UNCONTROLLED RE-ENTRIES OF MASSIVE SPACE OBJECTS

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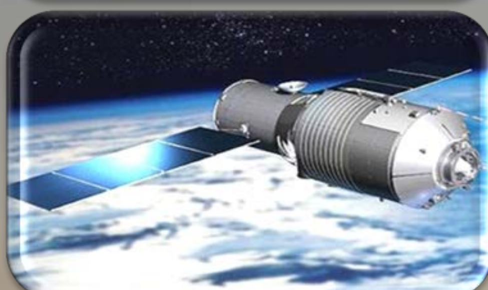
Outline

- Uncontrolled re-entries of massive space objects during the last decade

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



- Status and decay time evolution of the Chinese space station Tiangong-1

Premise

- **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

- To characterize in a synthetic way the **relevance of uncontrolled re-entries**, a re-entry magnitude M_R was defined at ISTI-CNR as follows

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

ISTI-CNR uncontrolled re-entry magnitude scale definition

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

- **Sources of data**

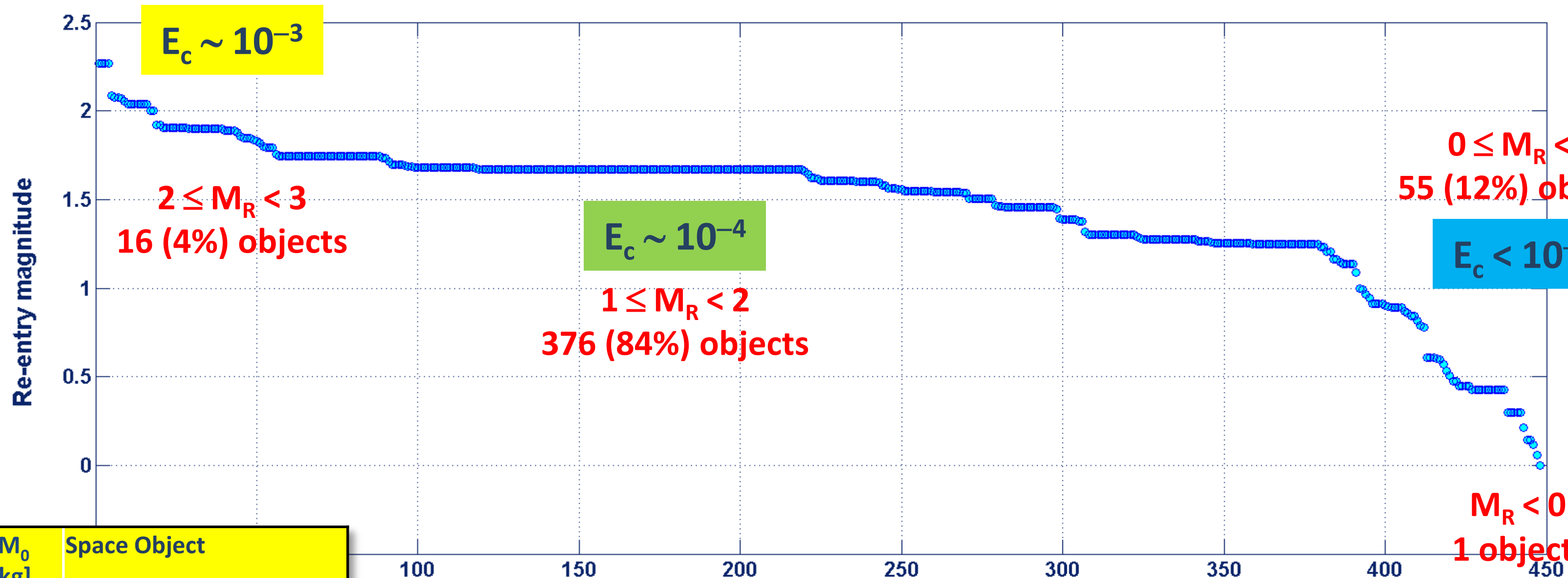
Orbit of re-entered objects: US Space-Track Organization (www.space-track.org)

Mass of re-entered objects: ESA's DISCOS Database (discosweb.esoc.esa.int); Gunter's Space Page (space.skyrocket.de); Spaceflight101 (spaceflight101.com)

Relevance of uncontrolled re-entries [2008 – 2017]

Large (RCS > 1 m²) catalogued intact objects re-entered into the Earth's atmosphere during the last decade [2008 – 2017]

- 366 rocket bodies (mass between ~50 kg and ~9 300 kg, 42 with mass < 500 kg)
- 82 spacecraft (mass between ~57 kg and ~13 525 kg – launch mass including propellants, 14 with mass < 500 kg)



M_R	M_0 [kg]	Space Object
2.268	9300	SL-16 (2011-065B)
2.268	9300	SL-23 (2011-001C)
2.268	9300	SL-23 (2011-037D)
2.268	9300	SL-23 (2015-074C)
2.078	6100	DRAGON/FALCON9 (2010-026A)
2.078	6000	CZ-7 (2016-042E)
2.072	6000	CZ-7 (2017-021B)
2.085	5916	PROGRESS-M 27M (2015-024A)
2.053	5668	UARS (1991-063B)
2.041	5502	CZ-2F (2008-047B)
2.041	5502	CZ-2F (2011-053B)
2.041	5502	CZ-2F (2011-063B)
2.041	5502	CZ-2F (2012-032B)
2.04	5500	CZ-2F (2013-029B)
2.04	5500	CZ-2F (2016-057B)
2.04	5500	CZ-2F (2016-061B)

Dry mass M_0 of the re-entering object [kg]	Re-entry magnitude M_R	All intact objects	Spacecraft	Rocket bodies
$M_0 \leq 50$	$M_R < 0$	1	0	1
$50 < M_0 \leq 500$	$0 \leq M_R < 1$	55 (12%)	14 (17%)	41 (11%)
$500 < M_0 \leq 5000$	$1 \leq M_R < 2$	376 (84%)	66 (80.5%)	310 (85%)
$5000 < M_0 \leq 9300$	$2 \leq M_R < 3$	16 (4%)	2 (2.5%)	14 (4%)
All re-entered intact objects		448	82	366

Re-entry frequency [2008-2017]

Large catalogued intact objects with mass > 500 kg re-entered into the Earth's atmosphere between 2008 and 2017

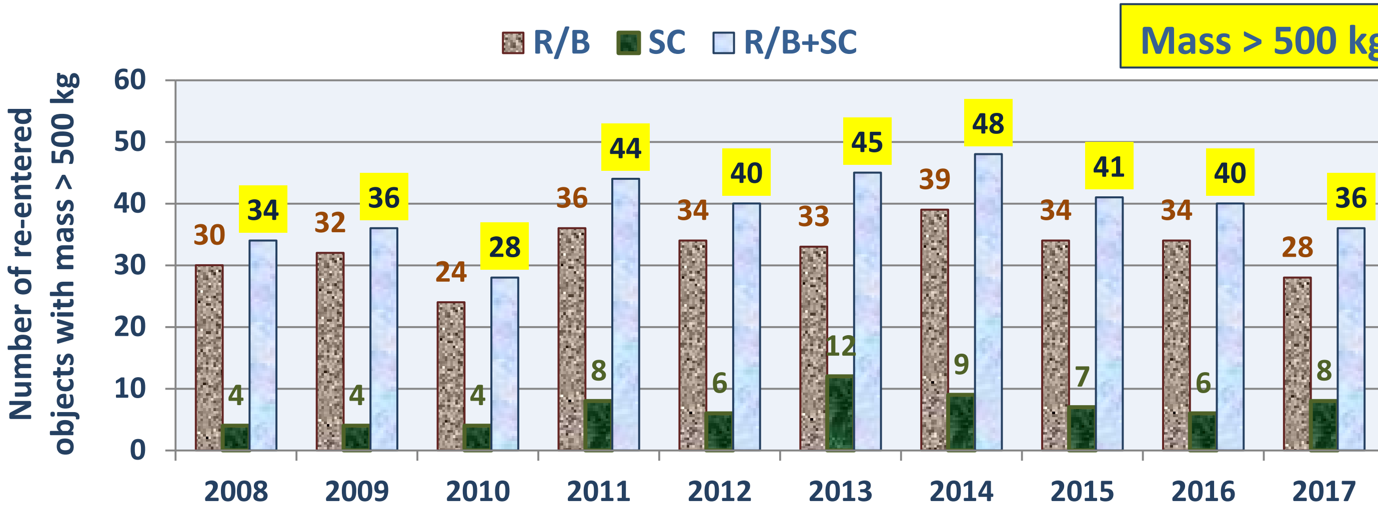
- 324 rocket bodies (~88% of large re-entered rocket bodies)
- 68 spacecraft (~83% of large re-entered spacecraft)

