Reentering Spacecraft Molnia 1-44. Comments

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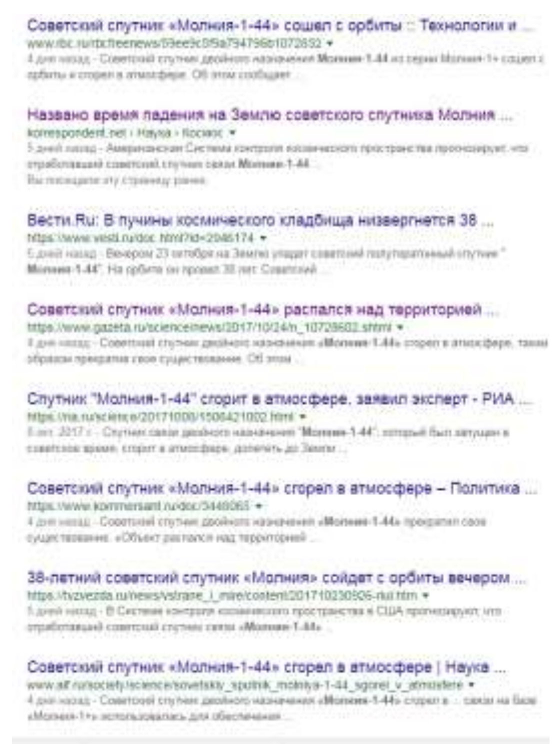
1. Introduction

In October 2017 mass media published a number of messages regarding the upcoming reentry of a large Russian satellite called Molnia 1-44.



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You can see information about those publications on the left.

That kind of events is considered dangerous because they could cause damage to objects on Earth. The publications reported about the time of the expected reentry, as well as the results of the determination of the actual orbit move down.

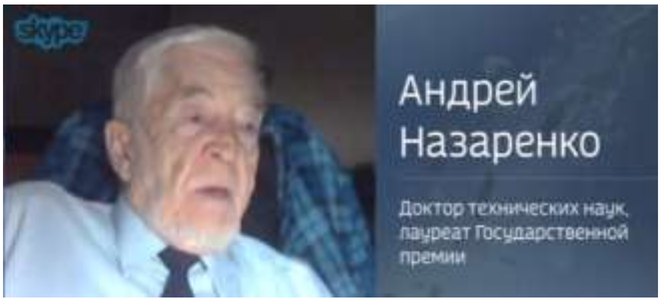
In particular, they reported:

The American Space Control system predicts that the former Soviet Molnia 1-44 Communications Satellite will move from its orbit on Monday, October 23, reported Interfax.

According to the constantly updated prediction, the termination of the ballistic existence of the satellite will happen on the evening of October 23. It will happen over the Pacific Ocean, a few hundred miles to the South of the Aleutian Islands.

Experts consider the satellite will be destroyed after entering into the atmosphere, but some of its unburned fragments can reach the surface of Earth.

On 22 October, representatives of the Russian TV channel 24 invited me to comment the event. They recorded the interview on October 22 and it went public the following day. The excerpt from the TV program is shown below with comments from the author and photos of famous expert W. Ailor (Aerospace Corporation) picturing the crash area of previous space debris.



On 24 October (after the reentering the satellite), the author had found on the Internet some official data on the timing and location of the satellite's decay, published by the United States Military Space Forces Command and the Aerospace Corporation. I had not found any Russian data.

2. The published data on the spacecraft Molnia 1-44 decay

The Table 1 contains the data of the American Space Surveillance System (SSS, site https://www.space-track.org). The important data are time of the orbital parameters determination (MSG_EPOCH) and the time of the reentry (DECAY_EPOCH). Besides, the following is provided: possible error of the estimated decay epoch (window, min), longitude and latitude of the point (deg).

