National Research Council of Italy

Institute of Information Science and Technologies

UNCONTROLLED RE-ENTRIES OF SIZABLE SPACECRAFT AND ROCKET BODIES: A POTENTIAL THREAT IN THE AIRSPACE AND ON THE GROUND

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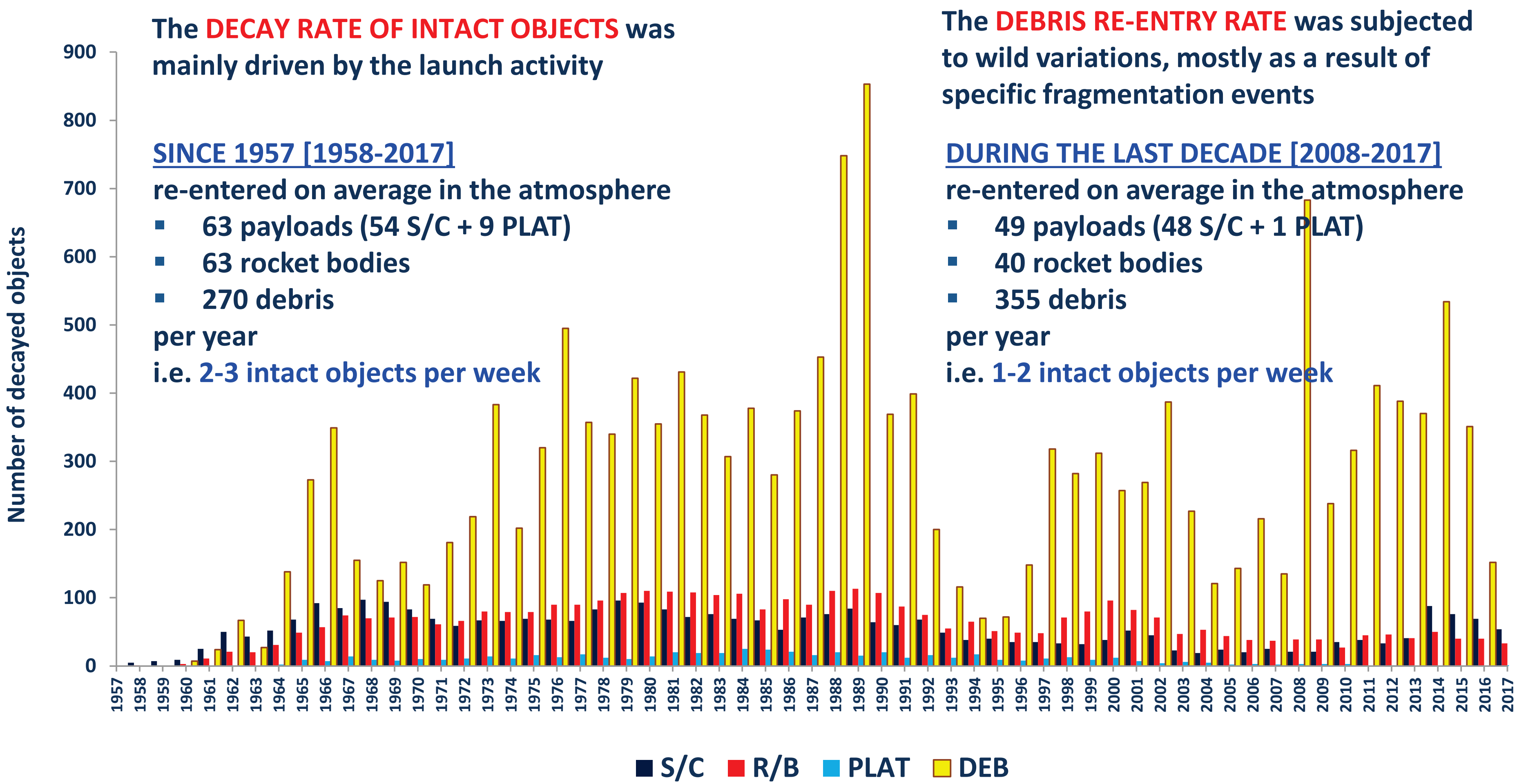
Re-entered cataloged objects

- More than 43 500 manmade space objects have been cataloged by the U.S. Space Surveillance Network (SSN) since the beginning of space activities in 1957
- Of these, more than 24 300 have re-entered so far into the Earth's atmosphere, accounting for almost 56% of the total: ~71% were orbital debris and ~29% were intact objects, i.e. spacecraft, platforms and spent upper stages. The associated returning mass, close to 30 000 metric tons, was mainly concentrated (~98%) in intact objects



Uncontrolled re-entries of large spacecraft and rocket bodies during the last 10 years [2008-2017]

Uncontrolled re-entries between 2008 and 2017

- Space hardware re-entries can be of two types

CONTROLLED → If the time of re-entry is controlled and the impact of debris is confined to a designated zone

UNCONTROLLED → If the time of re-entry and ground zone of impact are not controlled

- Over the last 10 years, between 2008 and 2017, almost 440 large (RCS > 1 m^2) intact objects have re-entered the Earth's atmosphere without control, with a total returning mass approaching 900 metric tons

DRY MASS M_0 [kg]	INTACT OBJECTS	SPACECRAFT	UPPER STAGES
$M_0 \leq 50$	1	0	1
$50 < M_0 \leq 500$	55 (12%)	14	41
$500 < M_0 \leq 5000$	376 (84%)	66	310
$5000 < M_0 \leq 9300$	16 (4%)	2	14
Total re-entries	448	82	366

	LARGE M > 50 kg		LARGE M > 500 kg		LARGE M > 5000 kg	
	No.	Mass [kg]	No.	Mass [kg]	No.	Mass [kg]
UPPER STAGES	366	754 142 (83%)	324	744 637 (83%)	14	93 808 (78%)
SPACECRAFT	82	157 098 (17%)	68	153 254 (17%)	3	26 482 (22%)
INTACT OBJECTS	448	911 240	392	897 891	17	120 290

> 900 metric tons of mass re-entered without control during the last 10 years

> 120 metric tons concentrated in objects with M > 5000 kg

- Therefore, approximately 90 metric tons belonging to large intact objects re-entered, on average, the Earth's atmosphere each year, and a mass fraction between 5% (4500 kg) and 15% (13 500 kg) might have crossed the airspace and hit the ground

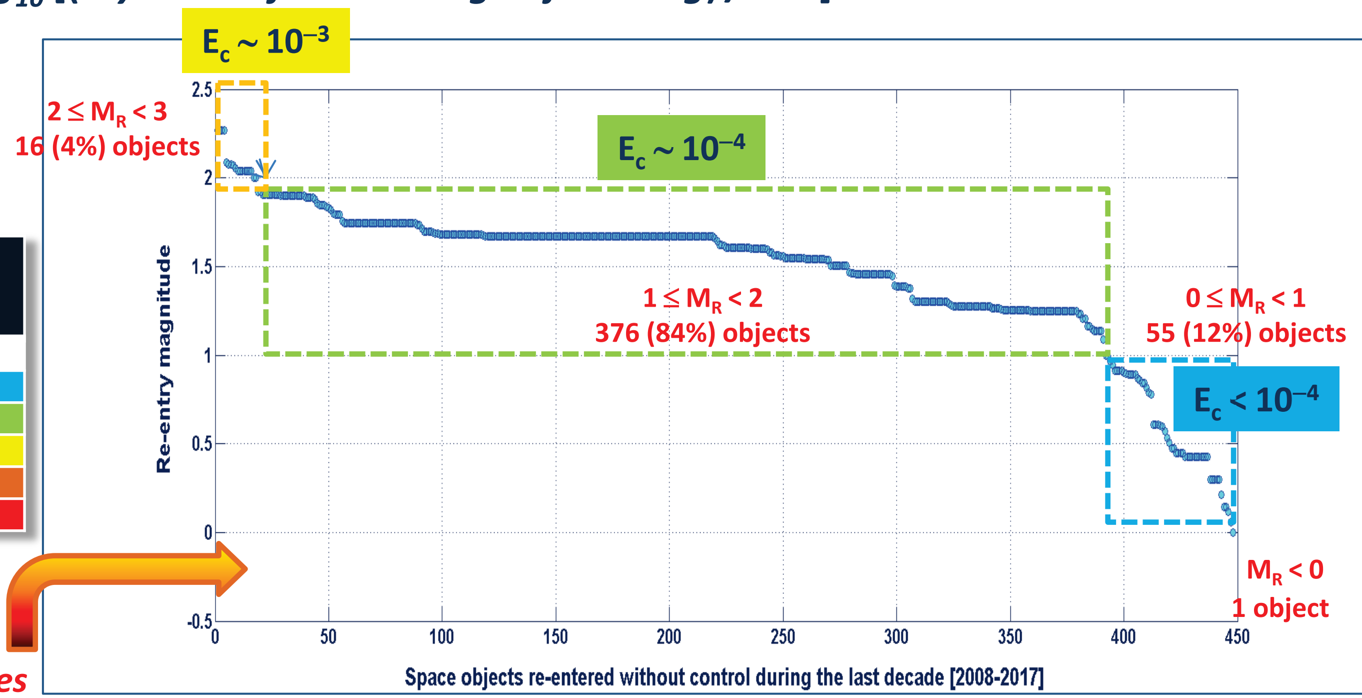
Relevance of uncontrolled re-entries

- At international level, an uncontrolled re-entry is considered at risk if the casualty expectancy exceeds 10^{-4}
- Unfortunately, detailed and reliable estimates of the casualty expectancy are publicly available only for very few objects (< 1% of the relevant ones)
- Other rough evaluation criteria must be used, based on size, mass or other important 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
- A re-entry magnitude M_R was defined at ISTI-CNR to roughly characterize, in a synthetic way, the relevance of uncontrolled re-entries

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

ISTI-CNR uncontrolled re-entry magnitude scale definition

Dry Mass M_0 of the re-entering object [kg]	Re-entry magnitude M_R
$M_0 \leq 50$	$M_R < 0$
$50 < M_0 \leq 500$	$0 \leq M_R < 1$
$500 < M_0 \leq 5000$	$1 \leq M_R < 2$
$5000 < M_0 \leq 50\,000$	$2 \leq M_R < 3$
$50\,000 < M_0 \leq 500\,000$	$3 \leq M_R < 4$
$500\,000 < M_0 \leq 5\,000\,000$	$4 \leq M_R < 5$



Relevance of uncontrolled re-entries during the last 10 years [2008-2017]

Relevance of historic uncontrolled re-entries

Object	Dry mass M_0 [kg]	Re-entry epoch	Re-entry magnitude M_R
Columbia (STS-107)	82 000	01-02-2003	3.214
Skylab	74 000	11-07-1979	3.169
Salyut 7/Cosmos 1686	40 000	07-02-1991	2.902
Salyut 2	18 300	28-05-1973	2.562
Cosmos 557	18 300	22-05-1973	2.562
Pegasus 1	10 000	17-09-1978	2.300
Pegasus 2	10 000	03-11-1979	2.300
SL-23 R/B 2011-001C	9300	19-03-2011	2.268
SL-23 R/B 2011-037D	9300	08-09-2011	2.268
SL-23 R/B 2015-074C	9300	02-01-2016	2.268
SL-16 R/B 1994-053B	9000	14-09-1994	2.254
SL-16 R/B 2000-056B	9000	11-10-2000	2.254
SL-16 R/B 2011-065B	9000	22-11-2011	2.254
SL-23 R/B 2017-086D	8307	27-01-2018	2.219
Tiangong-1	7150	02-04-2018	2.154
Dragon/Falcon 9	6100	27-06-2010	2.085
CZ-7 R/B 2016-042E	6000	28-07-2016	2.078
Progress-M 27M	5919	08-05-2015	2.072
UARS	5668	24-09-2011	2.053
Progress-M 17	5500	03-03-1994	2.040
CZ-2F R/B 2011-053B	5500	10-10-2011	2.040
Cosmos 954	4500	24-01-1978	Radioactive
Cosmos 1402 (object C)	990	07-02-1983	Radioactive