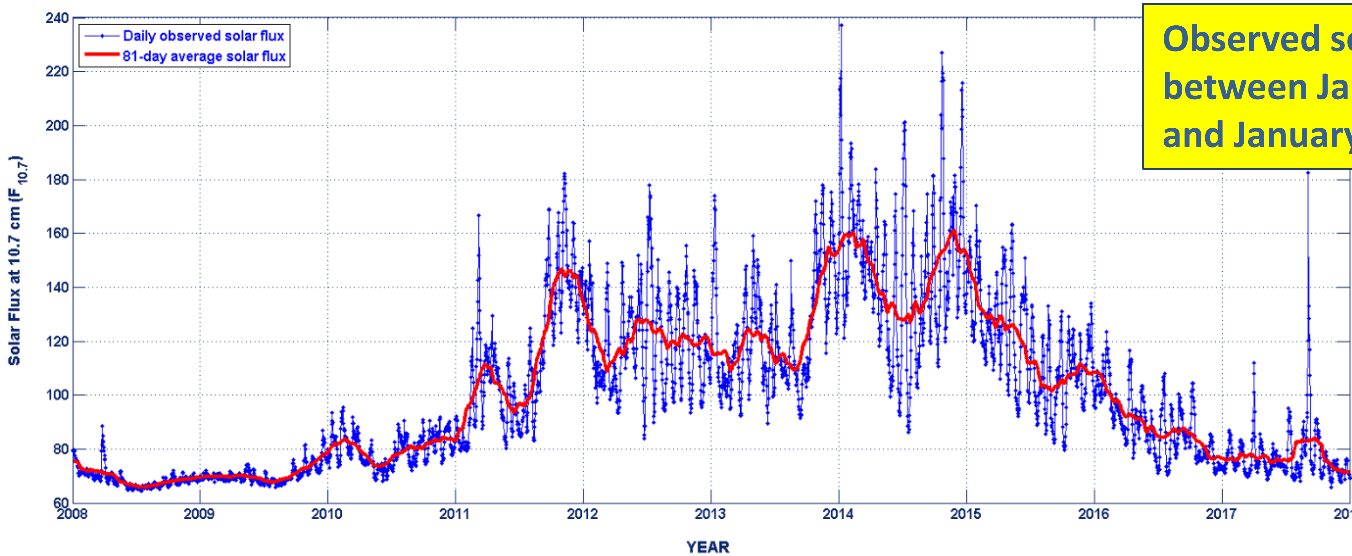
Average re-entries per year

- 32 rocket bodies
- 7 spacecraft
- 39 intact objects

~1 intact object every 1-2 weeks

Mass > 500 kg





Observed solar flux $F_{10.7}$ between January 2008 and January 2018

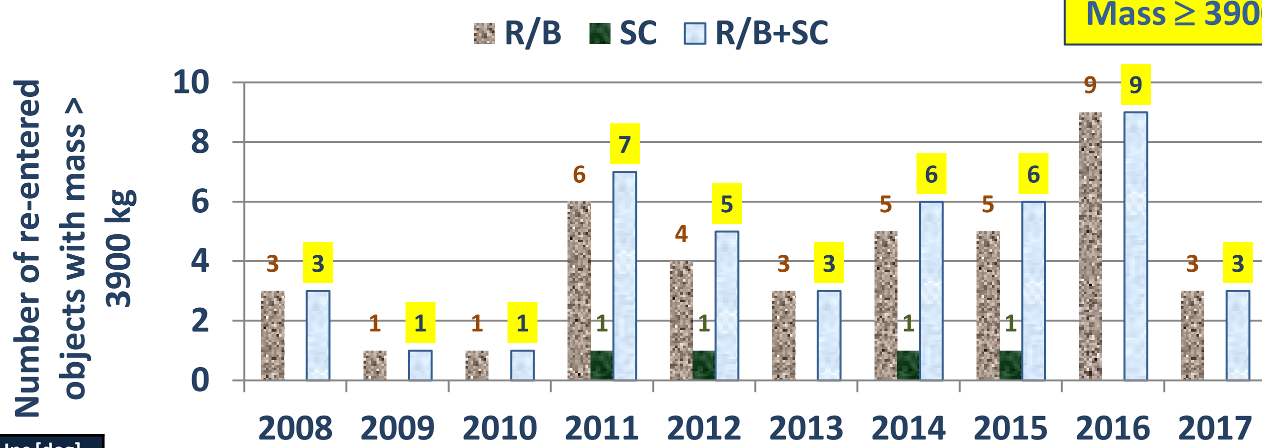
Re-entry frequency [2008-2017]

Large catalogued intact objects with mass ≥ 3900 kg re-entered into the Earth's atmosphere between 2008 and 2017

- 40 rocket bodies (~11% of large re-entered rocket bodies)
- 4 spacecraft (~5% of large re-entered spacecraft – *For Phobos-Grunt the propellant mass is included*)

Average re-entries per year

- 4 rocket bodies
- < 1 spacecraft
- 4-5 intact objects



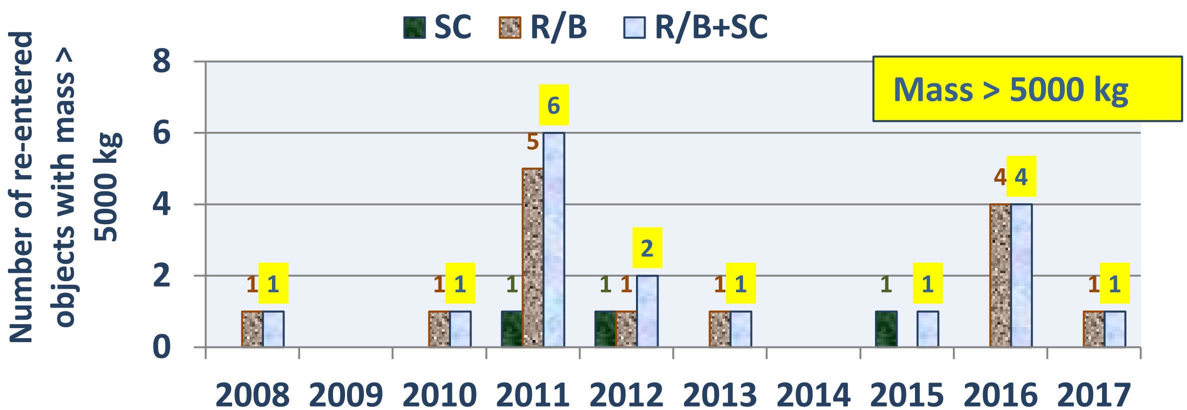
Space object	INTLDES	Re-entry epoch	Mass [kg]	Inc [deg]
CZ-2F R/B	2008-047B	17/10/2008	5502	42.39
DRAGON/FALCON 9	2010-026A	27/06/2010	6100	34.48
SL-23 R/B	2011-001C	19/03/2011	9300	51.39
SL-23 R/B	2011-037D	08/08/2011	9300	51.38
UARS	1991-063B	24/09/2011	5668	60.35
CZ-2F R/B*	2011-053B	10/10/2011	5500	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	13525	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

* *Used to launch Tiangong-1*

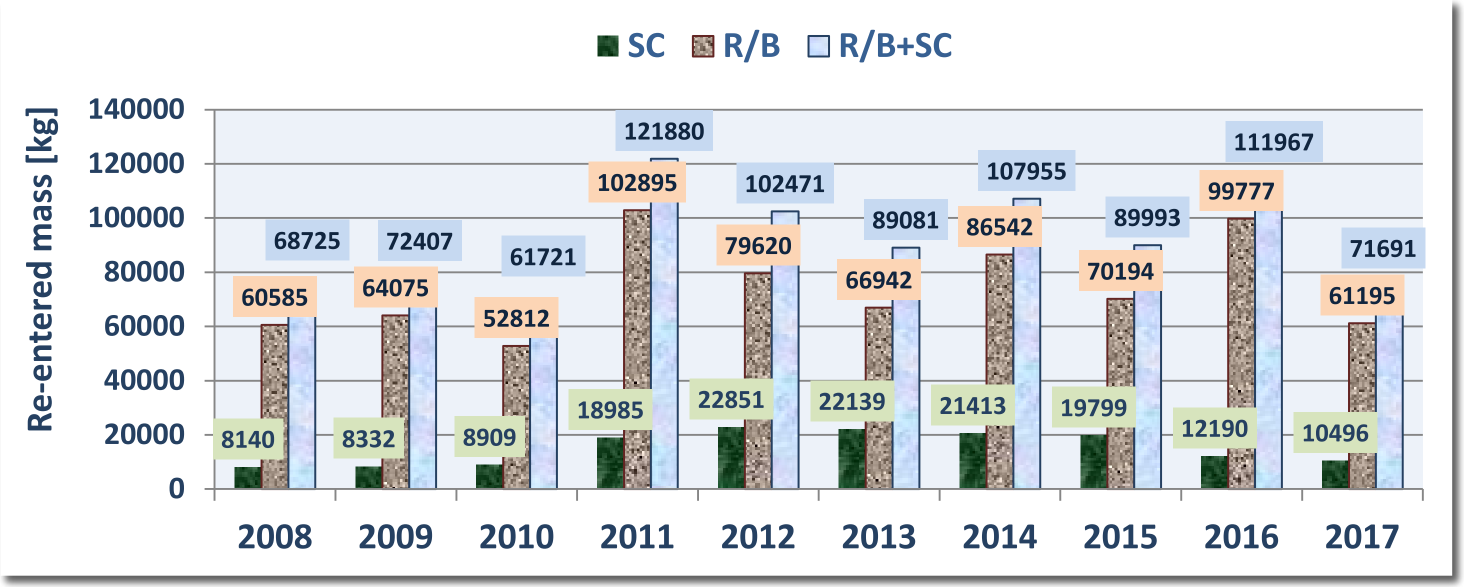
* *Used to launch Tiangong-2*

Large catalogued intact objects with mass > 5000 kg

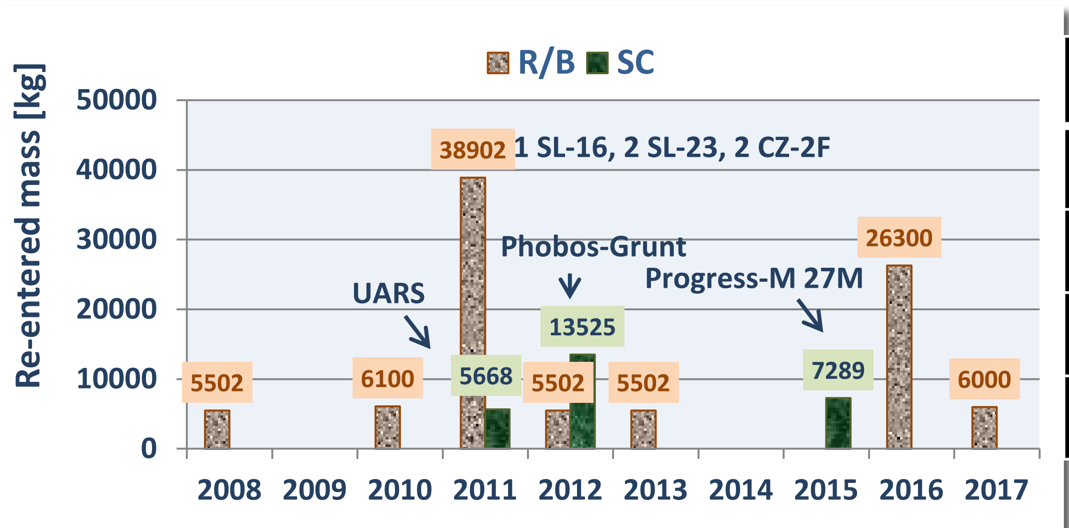
- 14 rocket bodies (~4% of large re-entered rocket bodies)
- 3 spacecraft (~4% of large re-entered spacecraft)
- 1-2 intact objects per year



