VII. Decay Epoch of the "Tiangong-1" Spacecraft.

January 15, 2018

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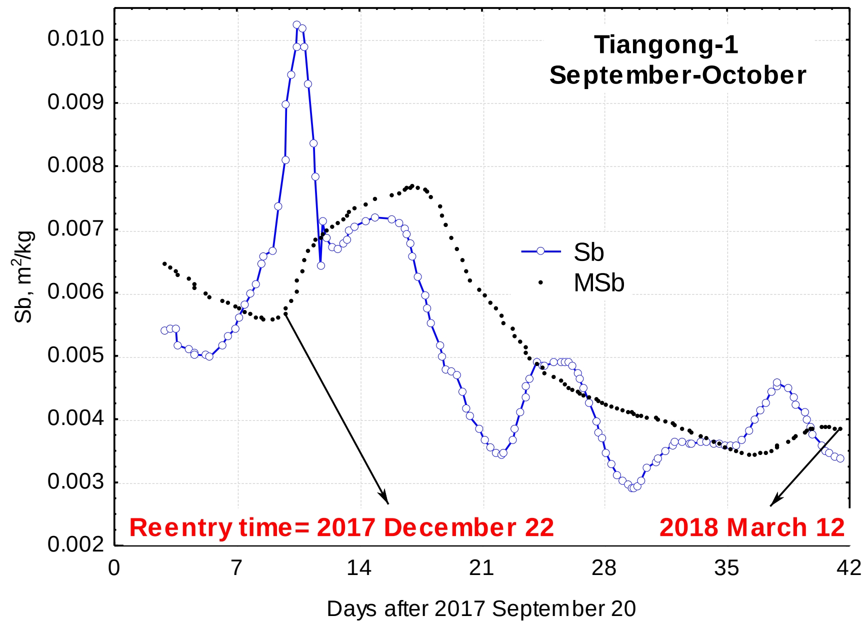
The materials presented below represent a continuation of the text under the same name, posted on the “satmotion.ru” website in November – December 2017 [1–6].

1. History of estimates for September–October, 2017



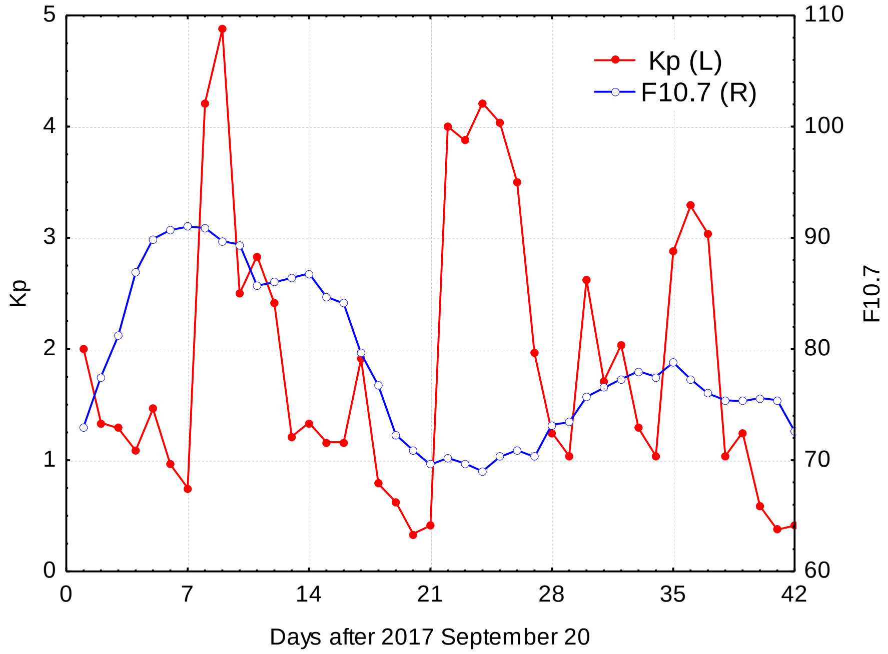


Figure 1. Changes in characteristics during September – October

Very high variations in ballistic coefficient estimates have been were observed during this period. The maximum differs from the minimum as much as 3.5 times! These variations are seen to be a consequence of the growth of solar and geomagnetic activity. According to the initial data for October 1, the expected reentry time of a satellite was December 22, 2017. According to the initial data for November 1, the expected reentry time of a satellite was March 12, 2018.