- The most critical re-entry event was that involving the Space Shuttle Columbia, in 2003. It led to 84 000 recovered fragments (38% of its entry mass)
- Skylab re-entered uncontrolled spreading debris across the Australian Outback. About 500 objects with a total mass of 20 tons (~25%) were retrieved
- The huge Salyut 7/Cosmos 1686 complex burned up and broke up over Argentina. At least three major fragments were retrieved after ground impact
- Salyut stations were nominally de-orbited in a controlled way, apart from Salyut 2 and Cosmos 557 (third space station in the Salyut program), due to attitude acquisition problems, and Salyut 7/Cosmos 1686 for exhausted propellant reserves
- The nuclear powered satellite Cosmos 954 re-entered over the Northwest Territories of Canada, scattering numerous radioactive fragments along a swath longer than 1000 km. Several other failed or deactivated Soviet RORSAT and US nuclear satellites have returned over the oceans, as was the case of the Cosmos 1402 reactor core, decayed over the South Atlantic
- Typically, the re-entry of large spacecraft catches more media and people attention than the re-entry of an equally, or even more massive, upper stage

Uncontrolled re-entry frequency

Large cataloged intact objects re-entered into the Earth's atmosphere between 2008 and 2017

Mass > 500 kg

Between 2008 and 2017

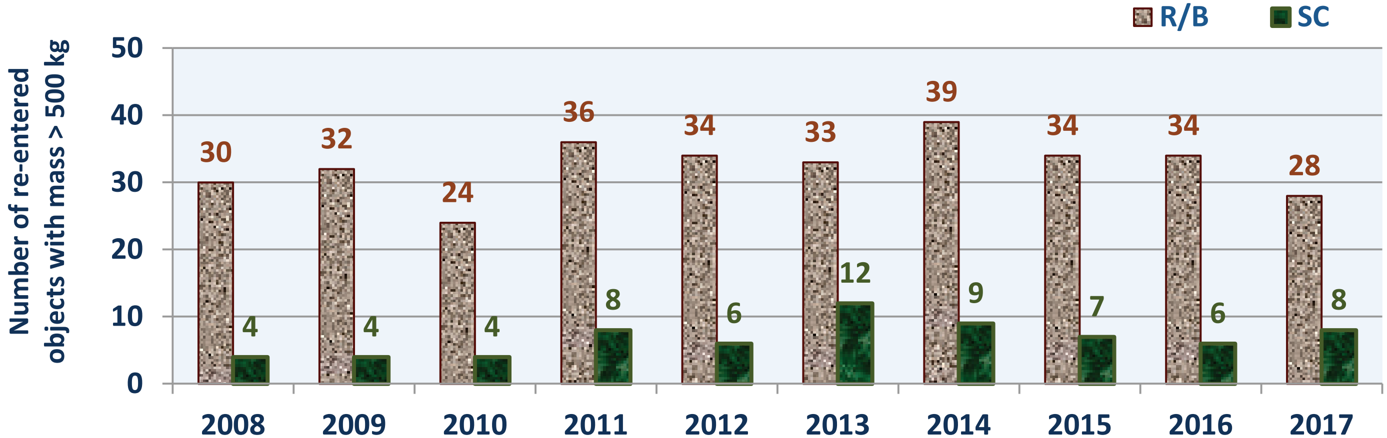
- 324 rocket bodies (~88% of large re-entered rocket bodies)
- 68 spacecraft (~83% of large re-entered spacecraft)

Average re-entries per year

- 32 rocket bodies
- 7 spacecraft
- 39 intact objects

Corresponding to

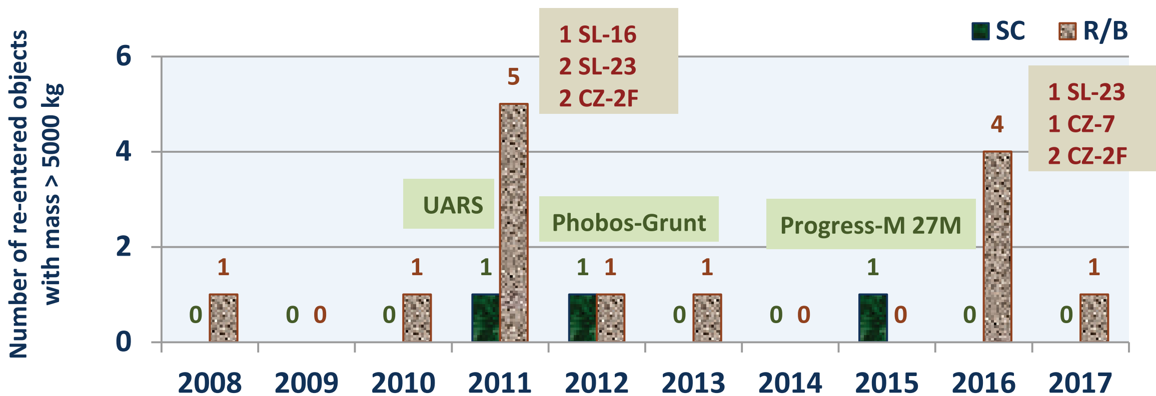
~1 intact object every 1-2 weeks



Mass > 5000 kg

Between 2008 and 2017

- 14 rocket bodies (~4% of large re-entered rocket bodies)
- 3 spacecraft (~4% of large re-entered spacecraft)
- **1-2 intact objects per year**

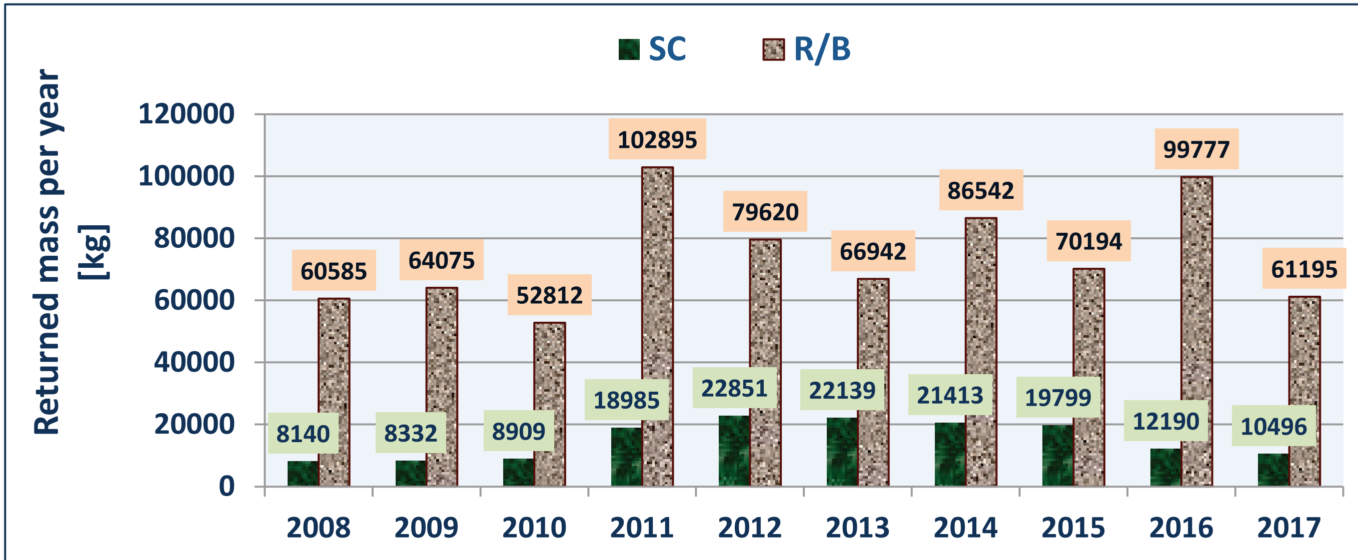


Returned mass

Mass > 500 kg

Average returned mass per year over the last decade

- Just over 74 metric tons concentrated in rocket bodies
- Little more than 15 metric tons belonging to spacecraft
- Almost 90 metric tons associated with intact objects



Mass > 5000 kg

UARS

Phobos-Grunt

Progress-M 27M

Used to launch Tiangong-1

More than 82% of the total mass (~11 150 kg) consisted of very toxic liquid hypergolic propellants