Re-entered mass [2008-2017]



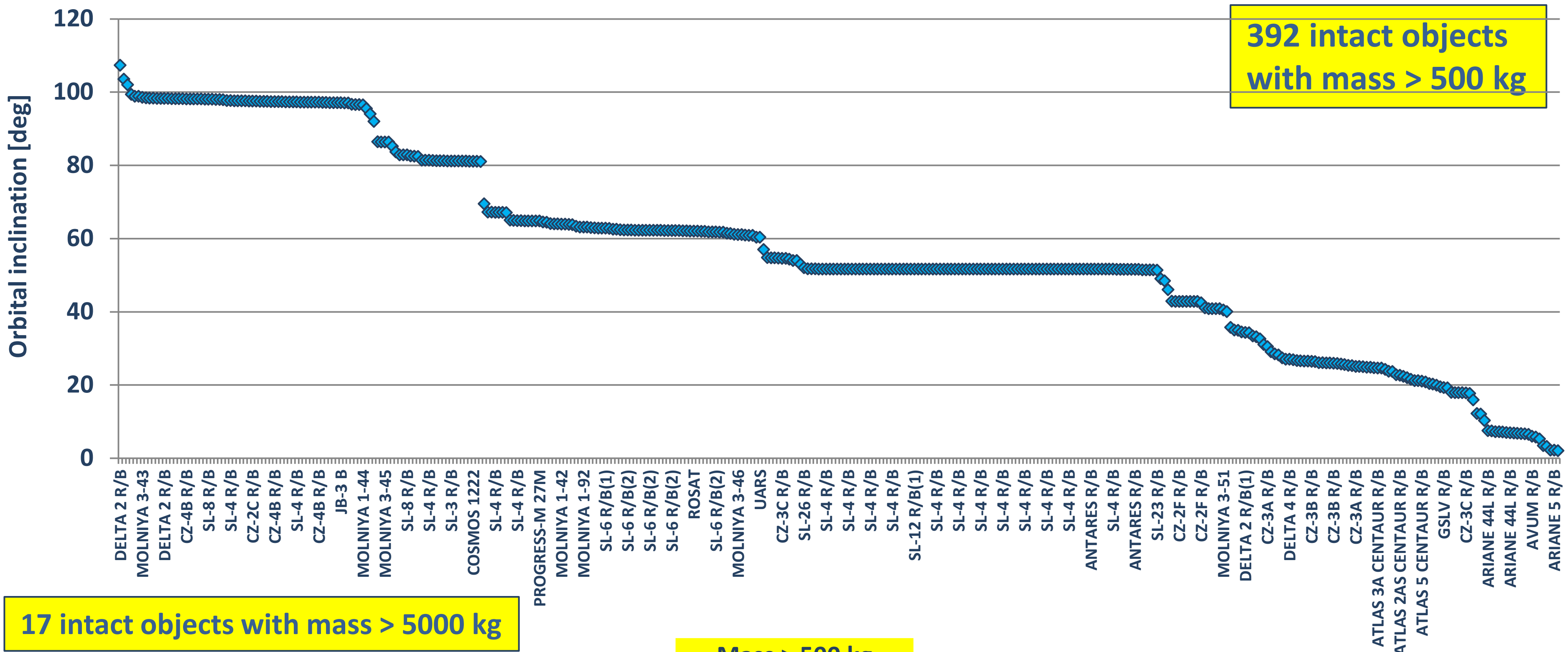
Mass > 500 kg



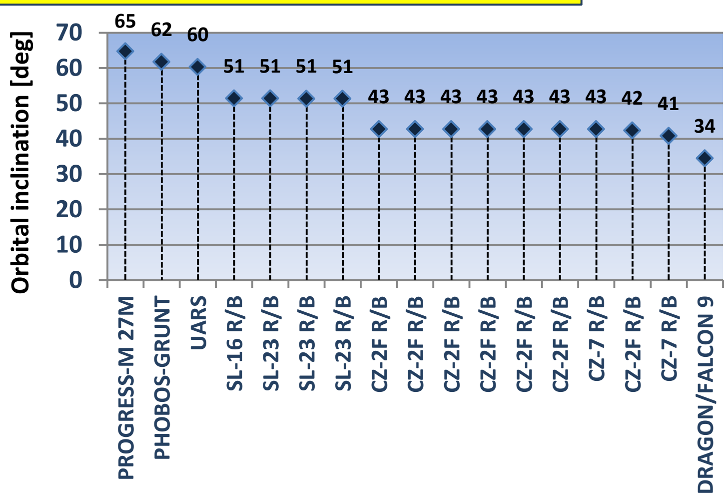
Mass > 5000 kg

	LARGE M > 50 kg		LARGE M > 500 kg		LARGE M > 5000 kg	
	No.	Mass [kg]	No.	Mass [kg]	No.	Mass [kg]
Rocket bodies	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

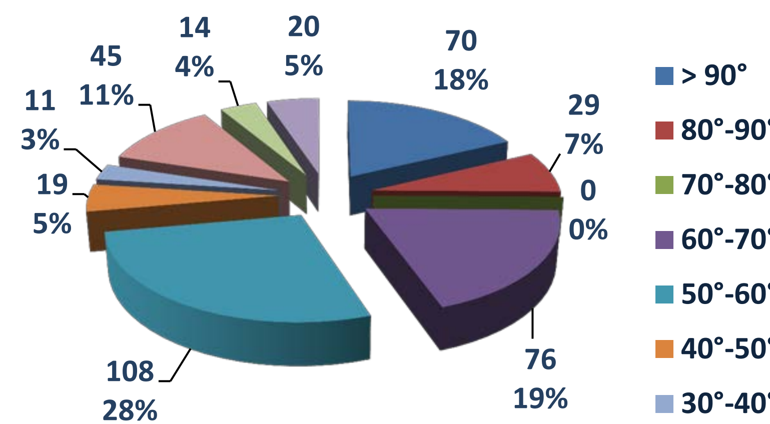
Orbital inclination of intact objects re-entered between 2008 and 2017



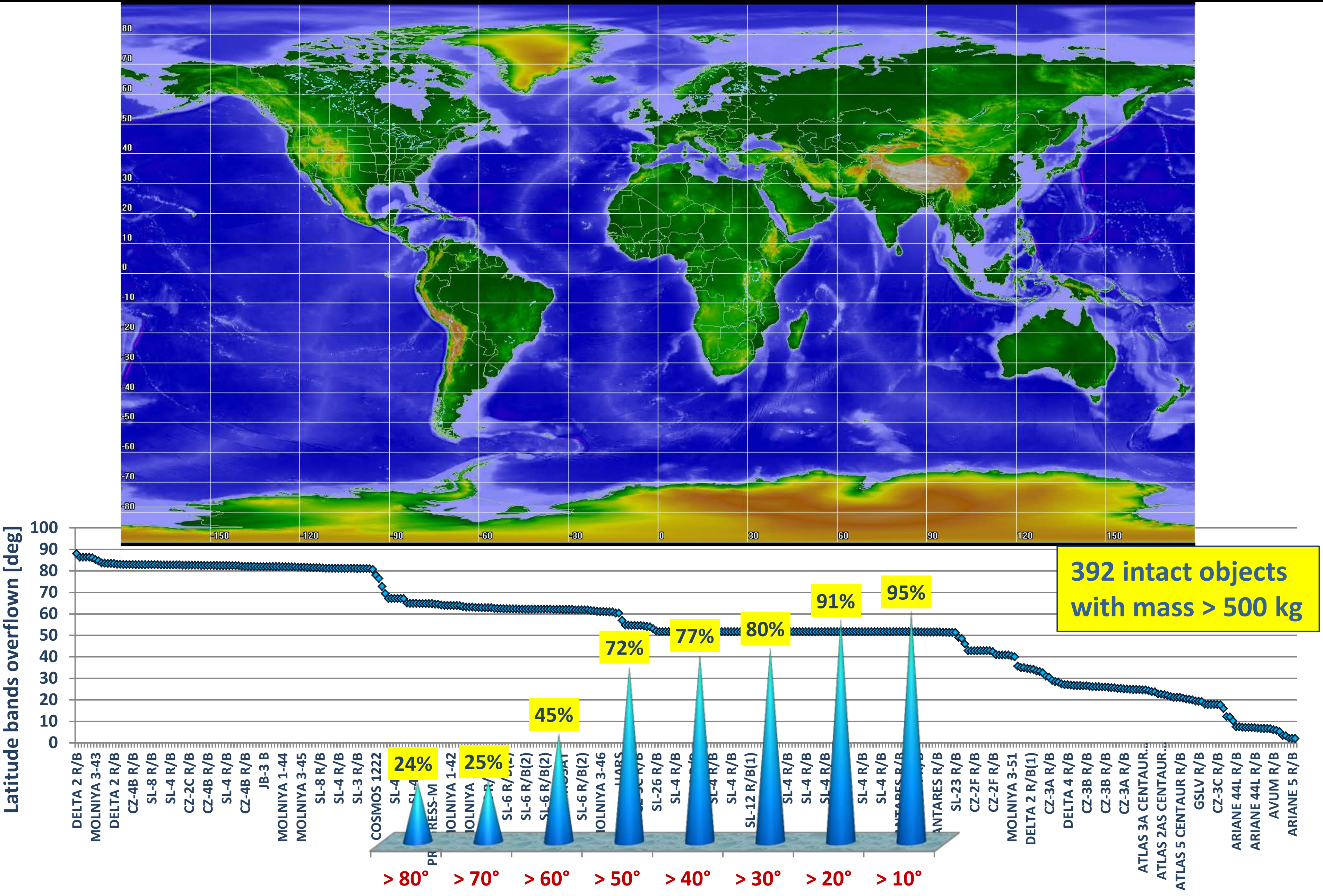
17 intact objects with mass > 5000 kg



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 by re-entered objects [2008-2017]