2. History of estimates for November – December, 2017

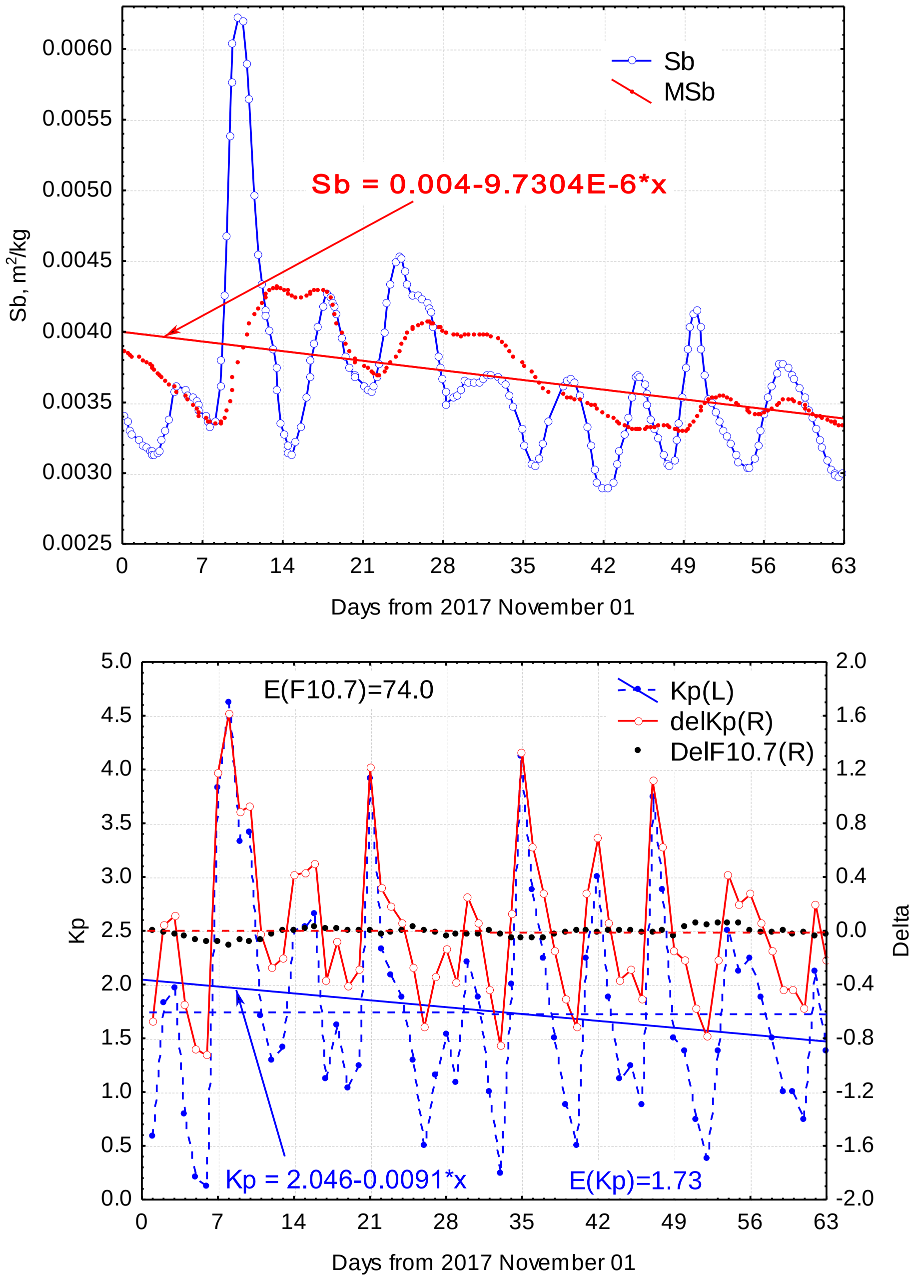


Figure 2. Changes in characteristics during November – December

It is evident from these data that the geomagnetic activity index (Kp) and spacecraft (SC) atmospheric drag estimates (Sb) have continued to decrease during this period. Based on the averaged estimates of ballistic coefficient, the following trend was constructed:

$$E(Sb) = 0.0040 - 0.00000973 * days. \quad (1)$$

During the 63-day interval, the decrease amounted 12% of the initial estimate.