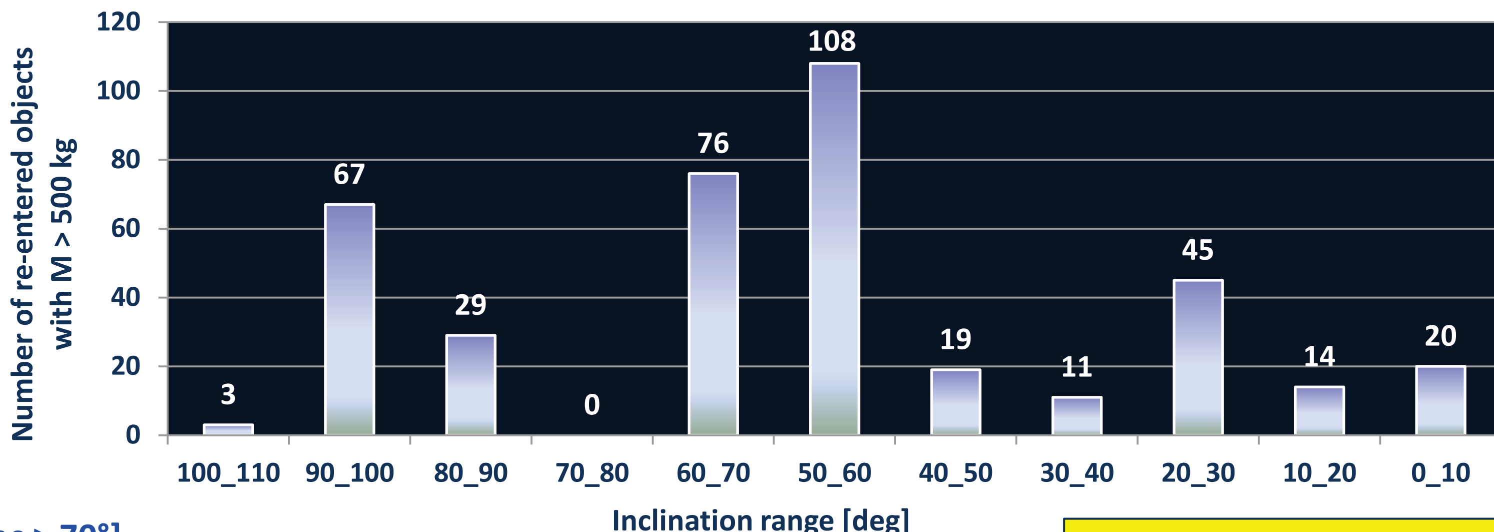
Used to launch Tiangong-2

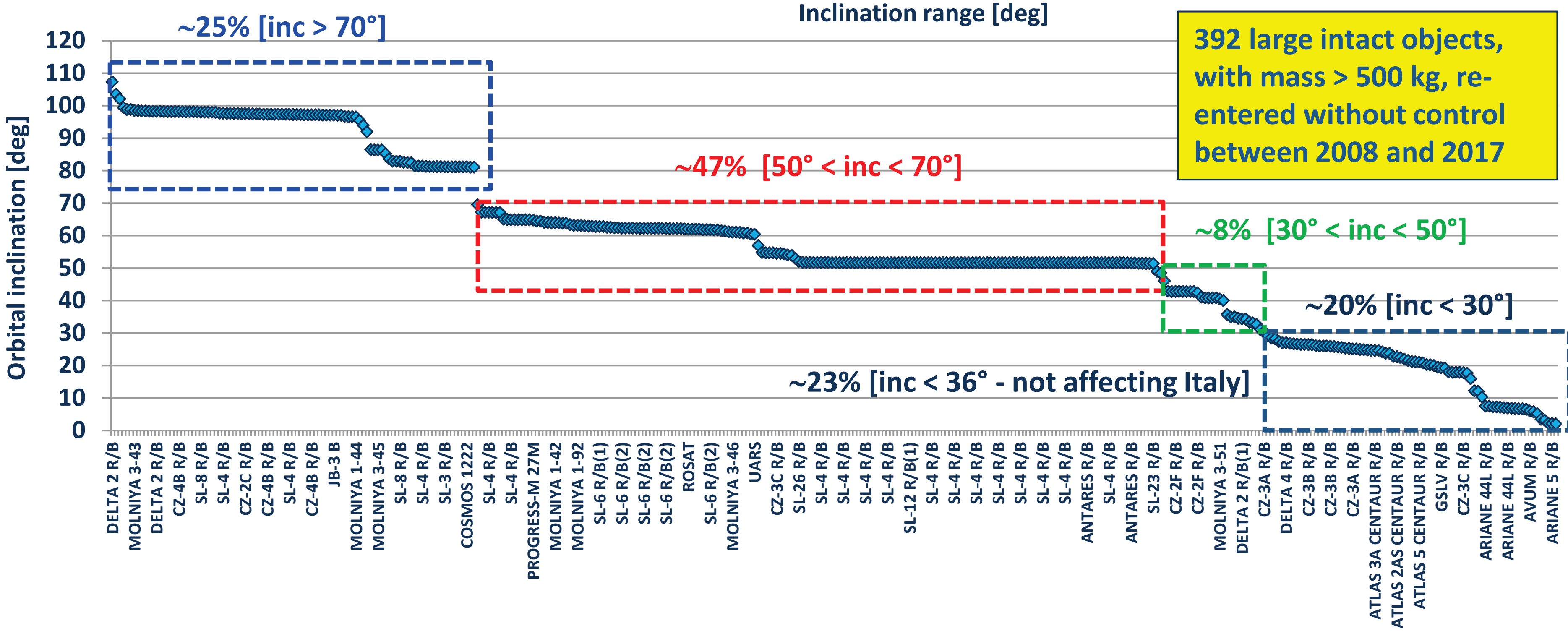
Space object	INTLDES	Re-entry epoch	Mass [kg]	Inc [deg]
CZ-2F R/B	2008-047B	17/10/2008	5502	42.39
DRAGON/FALCON 9	2010-026A	27/06/2010	6100	34.48
SL-23 R/B	2011-001C	19/03/2011	9300	51.39
SL-23 R/B	2011-037D	08/08/2011	9300	51.38
UARS	1991-063B	24/09/2011	5668	60.35
CZ-2F R/B	2011-053B	10/10/2011	5500	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