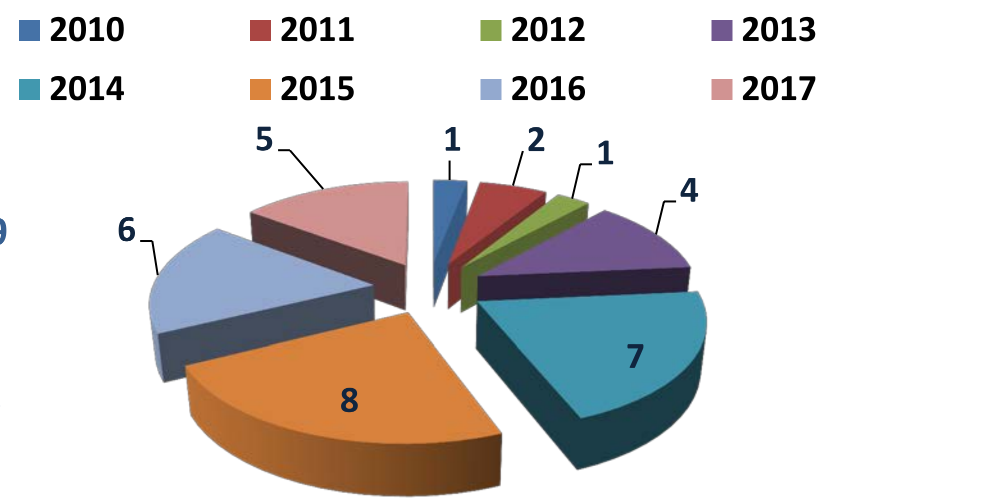


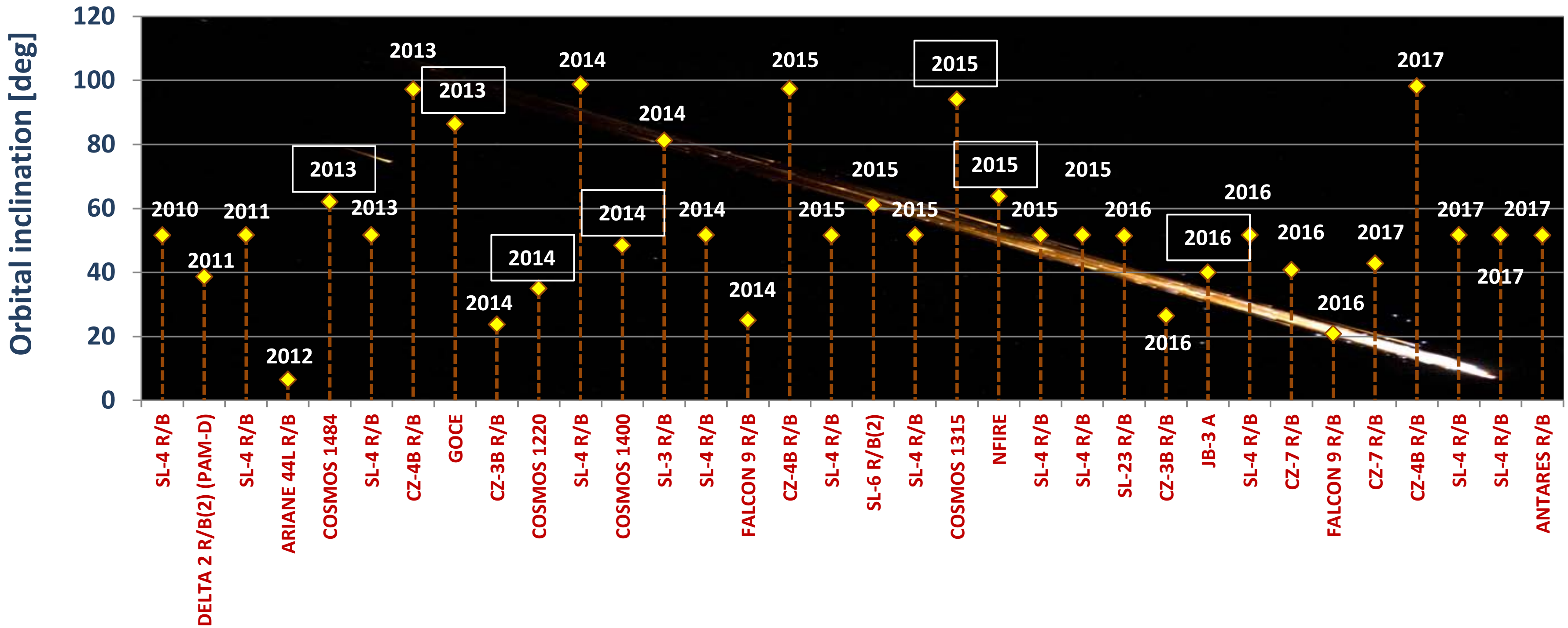
Sightings [2010-2017]

Source:
http://www.aerospace.org

34 sightings (27 rocket bodies and 7 spacecraft) out of 373 re-entries of large intact objects (299 rocket bodies and 74 spacecraft) between 2010 and 2017: i.e. in ~9% of the re-entry events

Moreover, also the re-entry of the Cygnus mass simulator (3800 kg) was sighted in 2013





Recovered re-entry debris (*http://www.aerospace.org/cords/research/reentry-data*)

1. A steel propellant tank and 2 titanium pressure spheres – identified as debris from **2nd stage of Delta II**
2. Several metal objects - probably debris from **3rd stage of GSLV**
3. A titanium rocket-motor casing - identified as debris from **3rd stage of Delta II**
4. A metallic sphere - probably a helium pressure tank from **2nd stage of Zenit 3F**
5. A metallic sphere - probably a helium pressure tank from **3rd stage of Ariane 4**
6. Two metallic spheres - probably helium pressure tanks from **3rd stage of CZ-4B**
7. A propellant tank - probably from **2nd stage of a Delta**
8. Small cylindrical tanks and a metal ring - probably from the **2nd stage of Falcon 9**
9. Two small spherical tanks - probably from the **2nd stage of Zenit 3F**
10. A composite overwrapped pressure vessel - identified as a pressure vessel from the **2nd stage of Falcon 9**
11. A composite overwrapped pressure vessel - believed to belong to the **Vega upper stage AVUM**
12. “Several” fuel tanks from the **2nd stage of Zenit 3F**

1.	2009-052C	2010	Mongolia Asia
2.	2007-037B	2011	Malawi Africa
3.	2003-058C	2011	Artigas Uruguay
4.	2011-001C	2011	Baggs Wyoming USA
5.	1997-016C	2012	Mata Roma Brazil
6.	2012-021C	2013	Buna Texas USA
7.	1975-077B	2013	Ngezi Zimbabwe Africa
8.	2014-052B	2014	Santa Rita do Pardo Brazil
9.	2015-074C	2016	Tuyen Quang Province Vietnam
10.	2016-050B	2016	Giliraja East Java Indonesia
11.	2012-006K	2016	Oddanchatram India
12.	2017-086D	2018	Puno region Peru

13. Three spherical tanks were found in the Spanish towns of Calasparra, Villavieja and Elda in November 2015 (identified as objects from a Centaur upper stage used to launch the spacecraft USA 200 - 2008-010A - on March 13, 2008) – no TLEs and decay time available

What to expect in 2018?

What has already happened?

- Uncontrolled re-entry, on 27 January 2018, of the Zenit-2SB second stage 2017-086D, with an empty mass of 8307 kg

- Uncontrolled re-entry, on 8 February 2018, of the C-25 cryogenic upper stage 2017-031B of the GSLV-MK3-D1 launcher, with a dry mass of ~5300 kg

What is going to happen?

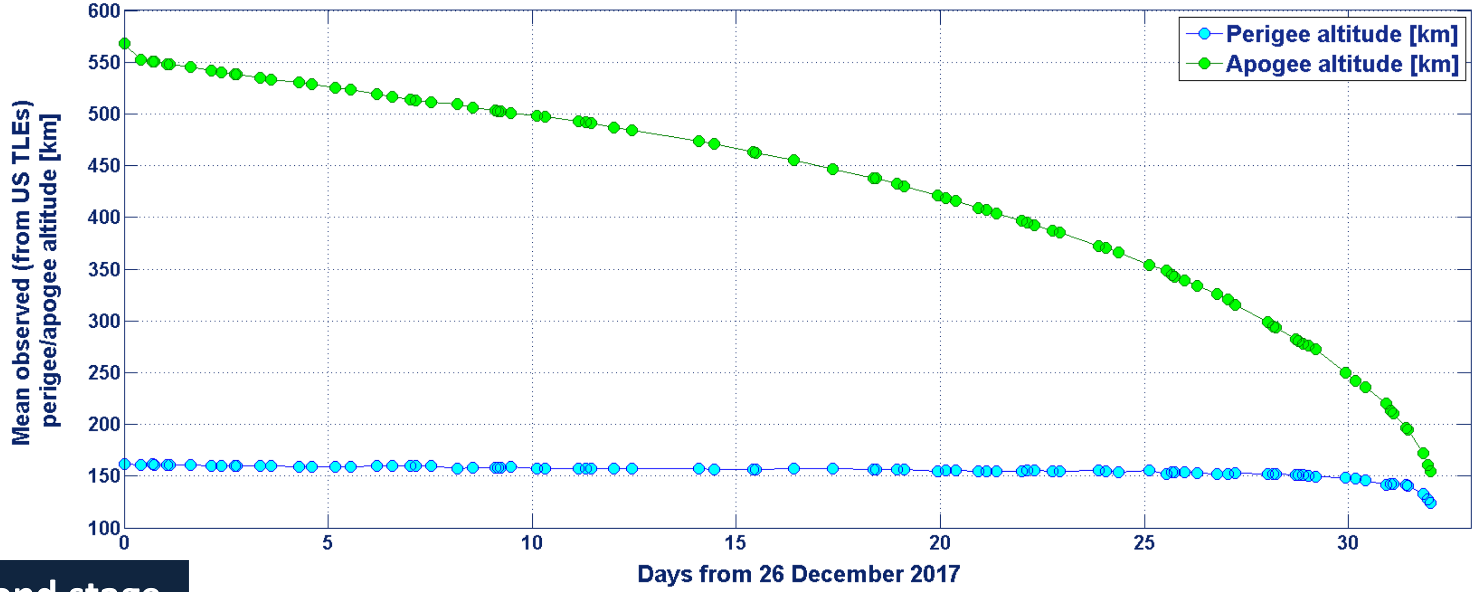
- Uncontrolled re-entry of the Chinese space station Tiangong-1, with a launch mass of 8500 kg