The lower figure shows the data on the geomagnetic and solar (F10.7) activity. Based on the data of the geomagnetic index (Kp) values, the following trend was constructed:

$$E(Kp) = 2.040 - 0.0091 * days. \qquad (2)$$

During the 63-day interval, the decrease amounted 28% of the initial estimate.

Thus, there has been a consistent change in the geomagnetic activity and in the level of SC atmospheric drag. This relationship is also confirmed by the data on variations of mentioned characteristics, calculated by the formula

$$\text{Delta } x = \frac{x - E(x)}{E(x)}. \qquad (3)$$

Variations of the Kp index, as well as of the F10.7 index, are also presented in the figure. One can see that variations of the first index are an order of magnitude higher, than those of the second index. This is a consequence of solar activity minimum in the considered period.

More convenient (for comparison) data on variations of different characteristics in November – December 2017, are presented in figure 3.

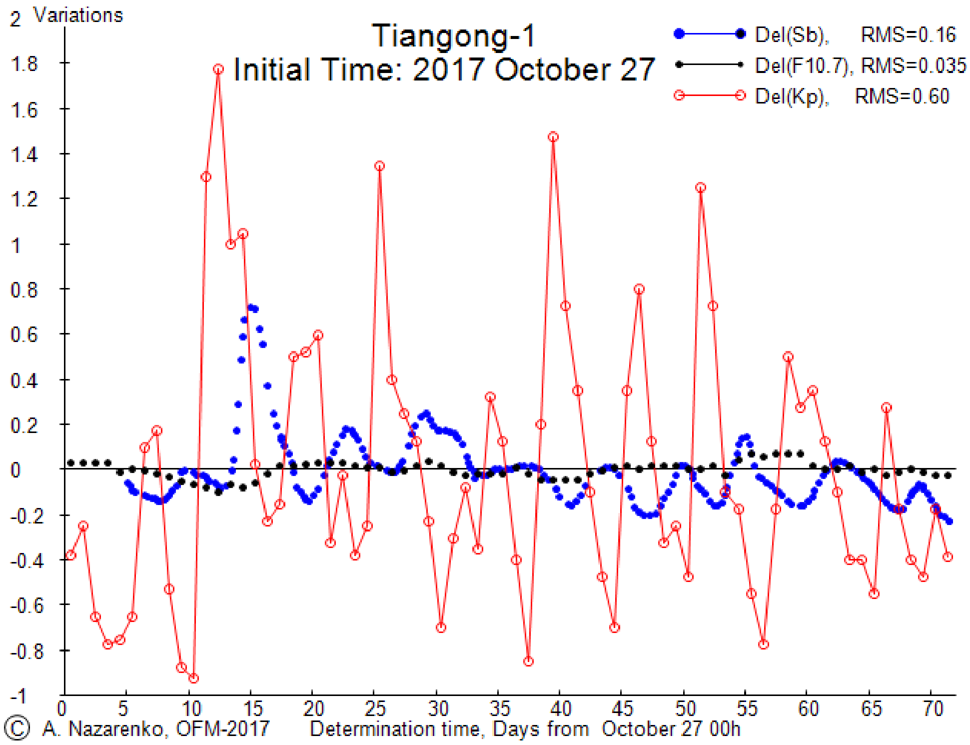


Figure 3. Normalized variation of characteristics in November-December

A careful examination of these data indicates that, during the minimum solar activity period, the SC atmospheric drag level variations were mainly caused by the geomagnetic activity variations (the red curve). To quantify this relationship, the mutual correlation function was constructed:

$$Cor(\tau) = \frac{E[Delta\ Sb(t) \cdot Delta\ Kp(t-\tau)]}{RMS(Sb) \cdot RMS(Kp)}. \qquad (4)$$

This correlation function is shown in figure 4. It was constructed based on the data of figure 3. Here we used the values: *RMS (Sb)* = 0.16 and *RMS (Kp)* = 0.60.

