20E-05	6.83E-05	4.42E-05
2035	9.56E-05	7.10E-05	4.59E-05
2040	9.90E-05	7.35E-05	4.75E-05
2045	0.000102	7.57E-05	4.90E-05
2050	0.000105	7.78E-05	5.03E-05





Projections of the re-entry casualty risk

- The **worst scenario** occurs when 20,000 satellites re-enter annually from orbits inclined by 35°. If this were the case, the casualty expectancy would be already 100 times higher than in 2020, and a further increase of the order of 25% would be recorded by 2050
- If 4000 satellites re-enter each year, the total casualty expectancy estimated in 2020 would increase by about 10-20 times, depending on the orbit inclination



Therefore, if no design for demise was implemented

- The addition of 4000 spacecraft re-entering annually would increase the probability of having at least one victim to nearly 30% per year
- 20,000 more satellites would boost it to almost 80%

The need to establish a cumulative risk limit

- Unlike the alert threshold of 10^{-4}, linked to single re-entry events, no cumulative risk limit exists for satellite re-entries over one year or more

- Therefore, even if the value of the casualty expectancy associated with each satellite is below the alert threshold of 10^{-4}, the re-entry of numerous satellites of this type every year could lead to unacceptable values of the associated re-entry risk, both on the ground and in the airspace

Is there an acceptable cumulative risk limit?

- The U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP) state that: "*In developing the mission profile, the program should limit the cumulative reentry human casualty risk from the constellation*". However, **no cumulative risk limit has been established for spacecraft re-entries**

- W.H. Ailor of the Aerospace Corporation suggested using the Range Commanders Council (RCC) document **RCC 321** as a guidance on how that risk might be managed

- Concerning acceptable risk criteria for the General Public (GP), the RCC document states that the collective risk for the GP must not exceed a casualty expectancy of 10^{-4} for any single mission. **If the annual risk is measured, collective risk for the GP should not exceed a casualty expectation of 3×10^{-3} on an annual basis**

- Applying this annual limit to each satellite constellation, or space system as a whole, could be a reasonable step in the right direction. However, the Starlink mega-constellation, for example, would have already marginally exceeded the proposed ceiling in 2020 (3.8×10^{-3}), and almost doubled this limit in 2021 (5.7×10^{-3}), if not D4D was implemented

Conclusions

- The launch of mega-constellations in low LEO, together with the disposal of satellites from higher orbits, will entail a significant increase of the kinetic casualty risk in the coming years
- The analysis based on the last 12 years, i.e. the time period preceding and partially overlapping such transition phase, confirms that the global casualty probability is still quite low, of the order or less than 2-3% per year
- However, if another 4000 or 20,000 satellites were to re-enter without control every year, the probability of having at least one casualty would become about 30% and 80%, respectively, probably reaching unacceptable values for safety on the ground and in airspace
- In order to minimize such risk, the components of a satellite should be designed and made of materials able to maximize the probability of being burned upon re-entry into the atmosphere
- However, also this strategy might not be the most appropriate over relatively long periods of time and for thousands of re-entering objects, due to the release, in the upper atmosphere, of large quantities of chemical substances having a negative impact on the environment
- There is therefore no simple way to address this issue, but it will still be essential that these problems are well analyzed and discussed to avoid running into an irreversible situation, where the re-entry risk is at that point too high to be controlled