The re-entry of the Zenit-2SB second stage

- **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**
- **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°**

COSPAR ID
2017-086D
Cat. Number
43090

Observed orbital decay



Zenit-2SB second stage	
Length	10.4 m
Diameter	3.9 m
Inert mass	8307 kg

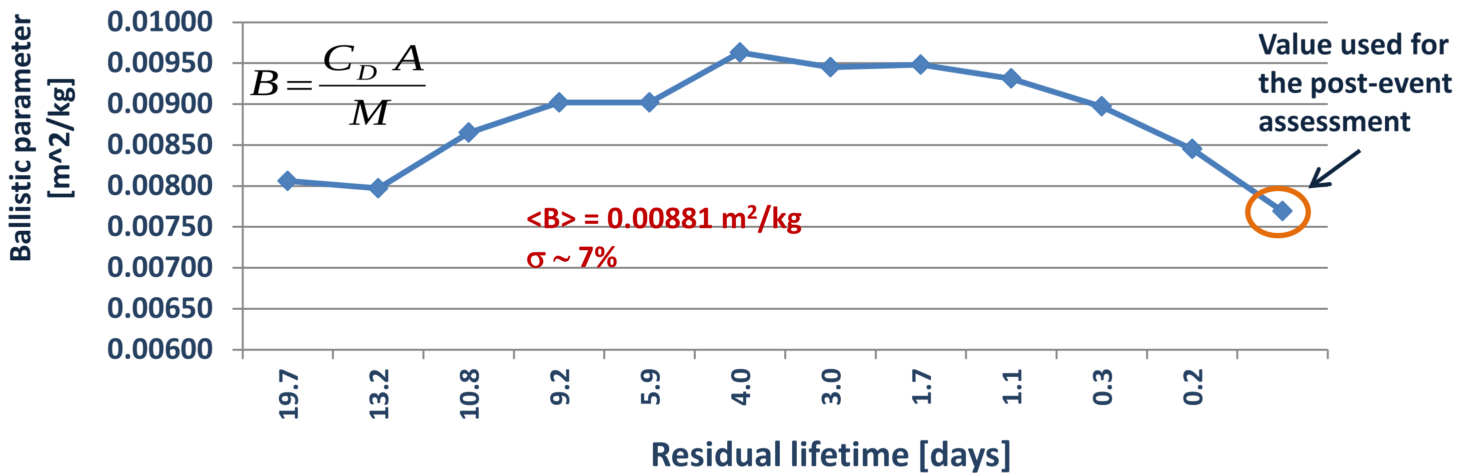
Physical characteristics of the Zenit-2SB second stage

The re-entry of the Zenit-2SB second stage

Orbital predictor
SATRAP
Atmospheric density model
NRLMSISE-00

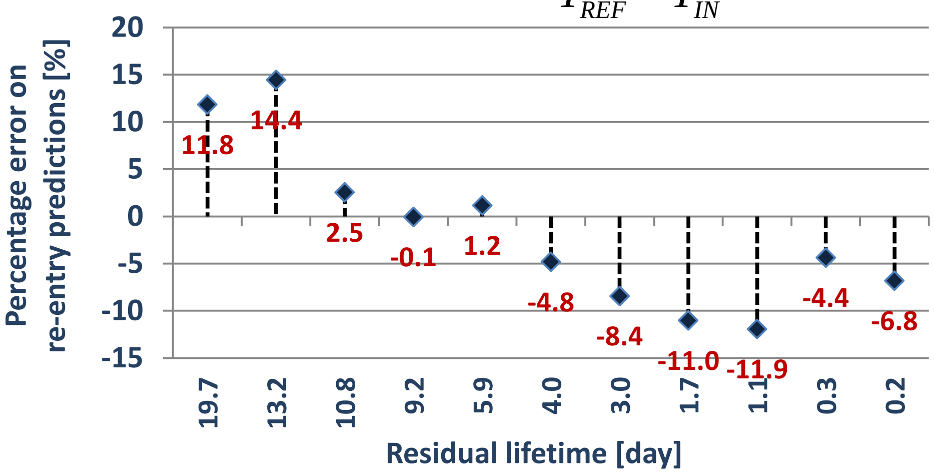
- 11 re-entry predictions
- A post-event assessment

Evolution of the ballistic parameter



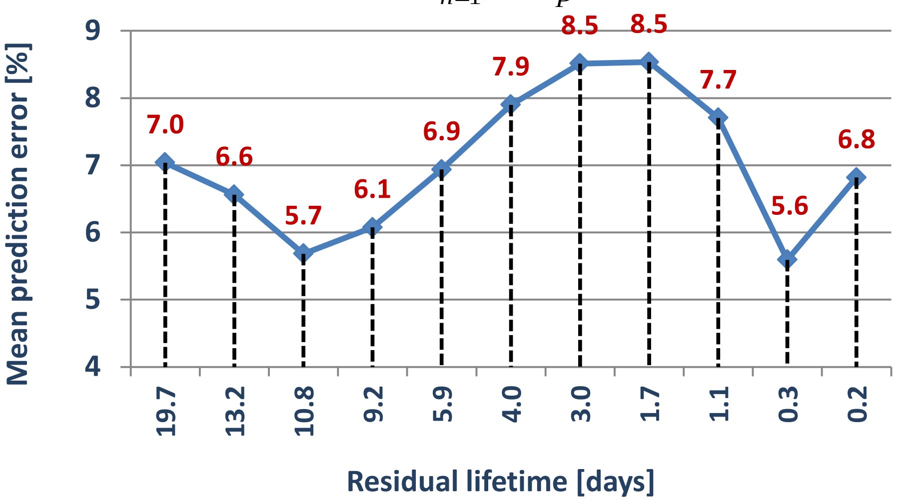
Percentage error affecting the estimate of the residual lifetime

$$PE_{RL} = 100 \times \frac{T_{PRED} - T_{REF}}{T_{REF} - T_{IN}}$$



Mean prediction error

$$MPE = \sum_{n=1}^{N_P} \frac{|PE_{RL}|}{N_P}$$



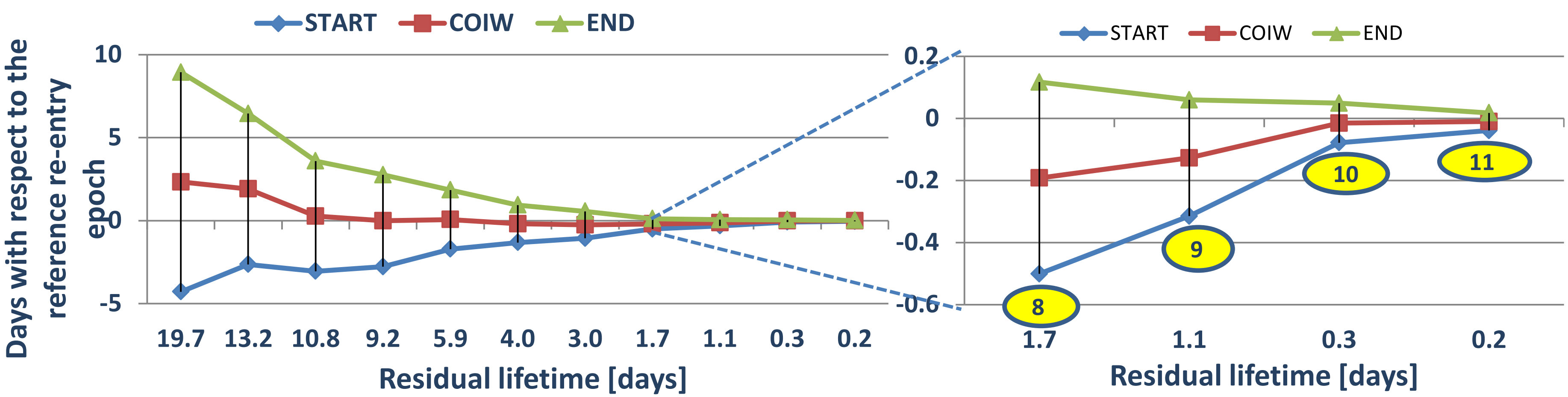
The re-entry of the Zenit-2SB second stage