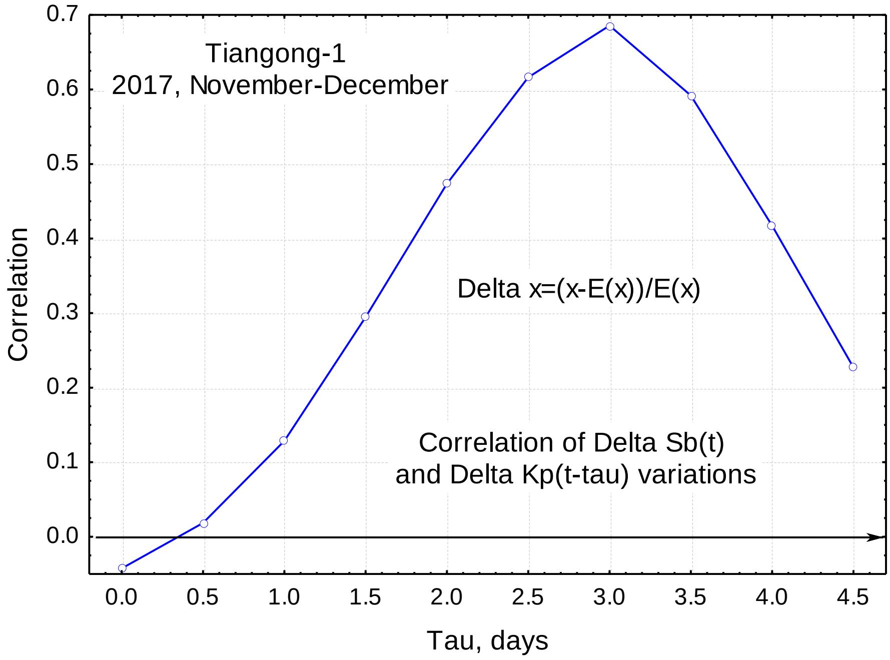


Figure 4. Mutual correlation of geomagnetic activity and SC atmospheric drag variations

The maximum correlation value (for $\tau = 3$ days) is ≈ 0.7. This testifies to a very significant relation between the geomagnetic activity variations and the SC atmospheric drag level. In this case, the time interval, on which the correlation has exceeded the value of 0.5, was 2 – 4 days. Such a lag in the observed atmospheric response to geomagnetic activity variations is a natural consequence of drag averaging over a fit span. The question on amplitude-phase characteristics of a satellite tracking system was considered in details in the article [8].

Thus, the cause for SC atmospheric drag weakening in November and December, which led to a substantial growth of the SC lifetime, was the observed decrease in the geomagnetic activity level during this period.

3. The results for January 15, 2018

For 60 preceding time instants of attribution of measurements, the SC orbital parameters were updated over the array of initial measurements, which were presented by the well-known TLEs [7]. The results of the most recent updating (for ID 7) are presented below. Here the coordinates (in km) and velocities (in km/sec) are presented in the Topocentric Equatorial Coordinate System (as in TLEs).

21928.760042 is the modified Julian date = January 14, $18^h\ 14^m\ 27.62^s$
5678.786760 - x
-3492.068733 - y
-0.499809 - z
2.9646605674 - Vx

4.8376955535 - Vy
5.2493992362 - Vz
0.00280 – Sb (ballistic coefficient, m^2/kg).

Figure 5 presents the ballistic coefficient estimates, the values of the geomagnetic disturbance index (Kp) and the minimized criterion for all preceding time instants of orbital parameters updating after January 03, 2018.