**The mass before re-entry includes propellants*

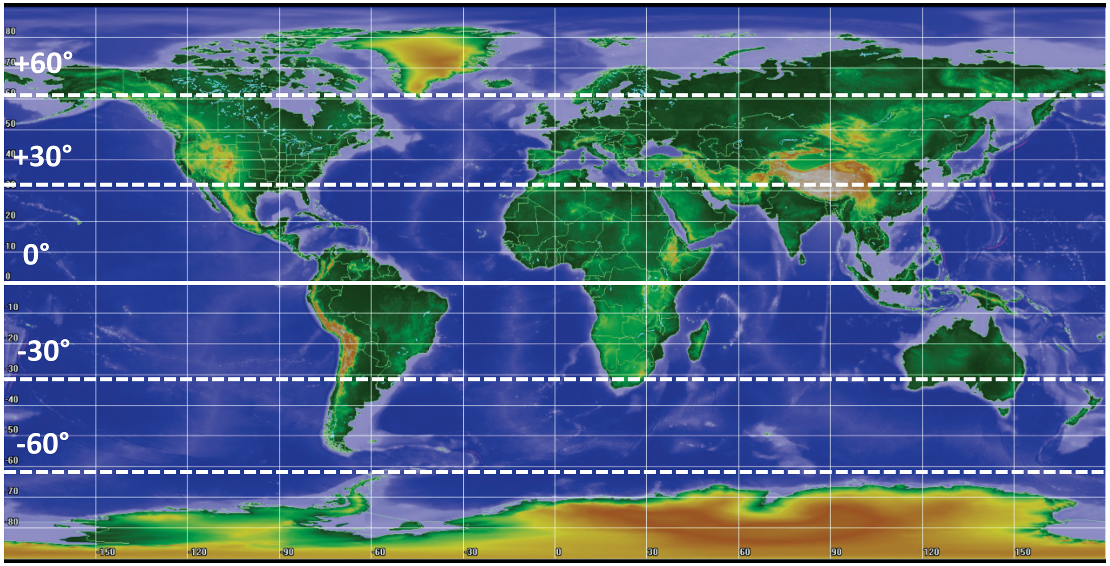
Distribution in inclination

Mass > 500 kg		
> 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%

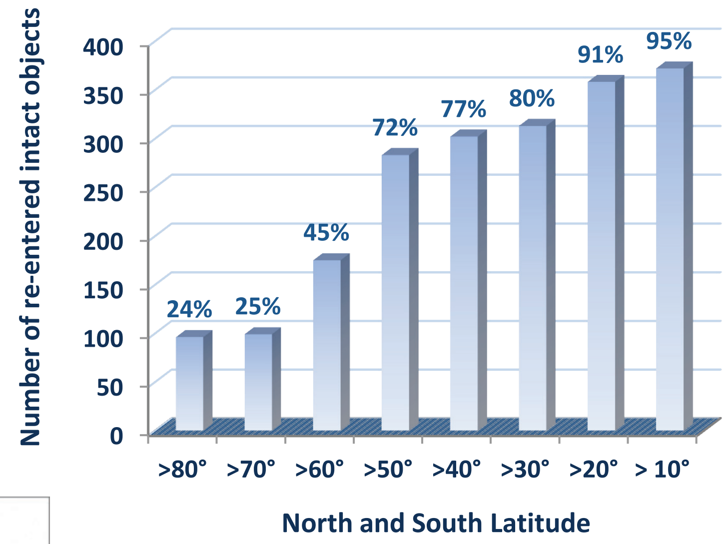


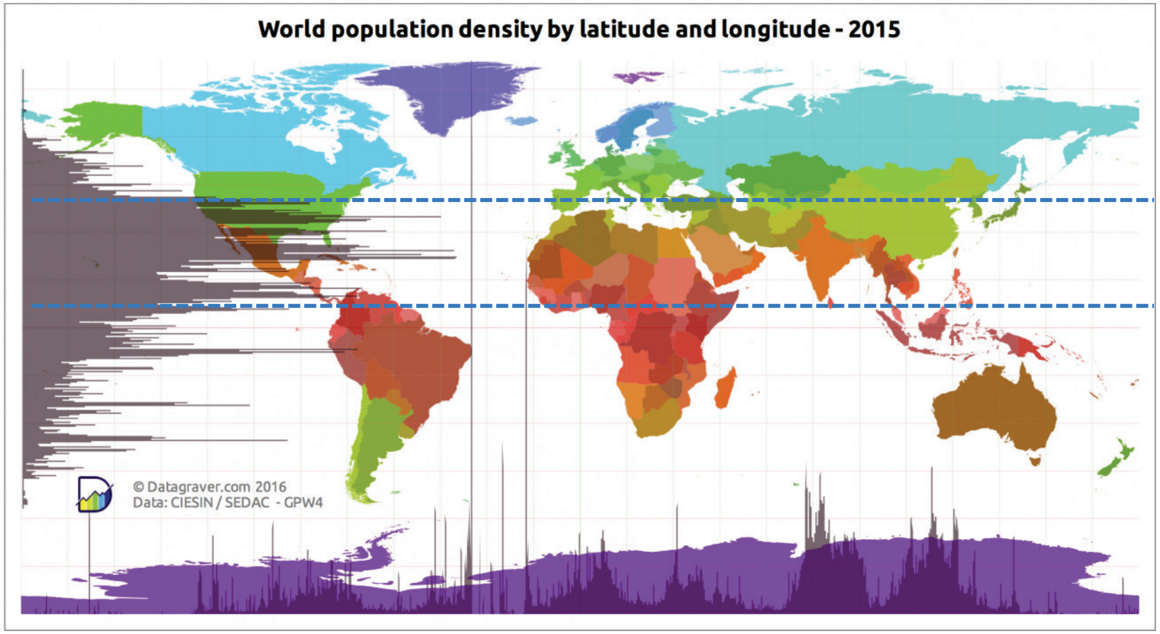


Latitude bands overflown



392 intact objects with mass > 500 kg

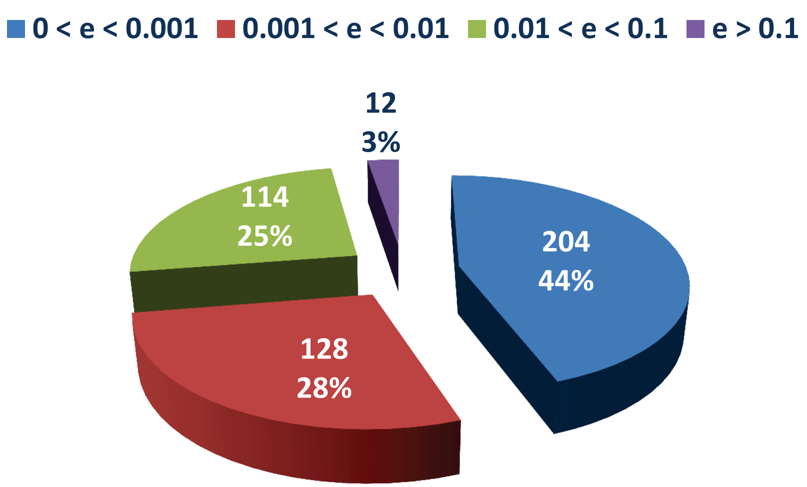


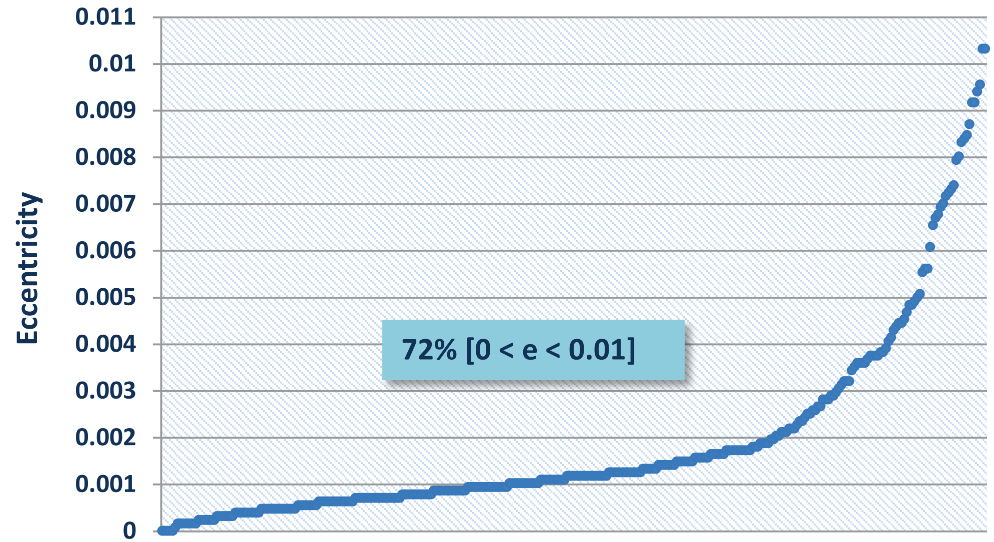


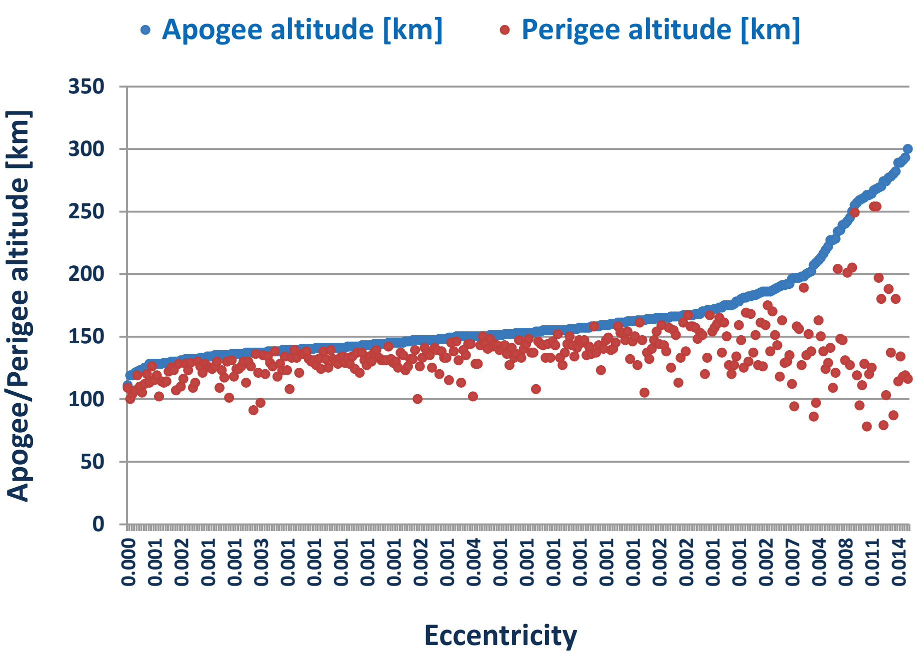
Maximum population density
~10° < LAT < ~40°

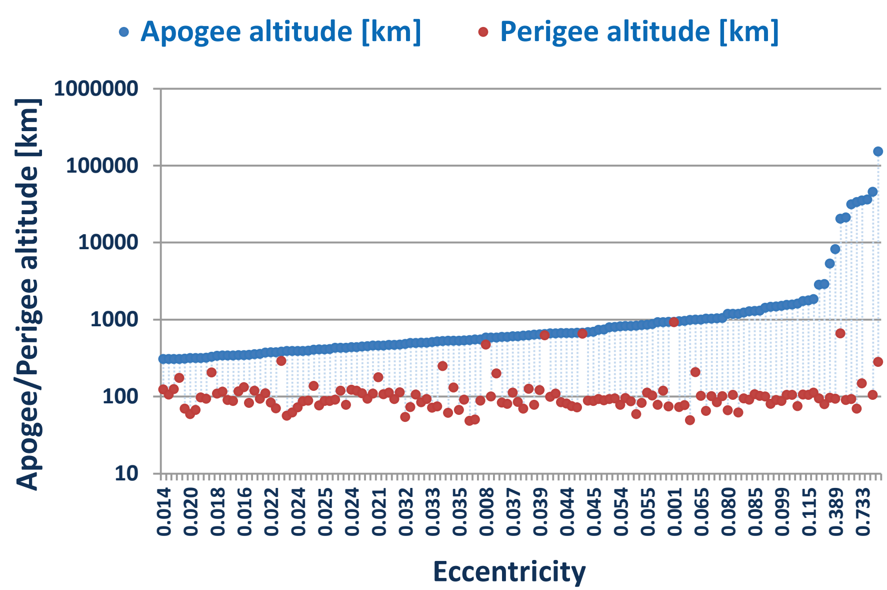
Credit: Datagraver.com

Eccentricity and perigee/apogee altitudes before re-entry





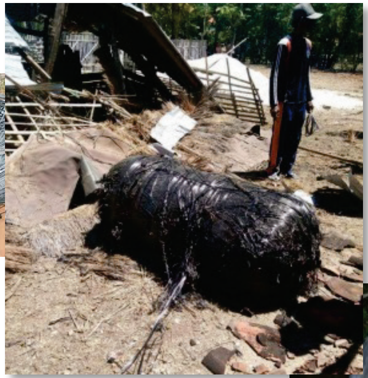




Eyewitnesses sightings and recovered debris

- FOR A NUMBER OF RE-ENTRY EVENTS EYEWITNESSES SIGHTINGS WERE REPORTED AND/OR PIECES OF DEBRIS WERE RECOVERED
- Sightings were reported [source: *Aerospace Corporation*] in ~9% of the uncontrolled re-entry events occurred between 2010 and 2017: 27 rocket bodies and 7 spacecraft out of 373 re-entries of large intact objects
- Moreover, 3 rocket bodies were sighted re-entering in the first half of 2018
- Still according to a database maintained by the *Aerospace Corporation*, major pieces of debris from space hardware re-entries have been recovered in at least 76 events, from 1960 to 2018, with masses varying from a few kilograms to 290 kg
- Apart from uncommon accidental cases, as the tragic loss of the Columbia Space Shuttle orbiter (2003), or the demise of Skylab (1979), the bulk of the re-entry fragments recovered so far on the ground comes from rocket bodies
- For uncontrolled re-entries occurred between 2008 and 2017, pieces of debris were retrieved in at least 12 events. All source objects were identified as spent upper stages: Delta II (3), GSLV (1), Zenit 3F (2), Ariane 4 (1), CZ-4B (1), Falcon 9 (2), AVUM (1), Centaur (1)
- Debris were also recovered in two re-entry events occurred in the first half of 2018: several fuel tanks from a 2nd stage of Zenit 3F (2017-086D), and a fuel tank from a CZ-3B (2017-078B) rocket body
- However, in spite of a not negligible amount of mass suspected to have survived re-entry during the last decade, and of at least 14 events in which rocket bodies components were retrieved, only trivial damages to property occurred and no case of personal injury was confirmed

AVUM 2012-006K COPV found near Oddanchatram, India (2016)



Pressure vessel from the 2nd stage of Falcon 9, found on the island of Giliraja, Indonesia (2016)

Spherical tank from the 2nd stage of Zenit 3F, found in the Tuyen Quans Province, Vietnam (2016)


Uncontrolled re-entries during the first half of 2018

Uncontrolled re-entries during the first half of 2018

16 spacecraft

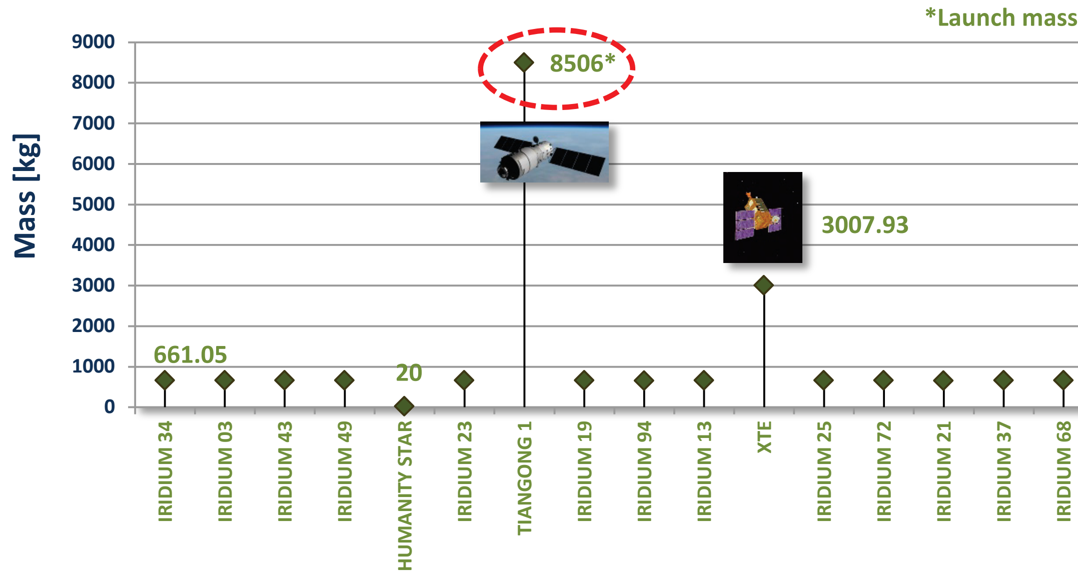
Returned mass: ~ 20 metric tons

i = 42.74°

- ❑ 2 April 2018: Chinese space station Tiangong-1

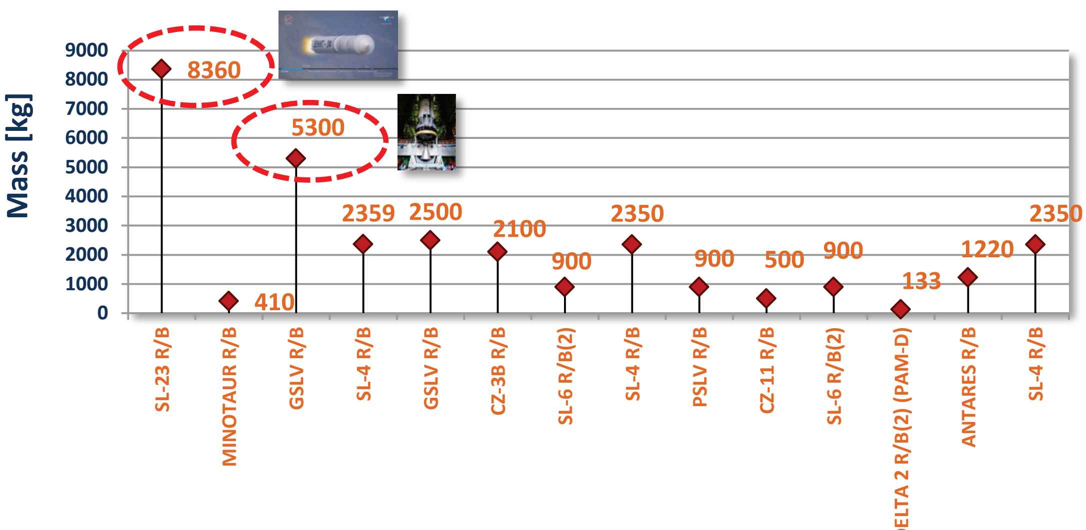
i = 22.97°

- ❑ 30 April 2018: Rossi X-ray Timing Explorer (RXTE or XTE) spacecraft



14 rocket bodies

Returned mass: ~ 30 metric tons



i = 51.37°

- ❑ 27 January 2018: Zenit-2SB second stage 2017-086D

i = 21.44°

- ❑ 8 February 2018: C-25 cryogenic upper stage 2017-031B of the Indian GSLV-MK3-D1 launcher