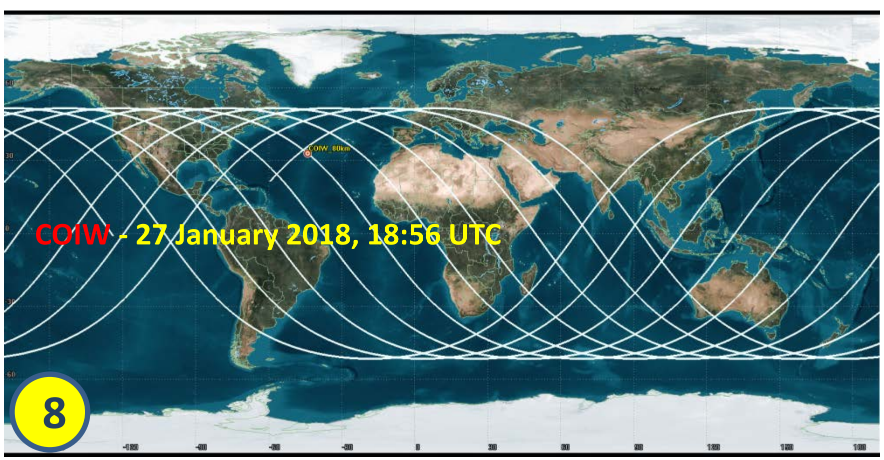
Re-entry uncertainty windows

Residual lifetime ± 30% - re-entry predictions 1-7

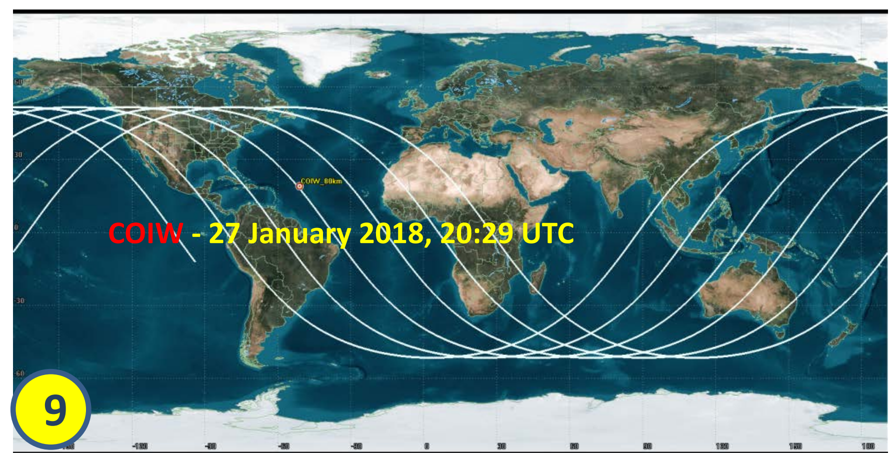
Residual lifetime ± 20% - re-entry predictions 8-11 & post-event assessment

Reference re-entry epoch: 27 January 2018, 23:32 UTC (JSpOC post-event assessment)



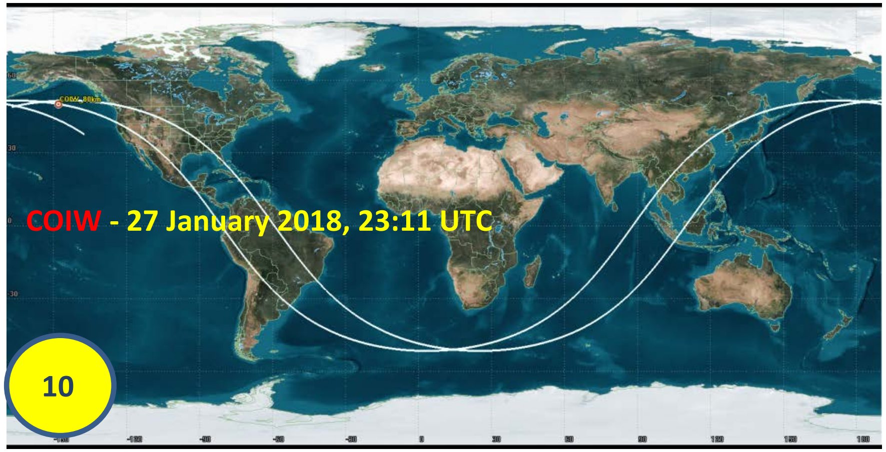


TLE: 26 January 2018, 05:49 UTC, Residual lifetime = $41^h\,42^m$

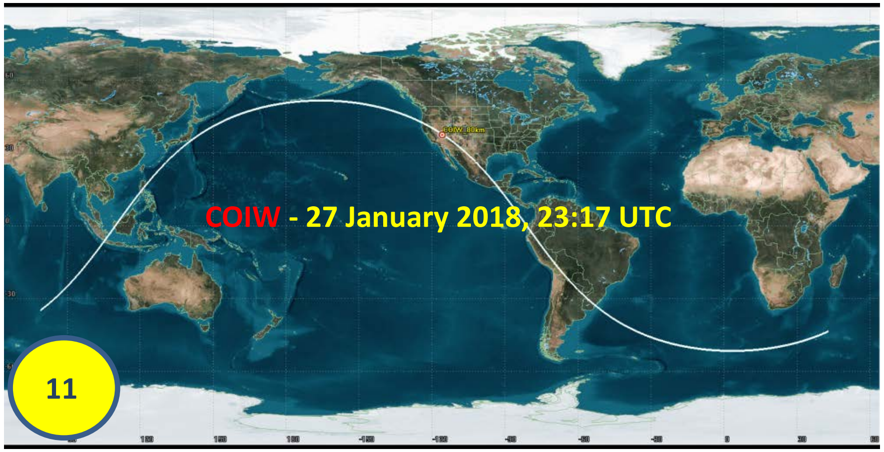


TLE: 26 January 2018, 21:58 UTC, Residual lifetime = $25^h\,34^m$

The re-entry of the Zenit-2SB second stage



TLE: 27 January 2018, 15:31 UTC, **Residual lifetime = $8^h\ 1^m$**



TLE: 27 January 2018, 19:52 UTC, **Residual lifetime = $3^h\ 40^m$**

Post-event assessment

TLE: 27 January 2018, 19:52 UTC

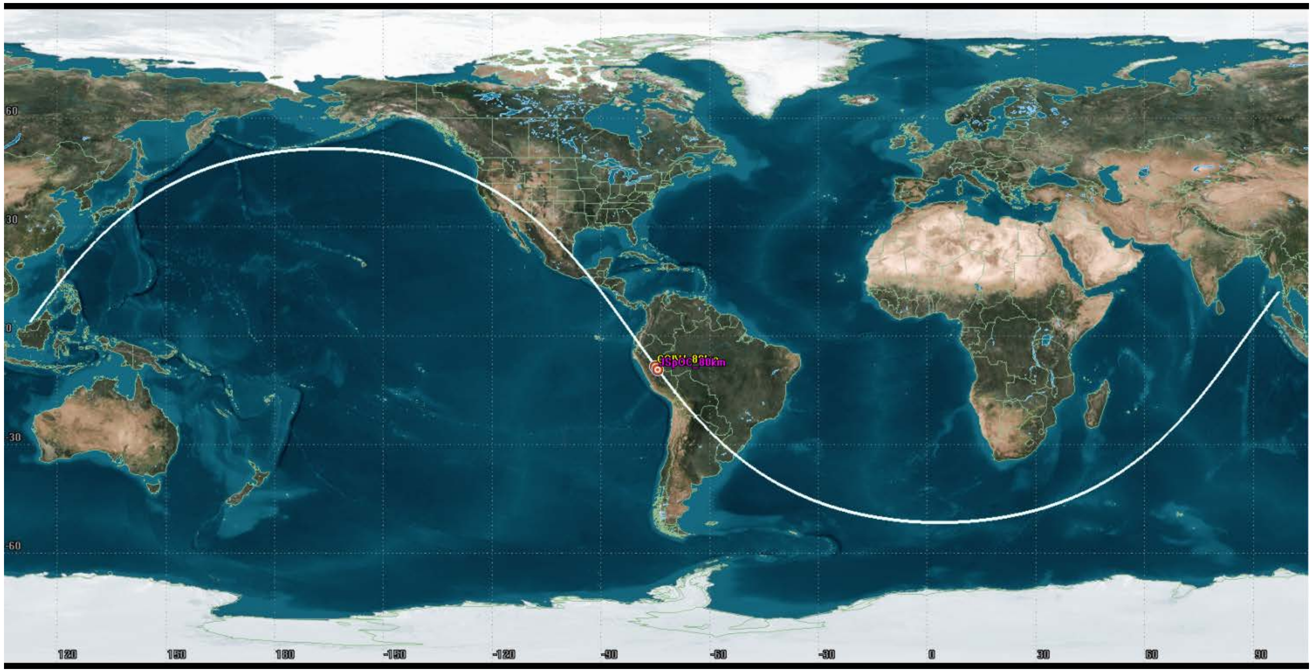
B = 0.0077 m^2/kg

Nominal re-entry epoch
27 January 2018, 23:32 UTC

Re-entry window: ±0.03 days
± 43^m12^s

Latitude: -8.38°

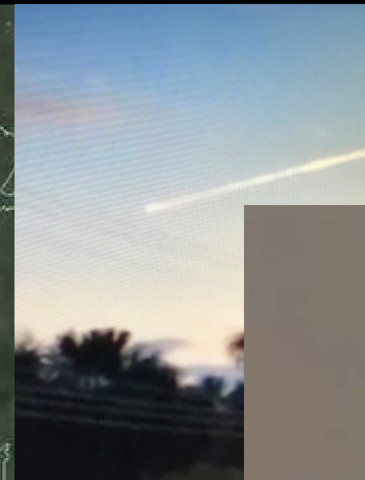
Longitude: 285.01°



The re-entry of the Zenit-2SB second stage

JSpOC decay epoch

27 January 2018, 23:32 UTC ± 1 min
Lat: -9.2°
Lon: 285.7°



Sighting

Recovered debris

© Peruvian Air Force / AFP

Source: Aerospace Corporation

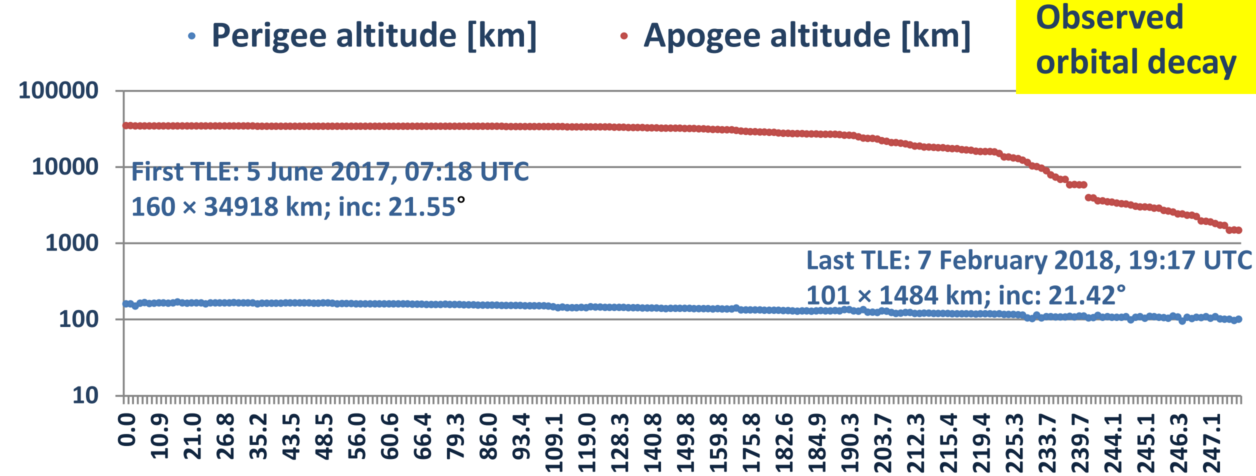
- ***«This object was sighted re-entering on 27 January 2018 at 23:32 UTC over Pucallpa, Peru»***
- ***«Several fuel tanks were recovered by the Peruvian Air Force near the Puno region of Peru after they were notified by local residence»***