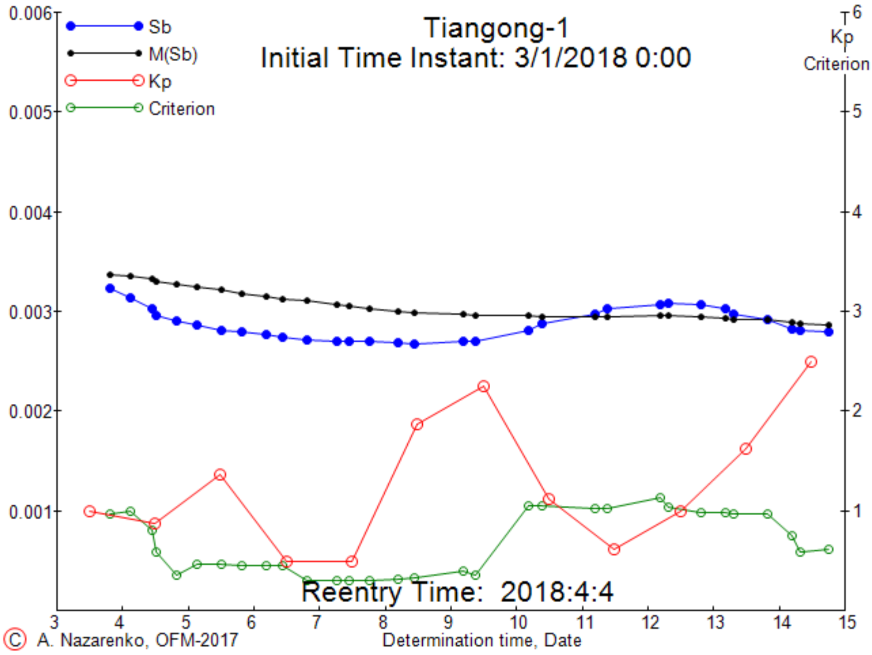


Figure 5. Values of ballistic coefficient, Kp and minimized criterion

The estimates of ballistic coefficient (Sb) have changed within the range from 0.00280 to 0.00337 m^2/kg, i.e. 1.2 times. Such a change is the lowest of all ballistic coefficient determinations considered earlier, which is typical for the solar activity minimum period. The highest drag variations have been observed during January 10–11, which reflects the local maximum of the Kp index on January 09. The black line marks the Sb estimates averaged over some preceding time interval (the sliding average). On the time interval after January 1 these estimates decreased by 15%.

The values of a minimized criterion, presented in the figure, have a meaning of the ratio of residuals to the calculated RMS of errors, averaged over the time interval of measurements. These values depend on the magnitude of current residuals and vary from 0.31 to 1.06. Under perfect tuning of algorithm parameters, their average value should be close to 1. The averaged value of the criterion (0.72) occurred to be essentially lower than 1, which is explained by a low level of disturbances on the considered time interval.

The last smoothed ballistic coefficient value (0.00287 m^2/kg) was used as a constant value in the prediction of SC motion until its entering the dense layers of the atmosphere. The relevant prediction results for the aforementioned initial data (ID 7) are shown in figure 6.

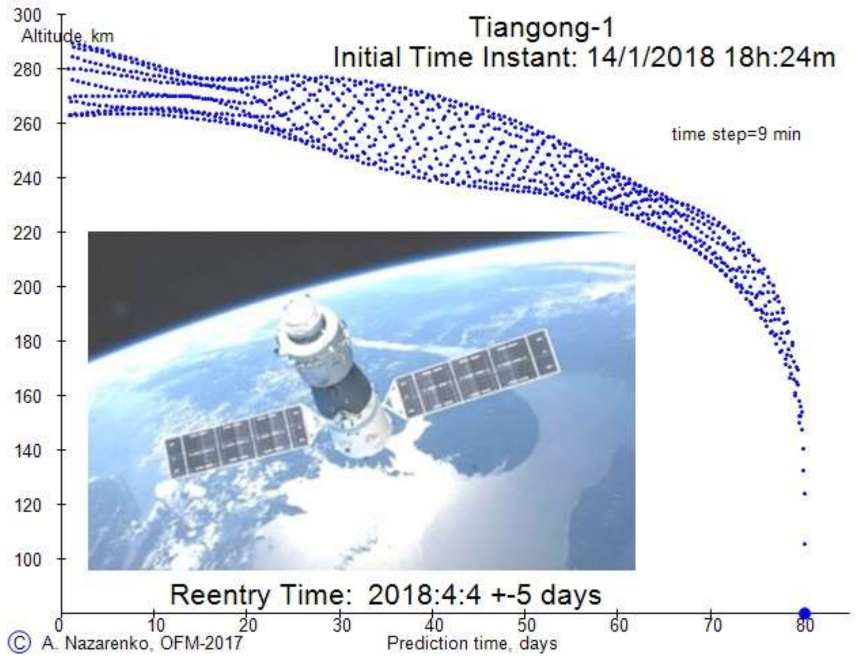


Figure 6. Change of the altitude on the prediction interval

Reentry Information.