The re-entry of the Zenit-2SB second stage 2017-086D

- The fourth launch, on 26 December 2017, of the Russian-Ukrainian expendable carrier rocket Zenit-3SLBF (or Zenit-2SB/Fregat-SB) put into orbit the Angola’s first geostationary communication satellite AngoSat-1 (failed in drift orbit)
- After separating from the Fregat upper stage, the Zenit-2SB second stage began its orbital decay, only subjected to natural perturbations, from an initial orbit of ~162 × 566 km in altitude and inclination of 51.37°

JSpOC decay epoch @ 80 km
27 January 2018, 23:32 UTC ± 1 min
Lat: –9.2°
Lon: 285.7°

Sighting

Recovered debris

© Peruvian Air Force / AFP

Source: Aerospace Corporation

- *«This object was sighted re-entering on 27 January 2018 at 23:32 UTC over Pucallpa, Peru»*
- *«Several fuel tanks were recovered by the Peruvian Air Force near the Puno region of Peru after they were notified by local residence»*

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

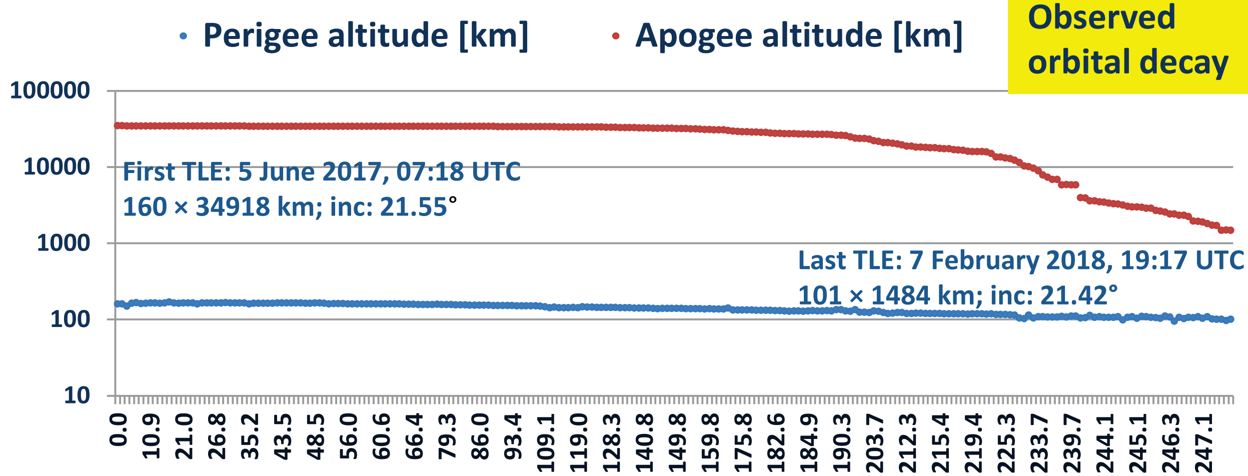
- The Indian Geosynchronous Satellite Launch Vehicle Mark III D1 (GSLV-MK3-D1) was used to launch the experimental Indian geostationary communication satellite GSAT-19 on 5 June 2017
- After releasing the spacecraft, the upper stage remained passive in a geosynchronous transfer orbit

COSPAR ID
2017-031B
Cat. Number
42748

C-25 Cryogenic upper stage

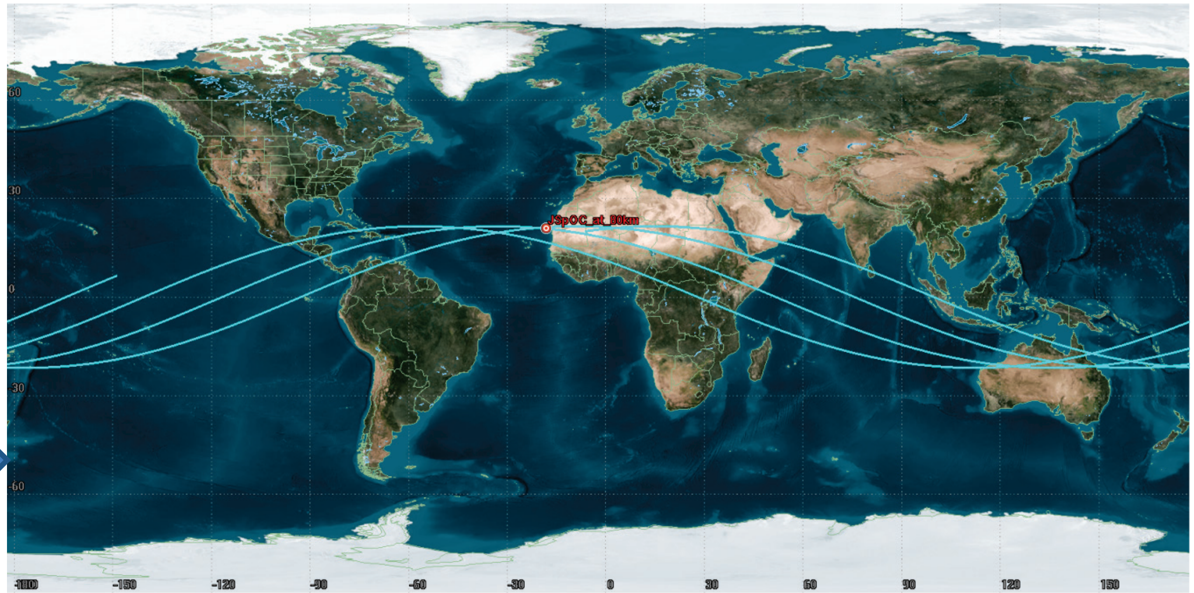
Length	13.55m
Diameter	4 m
Inert mass	~5300 kg

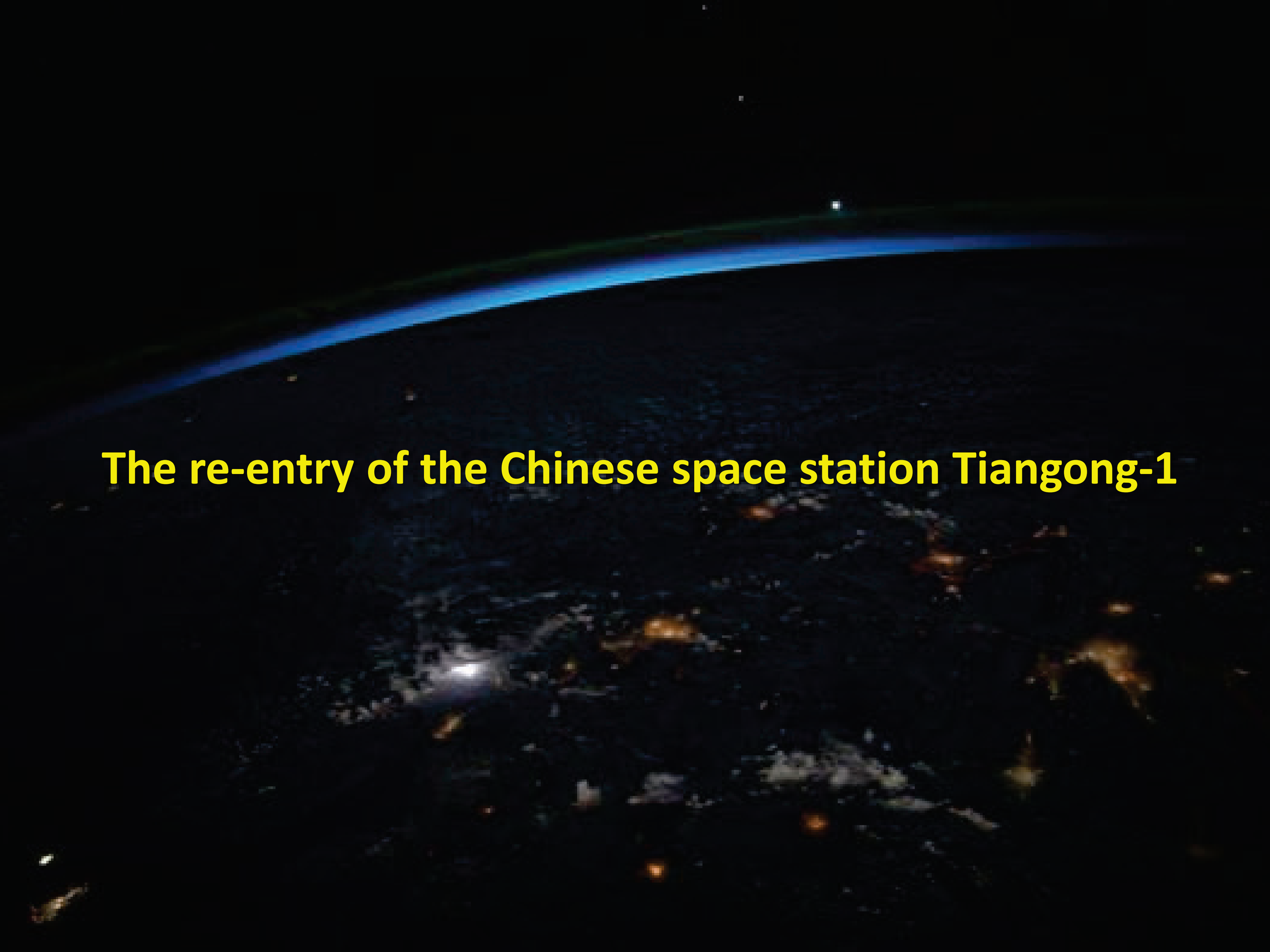
Observed orbital decay



JSpOC decay epoch @ 80 km
8 February 2018, 11:30 UTC
± 180 min
Lat: 21.1°
Lon: 341.9°

Sub-satellite ground tracks corresponding to the last JSpOC re-entry uncertainty window




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

The Chinese space station Tiangong-1

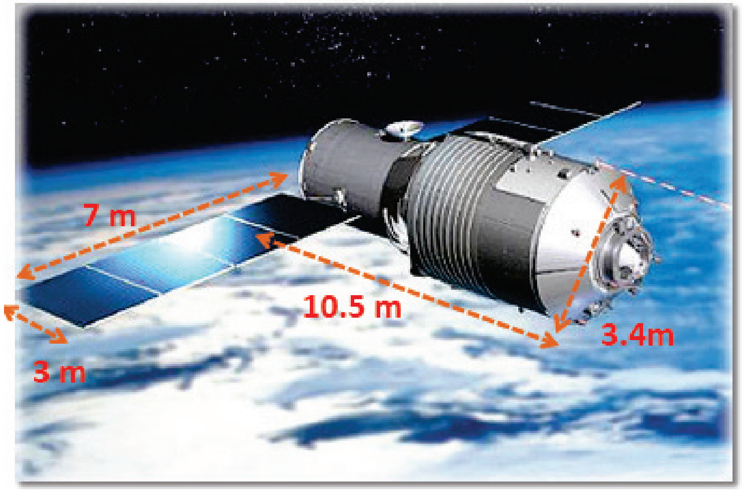
- Tiangong-1, launched on 29 September 2011, was the first Chinese space station, used both as human tended laboratory and target for testing orbital rendezvous and docking