Table 1. American Space Surveillance System data time

NORAD_CAT_ID	MSG_EPOCH	INSERT_EPOCH	DECAY_EPOCH	WINDOW	REV	DIRECTION	LAT	LON
11474	2017-10-23 14:38:00	2017-10-23 14:53:40	2017-10-23 14:38:00	1	58384	ascending	-28.6	23.5
11474	2017-10-23 11:45:00	2017-10-23 11:51:38	2017-10-23 14:02:00	29	58384	ascending	-28.6	23.5
11474	2017-10-23 07:57:00	2017-10-23 08:19:07	2017-10-23 14:11:00	60	58386	ascending	2.9	39.7
11474	2017-10-23 02:08:00	2017-10-23 02:14:11	2017-10-23 13:12:00	120	58384	descending	47.2	197.9
11474	2017-10-22 11:24:00	2017-10-22 11:31:13	2017-10-23 10:05:00	300	58382	ascending	61.6	179.3
11474	2017-10-21 11:57:00	2017-10-21 12:06:05	2017-10-23 08:07:00	540	58380	ascending	-29	113.3
11474	2017-10-20 12:23:00	2017-10-20 12:34:25	2017-10-23 10:25:00	840	58382	descending	13.3	268.2
11474	2017-10-19 23:45:00	2017-10-19 23:59:45	2017-10-23 13:21:00	1140	58384	descending	22.8	217.7

The top row show the latest data. They were received after the satellite decay. Other rows refer to previous results. They are presented in descending order of the time determination.

The last prediction decay epoch is shown in the second row: October 23, 14^h 02^m. It corresponds to a possible range of estimates ± 29 minutes. After the decay mass media reported that "the dual purpose satellite Molnia 1-44 "(The Molnia -1+" series) had broken into pieces over the territory of Zimbabwe." The second rows represent that area.

The decay epoch (14^h 38^m) specified in the first row of the table, differs from the data in the second row, but the coordinates on those rows are the same. The specified decay point (latitude 28.6°, longitude 23.5°) is not consistent with the prediction data from the previous section (to the South of the Aleutian Islands). The area south of the Aleutian Islands corresponds to the results of the prediction stated in the fourth row of the table. The reasons for the difference between the estimates of the decay epoch shown in the different rows of the Table 1 are due to the influence of unpredictable variations in atmospheric density. Experts know that the reentry forecast error is of order 10% remaining lifetime. Window estimates represented in the table correspond with that pattern. Those estimates are ≈ 20% of the remaining lifetime. Those estimates are formed without any influence from specialists (within a "margin"). In conclusion, the data of the United States SSS are from the results gained by their automated information processing system.

Aerospace Corporation's campaign site (http://www.aerospace.org/cords/reentry-predictions/) provides the following information about the reentry of the spacecraft Molnia 1-44.

Reentry Prediction

[Predicted Reentry Time:](#) 23 OCT 2017 14:46 UTC ± 1 hour
[Prediction Epoch:](#) 23 OCT 2017 10:07:42.382 UTC
[Prediction Ground Track:](#)

The map bears a round mark pointing the reentry point on October 23 at 14^h 46^m. Prediction is performed by ID for 07^h 42^m. The prediction interval was 424 min. The assigned window (± 1 hour) is 14% of the remaining lifetime. The result of the American SSS (14^h 00^m) is different from the data of the picture for 44 min. The area on the map for the time corresponds to the flight over South Africa. The results shown here are prepared by a department of the "Center for Orbital and Reentry Debris Studies" (CORDS). Manager is the mentioned before W. Ailor.

CORDS was established in 1997 to focus the corporation's research and technology applications in the areas of space debris, collision avoidance, and reentry breakup and to provide a single point-of-contact for organizations seeking to take advantage of Aerospace's more than 50 years of experience in these and related technical areas.

Outer space presents a number of hazards to spacecraft. Temperature extremes, radiation, solar flares, and micrometeoroids have long been essential considerations in spacecraft and mission design.

Collisions between manmade objects

Increasing use of space has brought a new source of risk — collisions between manmade objects. Given the high relative velocities of objects in space, even small untracked objects can damage critical sensors and spacecraft components.

Recent collisions have raised awareness of the growing hazard from space debris and the risk to space operations.

As users of space have recognized the hazards of space debris on operating satellites, plans have been made to deorbit old inoperative spacecraft and hardware back into Earth's atmosphere, where the heat of reentry will destroy the satellite and its components.

Unfortunately, some portions of the spacecraft — sometimes large components — may survive reentry and pose a hazard to people and property on the ground.