Tianging-1 is predicted to reenter on April 04, 2018, ±5 days.

Figure 7 presents the results of all 36 preceding determinations of Tiangong-1 SC reentry time after January 01, based on technique developed by the author. The average value of reentry time is ≈ March 28. Deviations from the average value do not exceed 10% of remaining lifetime. The RMS of errors amounted **3.3%**, which is several times lower than the traditional estimates of errors.

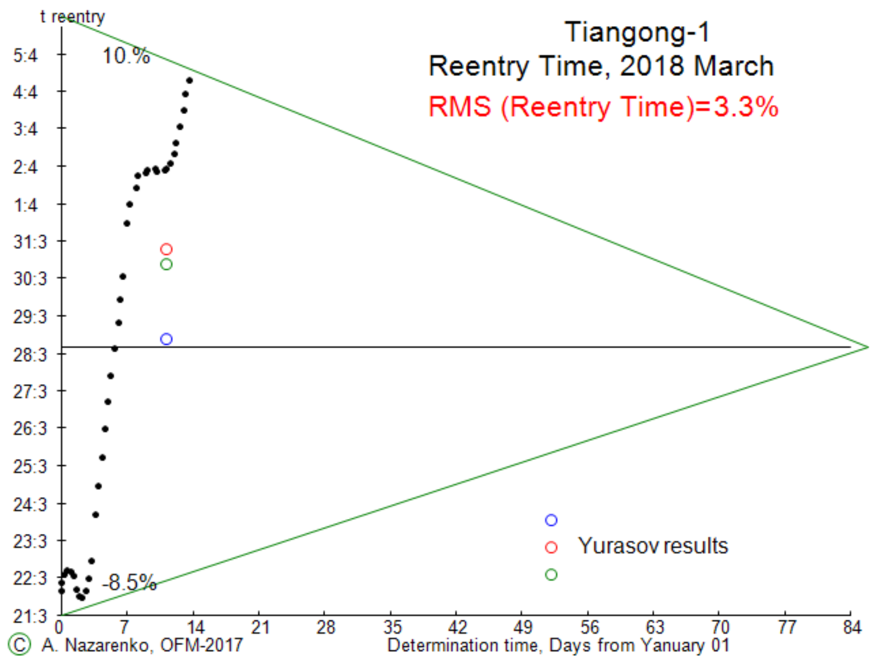


Figure 7. All determinations of Tiangong-1 SC reentry time in 2018

The lag in the reentry time is in line with the 15% decrease of average Sb values presented above.

4. Recent publication of other authors

a) Tiangong-1 is predicted to reenter in mid-late March 2018 ± 2 weeks.

This prediction was performed by the Aerospace Corporation on January 10, 2018.

How Difficult is it to Accurately Predict a Reentry?

Due to the uncertainties involved, it is very difficult to predict the exact timing of a space object's reentry. There are several sources of uncertainty which include: 1) significant variation in the density of the upper layers of the atmosphere, 2) significant uncertainties in the spacecraft orientation over time, uncertainties in some physical properties of a spacecraft, such as the exact mass and material composition, and 3) uncertainties in the exact location and speed of the space station. When aggregated, these factors translate into a reentry timing uncertainty that is roughly 20% of the "time to go" (the time between the date of prediction and the predicted date of reentry).

Will objects from this reentry hit me or my property?

It is highly unlikely that debris from this reentry will strike any person or significantly damage any property. The only known case of space debris striking a person is Ms. Lottie Williams of Tulsa, Oklahoma, who was struck by a small piece of space debris in 1996, but he was not harmed in any significant way. The Aerospace Corporation will perform a person and property risk calculation for the Tiangong-1 reentry a few weeks prior to the event.

b) Data by V.S. Yurasov (private message).