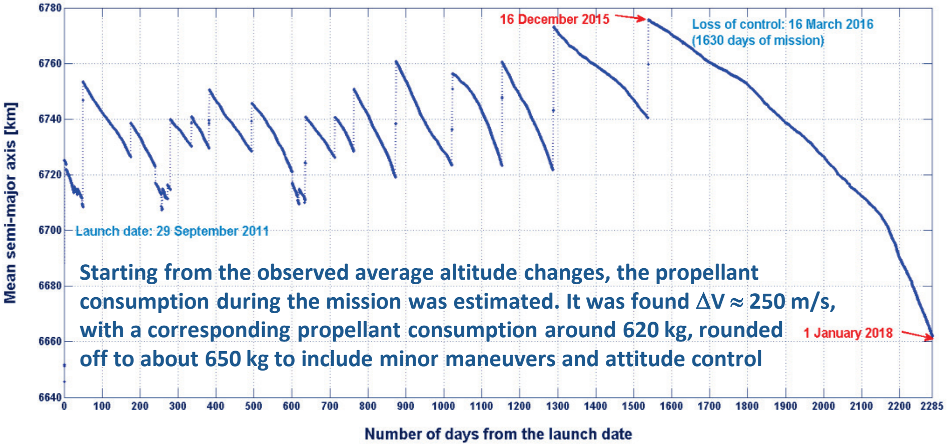
- The control of the space station was lost on 16 March 2016, preventing a targeted re-entry in the South Pacific Ocean Uninhabited Area (SPOUA)

USSTRATCOM catalog number	37820
COSPAR ID	2011-053A
Launch date	2011-09-29

Length	10.5 m
Diameter of the orbital module	3.4 m
Diameter of the service module	2.5 m
Solar panels	2 rectangular 7 m × 3 m

Total mass at launch	8506 kg
Propellant mass at launch	1000 kg
Total mass before re-entry	≈ 7550 kg
Dry mass before re-entry	≈ 7150 kg
Propellant mass before re-entry	≈ 350 kg
MMH – mono-methyl hydrazine	≈ 120 kg
N_2O_4 - nitrogen tetroxide	≈ 230 kg

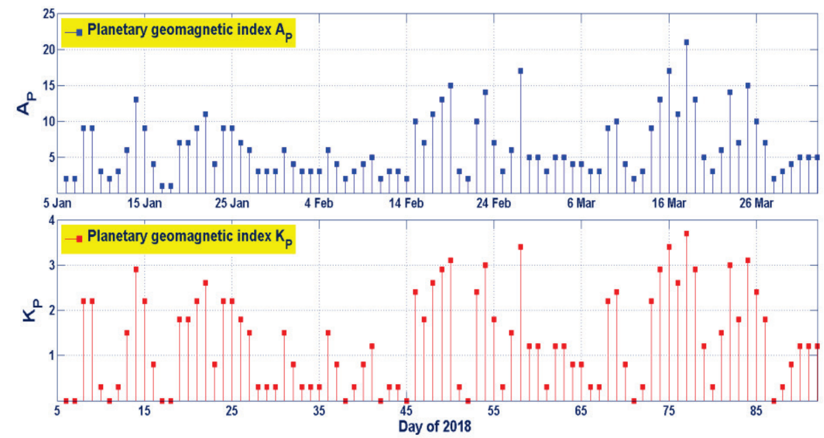




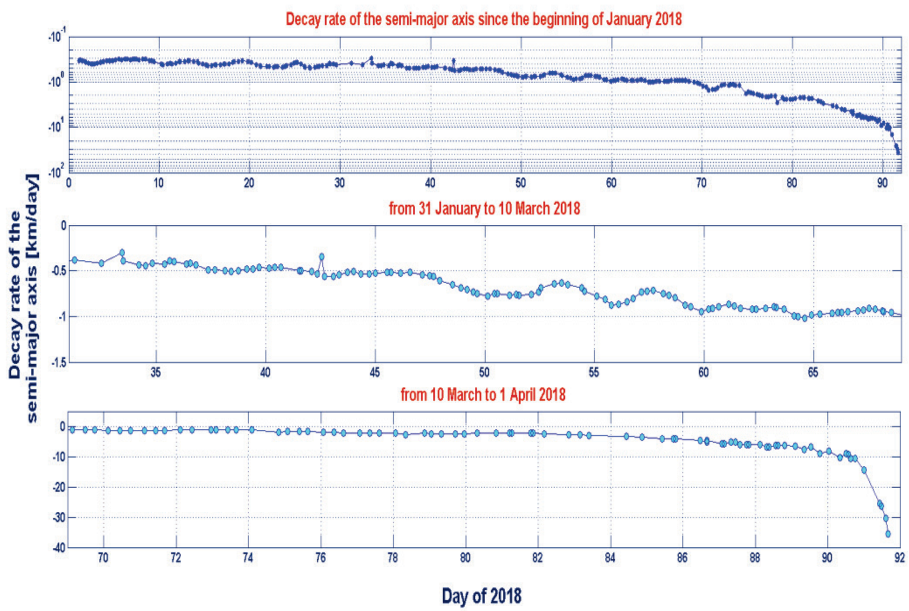
- The observations of the TIRA radar confirmed that Tiangong-1 lost a stable attitude soon after the failure in 2016. It assumed a precessing flat spin around its main axis of inertia, typical of a vehicle without control

Solar and geomagnetic activity during the re-entry campaign

- **The Tiangong-1 re-entry campaign occurred during a period of extremely low solar activity**



- **There were numerous G1 geomagnetic storms, and a single G2 storm, which significantly affected the orbit evolution of Tiangong-1, as highlighted by the oscillations observed in the semi-major axis decay rate**



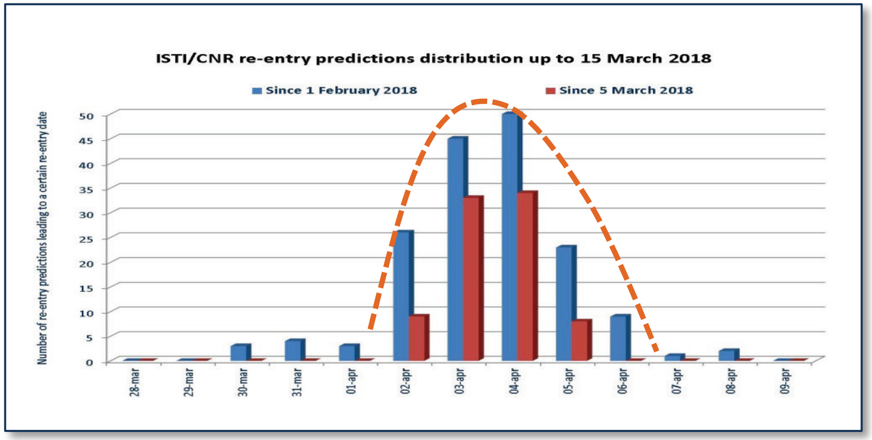
- **In such a low conditions of solar activity, as it was during the re-entry of Tiangong-1, also minor G1 storms could increase the local thermospheric density by more than 20% at the altitude of the Chinese space station**
- **The G2 storm, recorded during the night between 18 and 19 March, moved earlier the nominal re-entry of Tiangong-1 by nearly 31 hours**

Re-entry predictions carried out at ISTI-CNR

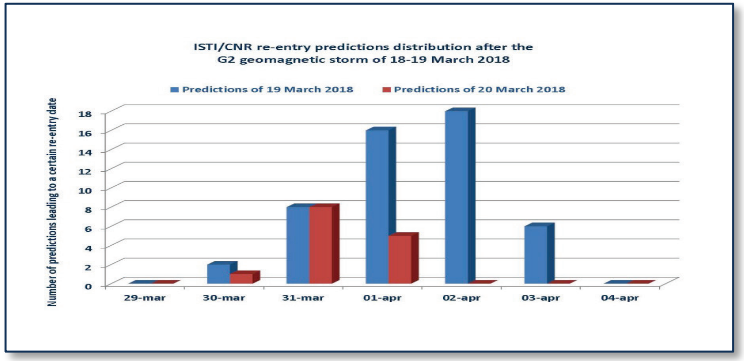
- ISTI-CNR participated in the re-entry campaign promoted by the Inter-Agency Space Debris Coordination Committee (IADC) for Tiangong-1, and provided also support to the Italian Space Agency (ASI) for the National Department of Civil Protection

- Hundreds of re-entry predictions were carried out since January 2018, using various combinations of atmospheric density models (NRLMSISE-00 and GOST2004) and time spans for the calibration of the ballistic parameter, in order to assess the sensitivity and the statistical distribution of the results within a spectrum of reasonable hypotheses

- From the beginning of February 2018, the re-entry time began to converge towards the first week of April

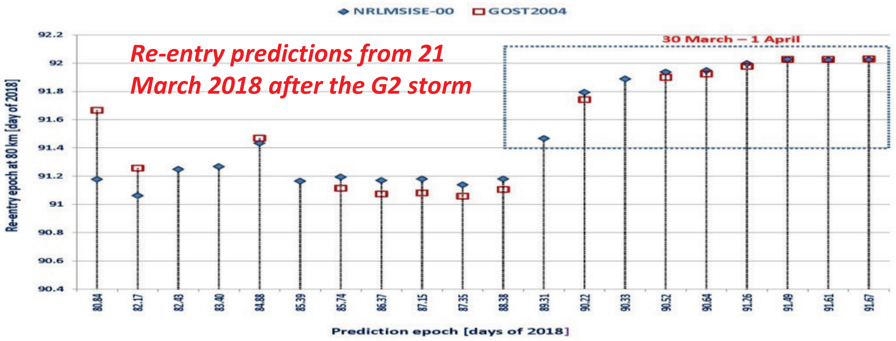


- The G2 storm, occurred during the night of 18-19 March, caused a significant shift of the re-entry time, concentrating the re-entry predictions from 30 March to 3 April 2018



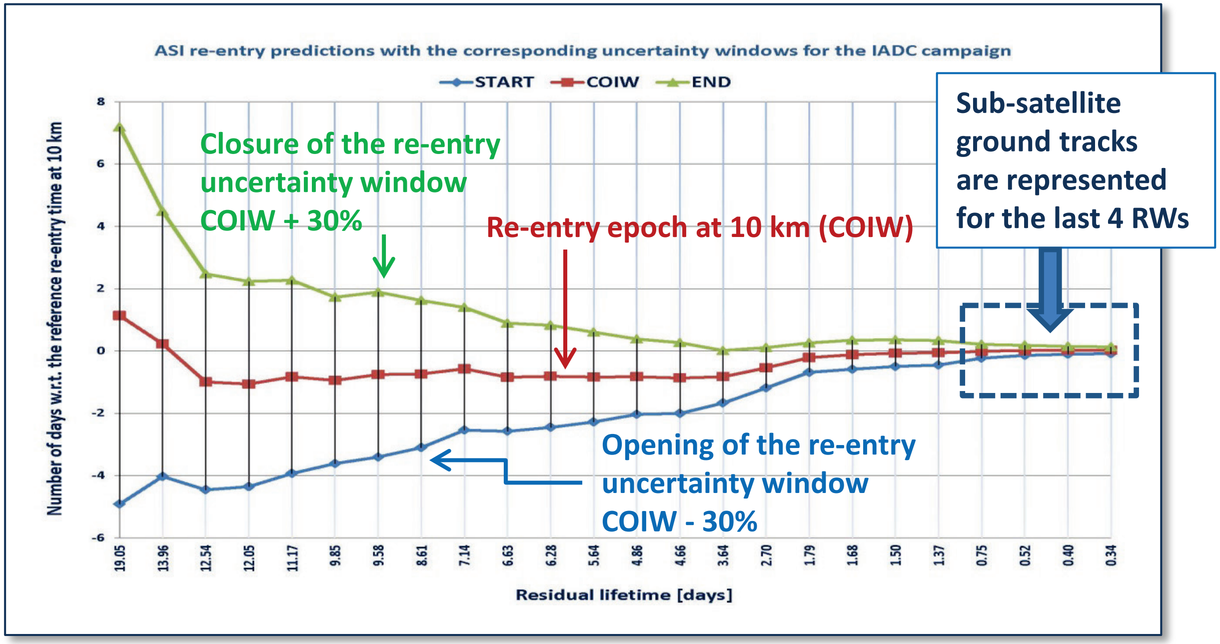
- From 21 March, the re-entry epoch has stably settled on 1 April. To be exact, in a 24-hour period between 01:00 UTC of 1 April and 01:00 UTC of 2 April