Re-entry of the C-25 cryogenic upper stage

- 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

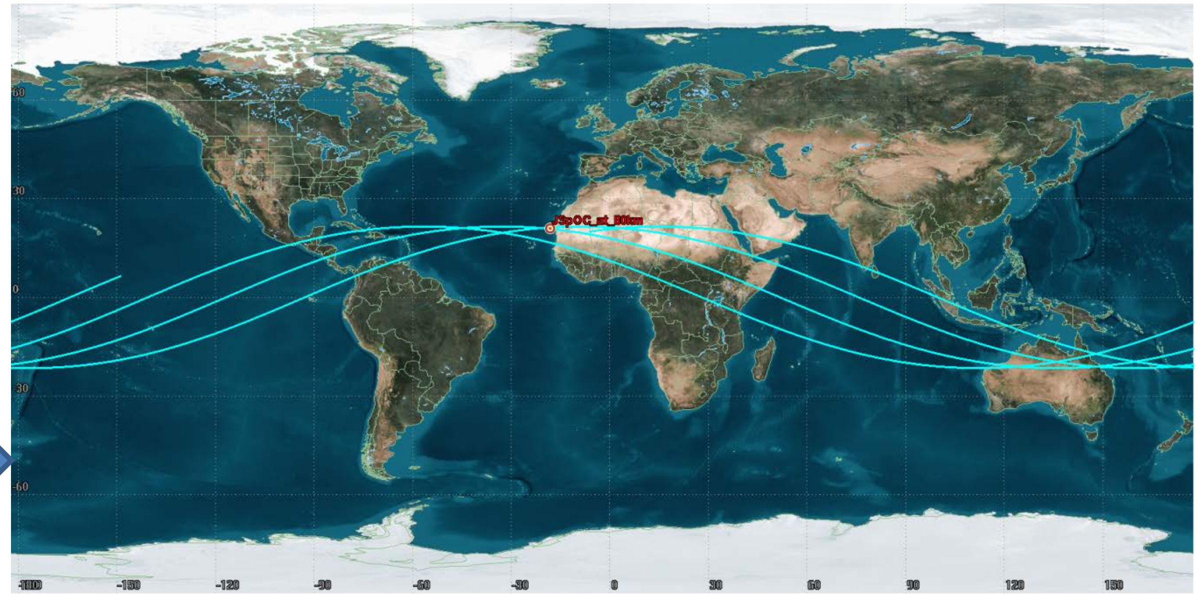
COSPAR ID
2017-031B
Cat. Number
42748

C-25 Cryogenic upper stage	
Length	13.55m
Diameter	4 m
Inert mass	~5300 kg



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

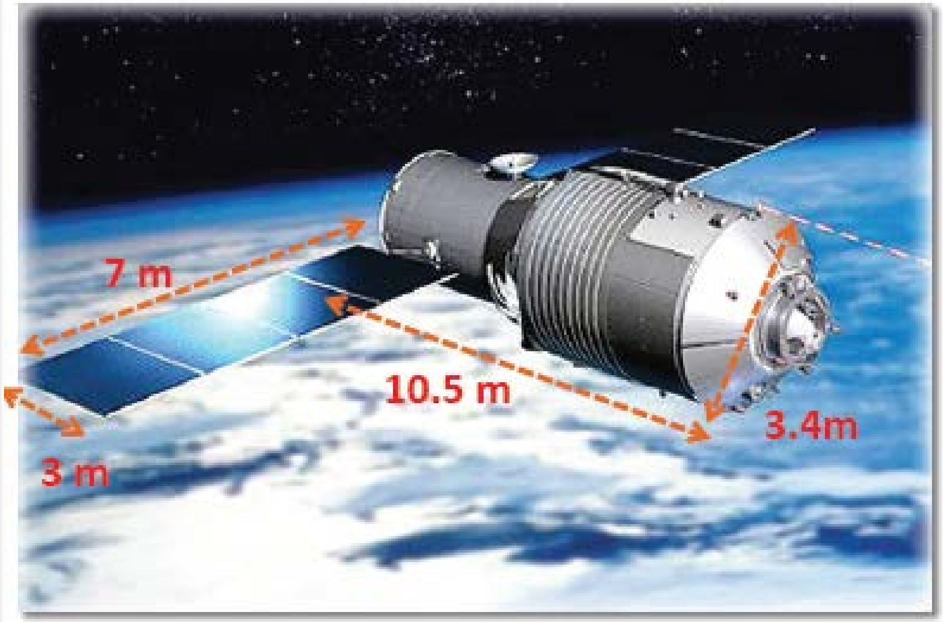
Sub-satellite ground tracks corresponding to the last JSpOC re-entry uncertainty window



The 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

Launch mass	8506 kg
Propellant at launch	1000 kg
Consumables at launch	≈ 350 kg
Current propellant*	≈ 350 kg
MMH	≈ 120 kg
N2O4	≈ 230 kg
Current consumables**	≈ 50 kg
Current mass#	≈ 7550 kg
Dry mass	≈ 7150 kg



* Propellant consumption from manoeuvre sequence: ≈ 650 kg

** Food, food packaging, water and oxygen consumption for 57 astronaut-days: ≈ 303 kg

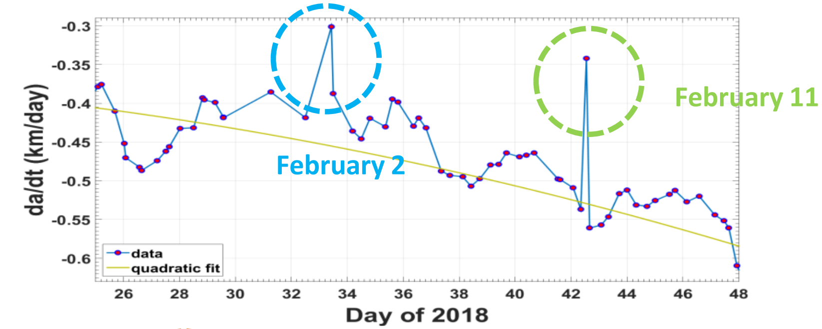
Comparable to the launch mass of Progress-M 27M (7289 kg)

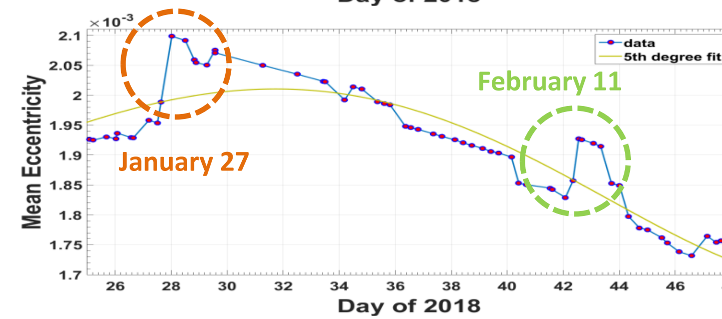
Status of Tiangong-1

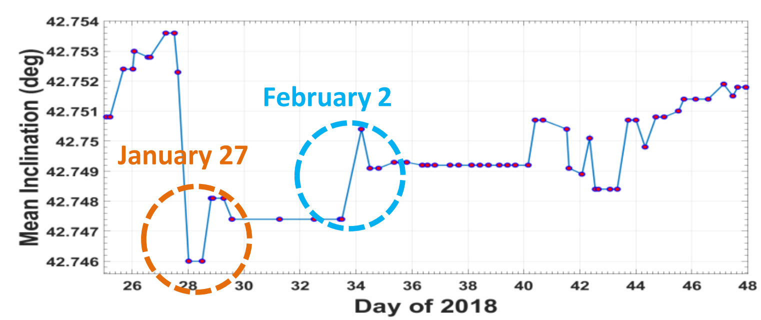
- The ground control of the space station was lost on 16 March 2016
- The autonomous on board attitude control remained, and still is, operational. According to China Manned Space Agency (CMSA): «*Its attitude kept stabilized and no anomaly occurred*» http://en.cmse.gov.cn/col/col1763/index.html
- The attitude is controlled through reaction wheels and reaction control thrusters
- Probably , the solar panels are kept pointed towards the Sun to guarantee the power supply needed to keep the station alive, and the body is aligned along the velocity vector
- The attitude control has an indirect effect on the orbit
  - by varying the effective drag cross-section
  - by producing a net ΔV when the reaction control thrusters are activated
- As an example, possible recent thrusting periods were identified in the TLEs of January 27, February 2 and February 11
- For instance, the net orbital effect of the thrusting occurred on 27 January 2018 corresponded to a ΔV of a few meters per second