The TLE processing results over the preceding week interval and the forecast of the SC motion until reentry:

Initial data time	Results	Atmospheric model		
		GOST 1984	NRLMSIS	GOST 2004
November 9, 2017	t reentry	March **10** 02^h	March **9** 06^h	March **7** 00^h
	Sb, m^2/kg	0.00384	0.00386	0.00368
December 1, 2017	t reentry	March **12** 03^h	March **9** 18^h	March **11** 22^h
	Sb, m^2/kg	0.00361	0.00389	0.00360
December 9, 2017	t reentry	March **14** 00^h	March **16** 12^h	March **18** 06^h
	Sb, m^2/kg	0.00367	0.00373	0.00347
December 19, 2017	t reentry	March **19** 14^h	March **21** 03^h	March **17** 14^h
	Sb, m^2/kg	0.00349	0.00361	0.00359
December 28, 2017	t reentry	March **19** 20^h	March **20** 18^h	March **20** 15^h
	Sb, m^2/kg	0.00347	0.00369	0.00346
January 12, 2018	t reentry	March **28** 10^h	March **30** 22^h	March **30** 10^h
	Sb, m^2/kg	0.00331	0.00341	0.00325

c) ESOC, Space Debris Office, 12 January 2018

→ TIANGONG-1 REENTRY UPDATES

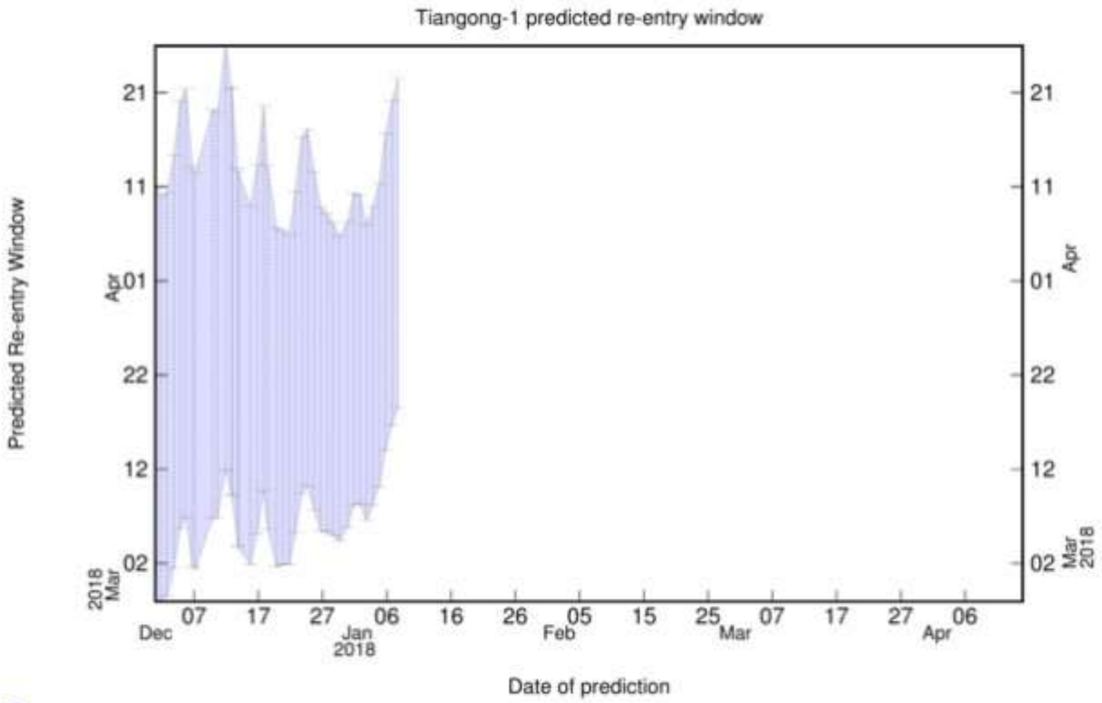
Latest reentry time window forecast provided by the Space Debris Office at ESA's ESOC mission control centre, Darmstadt, Germany.

Note: Read our updated FAQ

Update 12 January 2017

The current estimated window is ~17 March to ~21 April; this is highly variable.

Reentry will take place anywhere between 43°N and 43°S (e.g. Spain, France, Portugal, Greece, etc.). Areas outside of these latitudes can be excluded. At no time will a precise time/location prediction from ESA be possible.



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4. A.I. Nazarenko. Decay Epoch of the "Tiangong-1" Spacecraft. December 10, 2017. Site satmotion.ru

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7. http://www.space-track.org
8. V. A. Bratchikov, A. I. Nazarenko, Investigation of the sensitivity of a system for the tracking of the motion of an artificial Earth satellite, Avtomat. i Telemekh., 1991, Issue 5, 80–86