- Within this 24-hour period, the only important shift occurred since 30 March, when an unusually long period of quiet geomagnetic conditions led to a cooling down of the atmosphere, with a consequent reduction of the density and a progressive extension of the residual lifetime of Tiangong-1



Re-entry uncertainty windows

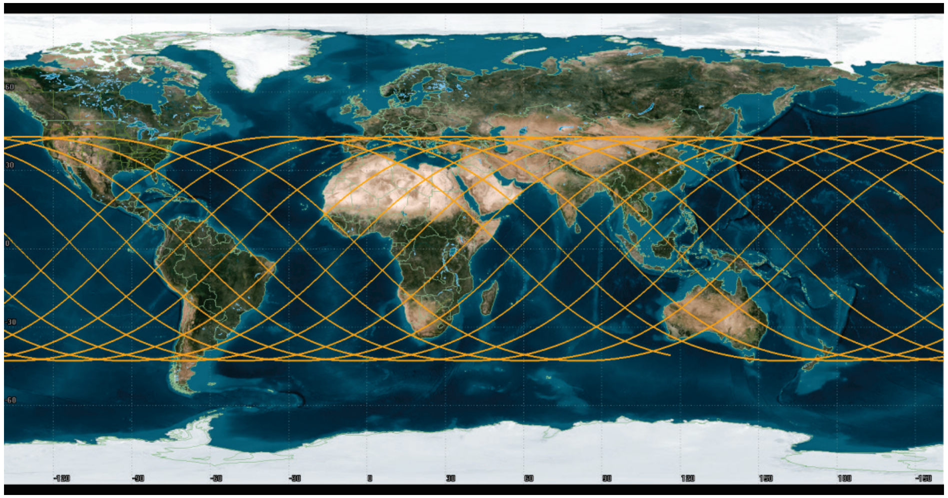
- The orbital evolution of objects re-entering the Earth's atmosphere from nearly circular LEO orbits ($e \leq 0.01$) is mainly driven by the atmospheric drag
- Hence, the uncertainties affecting the re-entry predictions are dominated by the modeling of the atmospheric drag, which is characterized by inherent inaccuracies and biases related to:
  - The physical properties and attitude of the satellite (ballistic parameter)
  - The atmospheric density model, and the prediction of solar and geomagnetic activity affecting the atmospheric temperature, and the local atmospheric density as a consequence
- On the basis of the statistical distribution of all predictions carried out at ISTI-CNR during the first 20 IADC re-entry campaigns, it was found that **an uncertainty time window able to guarantee a confidence level of ~90% should assume an amplitude of about ±20% around the computed nominal re-entry time. An uncertainty window amplitude of ±30% would be needed to achieve a confidence level of ~95%**



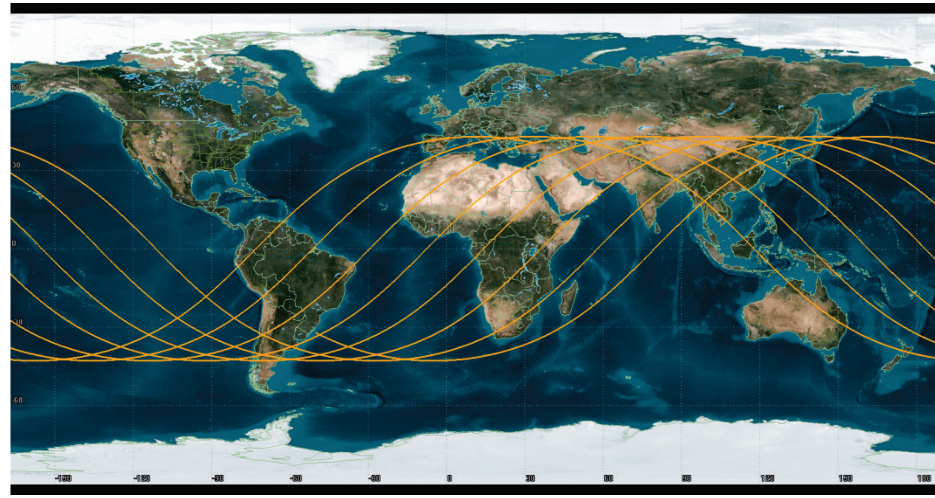
- Therefore, considering that the re-entry uncertainty windows for Tiangong-1 had to be used for civil protection applications, they were defined in order to guarantee a confidence level of at least 95%
- With this choice, none of the re-entry uncertainty windows was violated by the post-event reference re-entry epoch, confirming the validity of the approach adopted

Sub-satellite ground tracks corresponding to the last 4 re-entry uncertainty windows

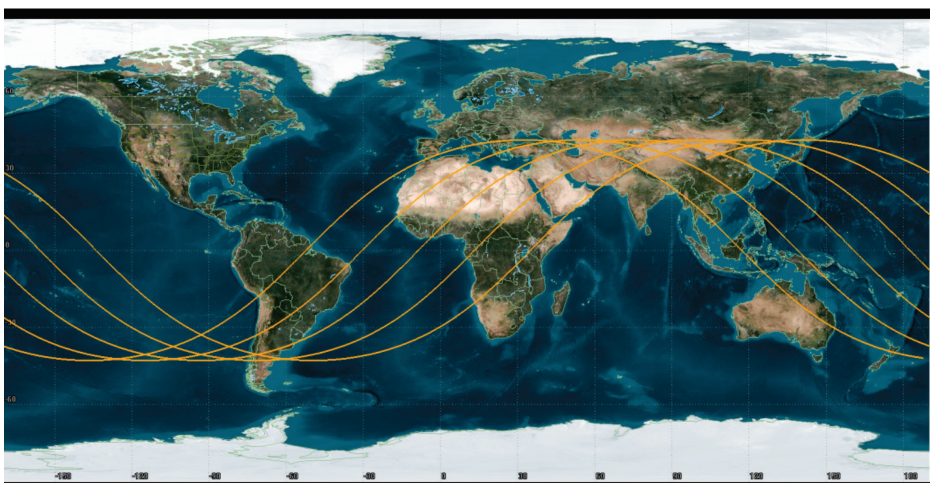
- The orbit on which the re-entry of Tiangong-1 actually occurred had already been identified nearly 18 hours before the final decay, but only the last uncertainty window allowed the exclusion of a re-entry over Italy with the targeted confidence level (> 95%)



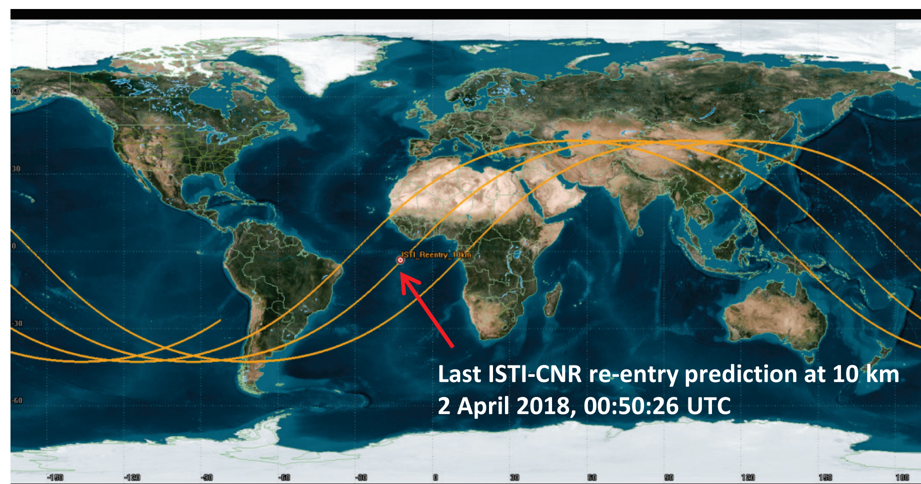
Uncertainty window computed ~34 hours before re-entry



Uncertainty window computed ~18 hours before re-entry



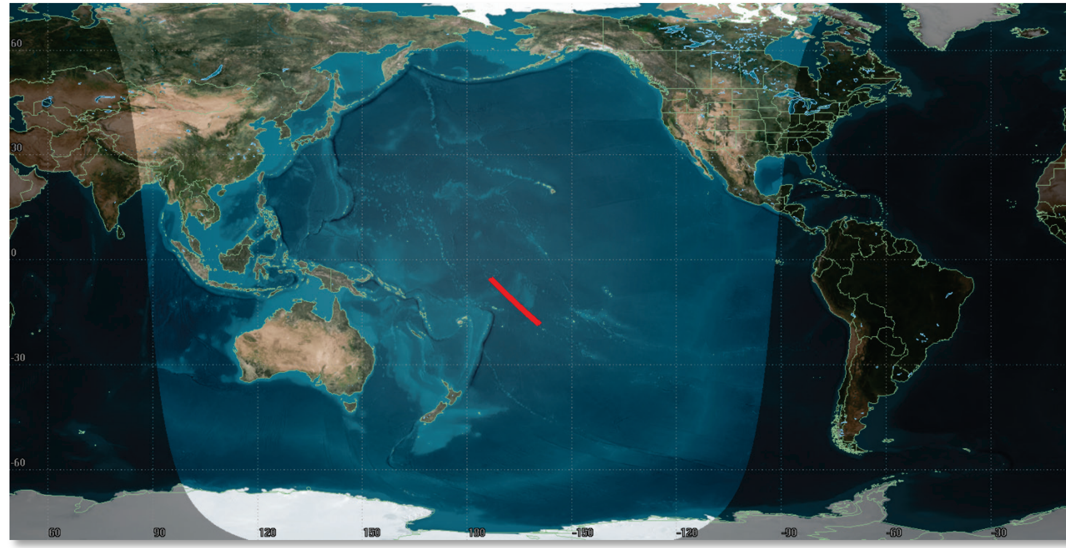
Uncertainty window computed ~13 hours before re-entry



Uncertainty window computed ~9 hours before re-entry

Identification of the re-entry area

- After the re-entry, JSpOC issued a note, declaring that Tiangong-1 had plunged in the middle of the Pacific Ocean, just after midnight of 1 April 2018
- The re-entry at 80 km of altitude would have occurred at 00:10 UTC of 2 April 2018, while the IADC reference altitude of 10 km would have been reached at 00:16 UTC
- During the 8 hours preceding the re-entry, the US space surveillance network was not able to produce new orbit determinations
- Therefore, the final estimate of the re-entry epoch seems to be the result of further «adjustments» of the last «old» orbit solution, in which the ballistic parameter increased at the end, causing an earlier re-entry time



Area of possible dispersion of the fragments of Tiangong-1 if the post-reentry assessment released by JSpOC was correct