Significant manoeuvres occurred from 20 January to 18 February 2018

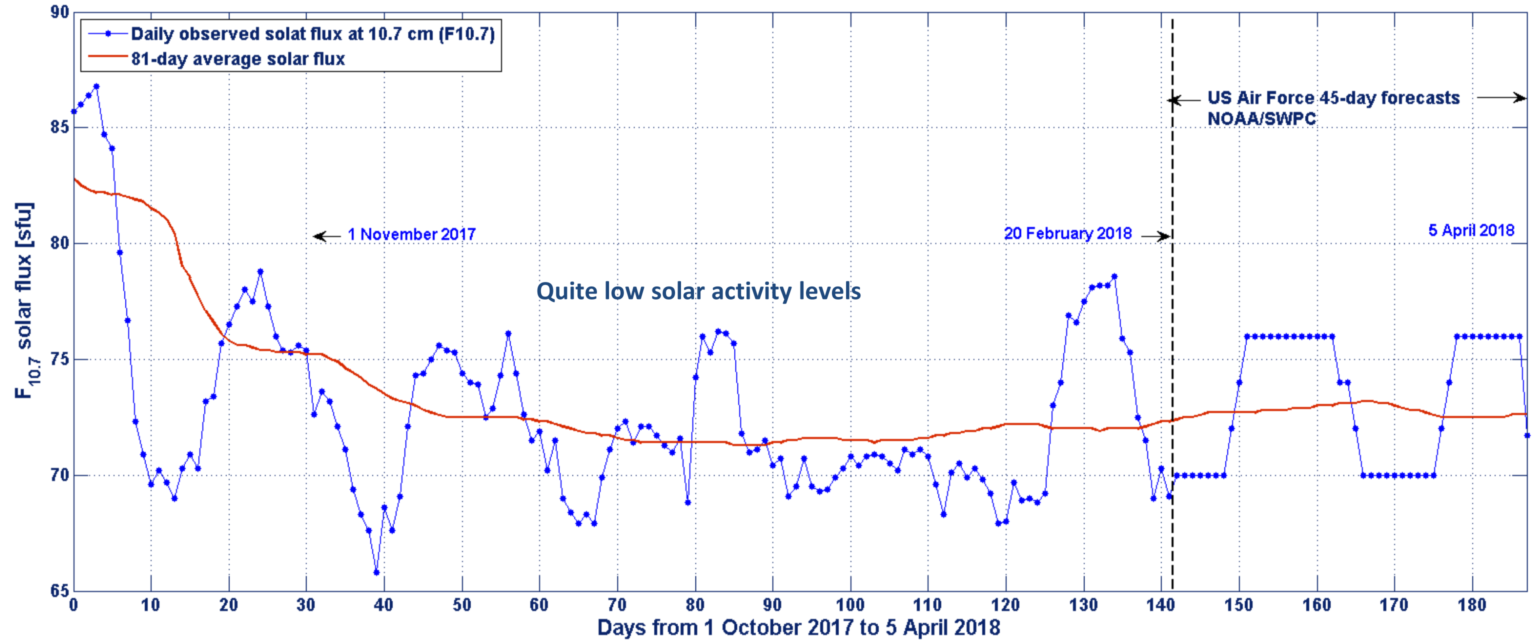
Maneuver day	B^*	$\frac{da}{dt}$	a	e	i	ω
January 27			X	X	X	X
February 2	X	X	X		X	X
February 11	X	X	X	X		X

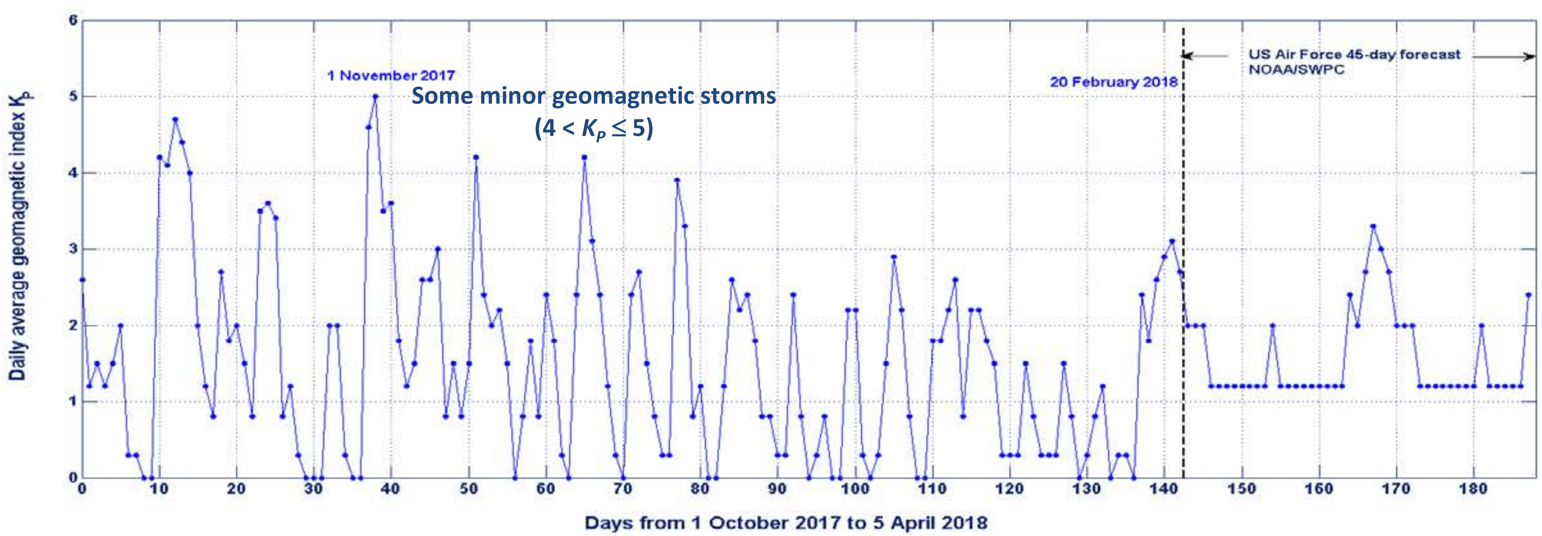




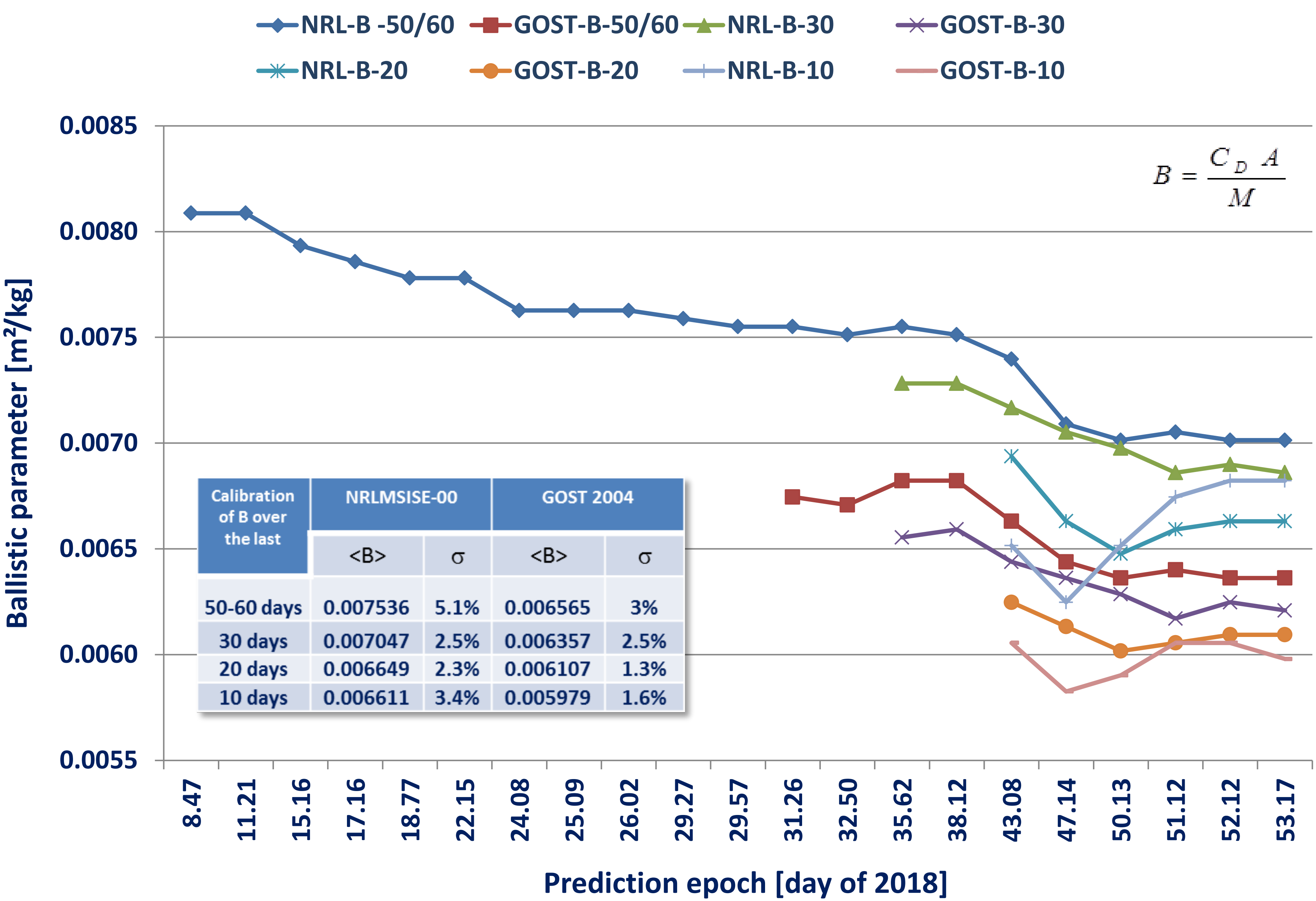


Environmental conditions





Estimate of the Tiangong-1 ballistic parameter



$$B = \frac{C_D A}{M}$$

Calibration of B over the last	NRLMSISE-00		GOST 2004	
	<B>	σ	<B>	σ
50-60 days	0.007536	5.1%	0.006565	3%
30 days	0.007047	2.5%	0.006357	2.5%
20 days	0.006649	2.3%	0.006107	1.3%
10 days	0.006611	3.4%	0.005979	1.6%

Forecasting the Tiangong-1 re-entry epoch