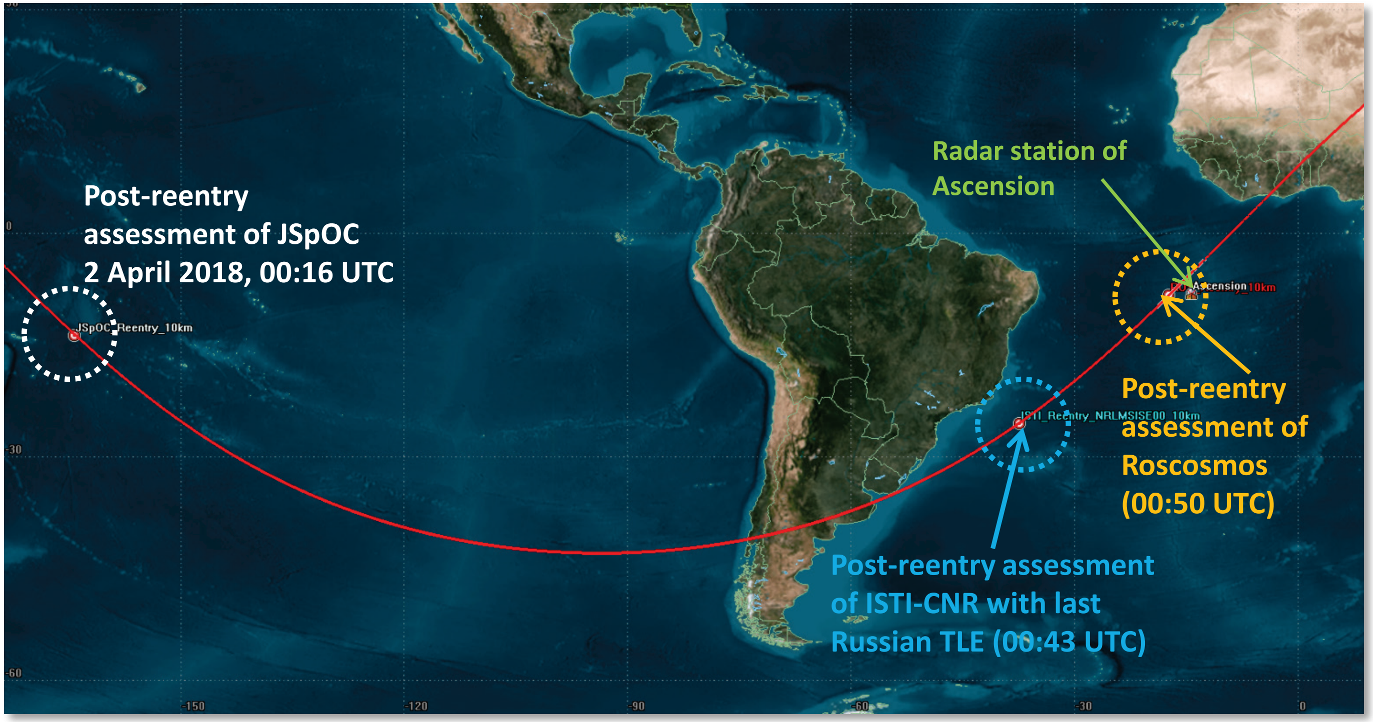
```
1 37820U 11053A 18091.67159150 .05839629 93439-6 12719-3 0 9991
2 37820 42.7393 196.1141 0005983 335.0656 24.9878 16.46430482373982
```

```
1 37820U 11053A 18091.67159262 .04847022 93097-5 11856-3 0 9991
2 37820 42.7368 196.1112 0003886 340.8150 19.2351 16.46105415373983
1 37820U 11053A 18091.67159643 .06702538 93469-6 14209-3 0 9996
2 37820 42.7393 196.1141 0005983 335.0657 25.0237 16.46560555373989
```

- However, after the re-entry, Roscosmos uploaded in the IADC re-entry database a further TLE based on the last pass over the Russian sensors
- Such orbital elements were then acquired during the last orbit, when Tiangong-1 had a geodetic altitude of just 125 km

When and where Tiangong-1 actually re-entered?

- Using the last Russian TLE, the re-entry time reported by JSpOC would have been obtained only by increasing the atmospheric density, computed with the NRLMSISE-00 model, by more than 5 times
- Hence, or the last Russian orbit was not precise and the re-entry actually occurred in the Pacific Ocean, not far from the «graveyard of satellites», or it occurred, instead, in the South Atlantic Ocean, between the Uruguay coast and Ascension Island



Post-re-entry assessments of Roscosmos and ISTI/CNR, at 10 km of altitude, based on the last Russian TLE, compared with that of JSpOC, based on the last US TLE

- Also the solution obtained by Roscosmos would have been compatible with the fact that no pass was acquired by the Ascension Island tracking radar

Assessing the risk of the Tiangong-1 uncontrolled re-entry

Classification of the risk

- The uncontrolled re-entry of Tiangong-1 presented two types of risk: mechanical and chemical
  - The mechanical risk was related to the impact on the ground of fragments with a kinetic energy > 15 J, and to the crossing of the airspace by debris with a mass > 100 g
  - The chemical risk was instead related to the possible contamination from mono-methyl hydrazine (MMH) [CH_6N_2], extremely toxic, and from nitrogen tetroxide [N_2O_4], the aggregation state (liquid or solid) of which was unknown
- Concerning the global *casualty expectancy*, not having any reliable source, it was estimated to be of the order of 10^{-3}, corresponding to an ISTI-CNR «yellow» alert code

Fragmentation analysis

- Again, not having any reliable information on the nature and dispersion of the fragments generated by the endo-atmospheric breakup of Tiangong-1, the analogy with previous cases was exploited
- Herein, the breakup process of the NASA's satellite UARS, re-entered in 2011 with a dry mass of 5668 kg, was considered as a reference case
- Assuming the fragmentation of the main body at 80 km, the falling debris would have scattered on the ground approximately along the sub-satellite re-entry ground track, from 500 to 1800 km downstream of the sub-satellite point corresponding to a re-entry at 80 km
- Concerning the dispersion of the fragments perpendicularly to the re-entry trajectory, it was assumed a safety swath of $\pm$120 km, perpendicularly to the re-entry trajectory of the intact object, which was reduced to $\pm$100 km about 36 hours before re-entry

Risk time windows and ground tracks for Italy

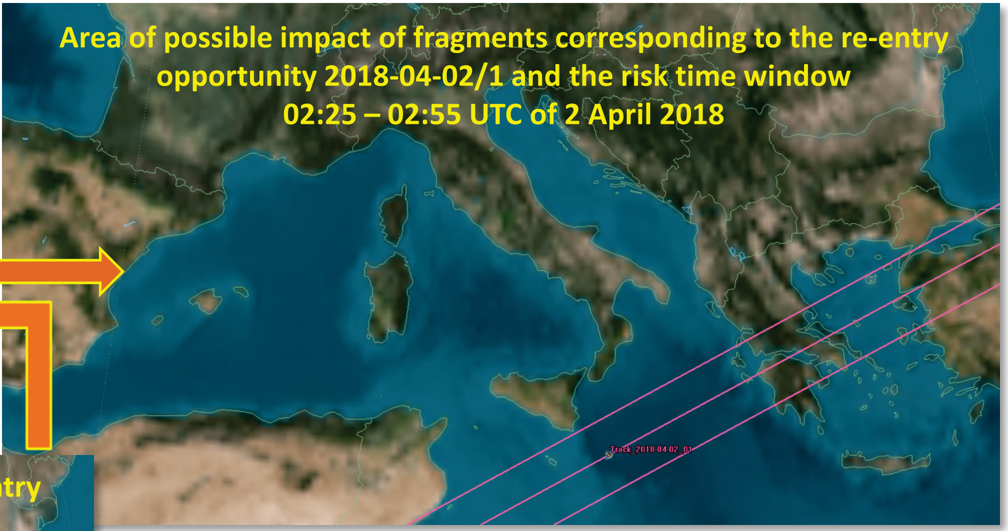
- During 1 and 2 April 2018, eight overflights of the Italian territory were possible. In each one, the re-entry was very unlikely, but theoretically possible
- Hence, for each of these possibilities, the risk time windows and geographic areas associated with fragments hitting the national territory and crossing the airspace, down from an altitude of 18 km, were estimated

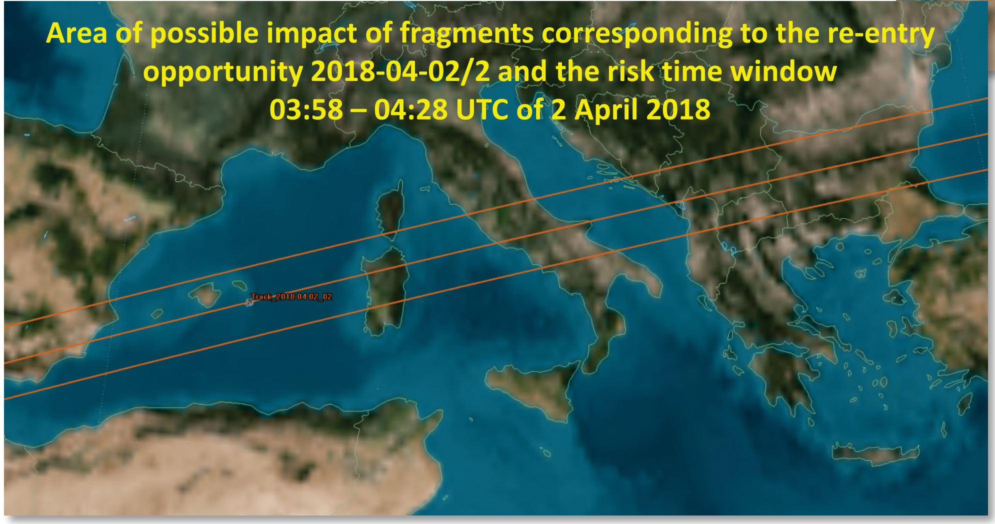
Risk time windows of 1 April

Re-entry opportunity **2018-04-01/1**: **03:02 – 03:32 UTC**
Re-entry opportunity **2018-04-01/2**: **04:34 – 05:04 UTC**
Re-entry opportunity **2018-04-01/3**: **06:05 – 06:35 UTC**
Re-entry opportunity **2018-04-01/4**: **07:38 – 08:08 UTC**

Risk time windows of 2 April

Re-entry opportunity **2018-04-02/1**: **02:25 – 02:55 UTC**
Re-entry opportunity **2018-04-02/2**: **03:58 – 04:28 UTC**
Re-entry opportunity **2018-04-02/3**: **05:30 – 06:00 UTC**
Re-entry opportunity **2018-04-02/4**: **07:02 – 07:32 UTC**





- The evolution and the progressive contraction of the global uncertainty window allowed the exclusion of most of these possibilities well in advance
- At 9:10 UTC of 1 April, the first three opportunities of 2 April still remained in play, and reduced to the first two at 14:30 UTC
- At 19:00 UTC of 1 April, it was finally possible to exclude also the second opportunity of 2 April, practically eliminating any risk for the Italian territory

Conclusions

- Even if the risk related to the re-entry of manmade space objects is still extremely low, it cannot be commonly accepted as being inevitable
- Furthermore, it cannot be excluded that uncontrolled re-entries of sizable space objects might become of greater concern in the future, as a consequence of the increased use of space and of growing population density on the ground
- The lessons learned from past uncontrolled re-entries of massive bodies suggest that, even if still small compared to other commonly accepted risks related to the lifestyle, or workplace and household safety, the risk of being hit by falling orbital debris for aircraft in flight, or people and property on the ground, cannot be absolutely neglected
- Moreover, 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, as shown in this presentation, the uncontrolled re-entries of objects probably violating such casualty upper limit may be relatively frequent, even though generally unknown to governments and the public at large
- For instance, there are several large upper stages, with masses around 4 metric tons or more, which still mostly re-enter without control
- Finally, 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, as it was the case for the Russian cargo vessel Progress-M 27M and the Chinese space station Tiangong-1

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