Reentry breakup recorder (REBR)

As part of its ongoing research into orbital debris, CORDS spearheaded development of a tool called the Reentry Breakup Recorder (REBR). This is a small, autonomous device that records temperature, acceleration, rotational rate, and other data during the reentry of space hardware into the Earth's atmosphere and its subsequent breakup due to aerodynamic heating and loads. [Click here](#) to read about the REBR and Aerospace's role in developing this unique instrument.

3. Using method of the optimal filtration of the measurement

The author has been working for many years on the problem of determining and predicting the motion of satellites in the atmosphere ([1] - [12]). The first publication on the reentry time determination refers to 1991. Based on the materials of the accumulated experience, it was the improved method for determining and predicting orbits considering the influence of random perturbations developed, called the Method of Optimal Filtration of Measurements (OFM). It is show that the application of the method provides greater precision than the traditional approach.

Data on the reentry of the spacecraft Molnia 1-44 served as an occasion to preform corresponding calculations using the OFM methodology. The source data (measurements) in the form of the TLE at the previous monthly time interval were downloaded on October 23 from the SSS site (105 sets of orbital elements). The figure 1 represents some of the results. Each point is the result of the processing of the eight preceding measurements in the format of TLE.

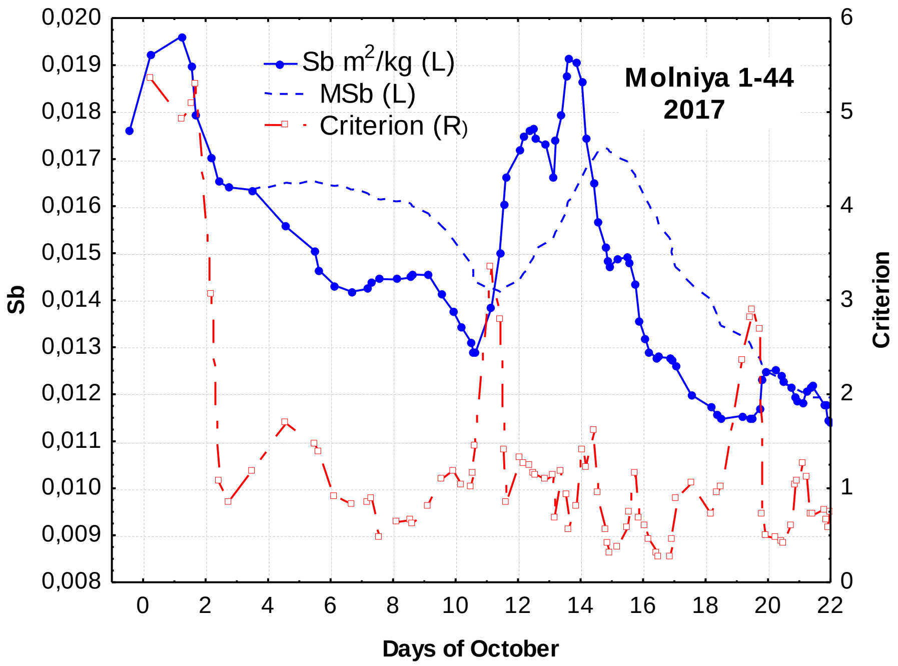


Figure 1. Estimating the Ballistic Factor

The estimates of the ballistic factor (Sb) vary between 0.0115 and 0.0195 m^2/kg, i.e. in 1.7 times. These estimates play an important role because they are used as source data for the calculation of atmospheric braking of the spacecraft. If the Sb values, reflecting the changes in the density of the atmosphere, would be constant, the error of the spacecraft movement prediction would be much smaller. It is the unpredictable variations in atmospheric braking that are the main cause of the error of the given task solution. The most severe variations of braking were observed on October 1 and 2, as well as within the period from October 11 to 15. The blue dotted line is the average Sb values at some previous time interval (moving average). They are used to generate the source data for the prediction. The red dotted line shows the estimates of the minimizing criterion, which depends on the residual injunctions. As we can see the maximum of the criterion had occurred at times when a significant change of the Sb estimates was made. This is a natural consequence of the deterioration of the consistency of the applied motion model and specific measurements.

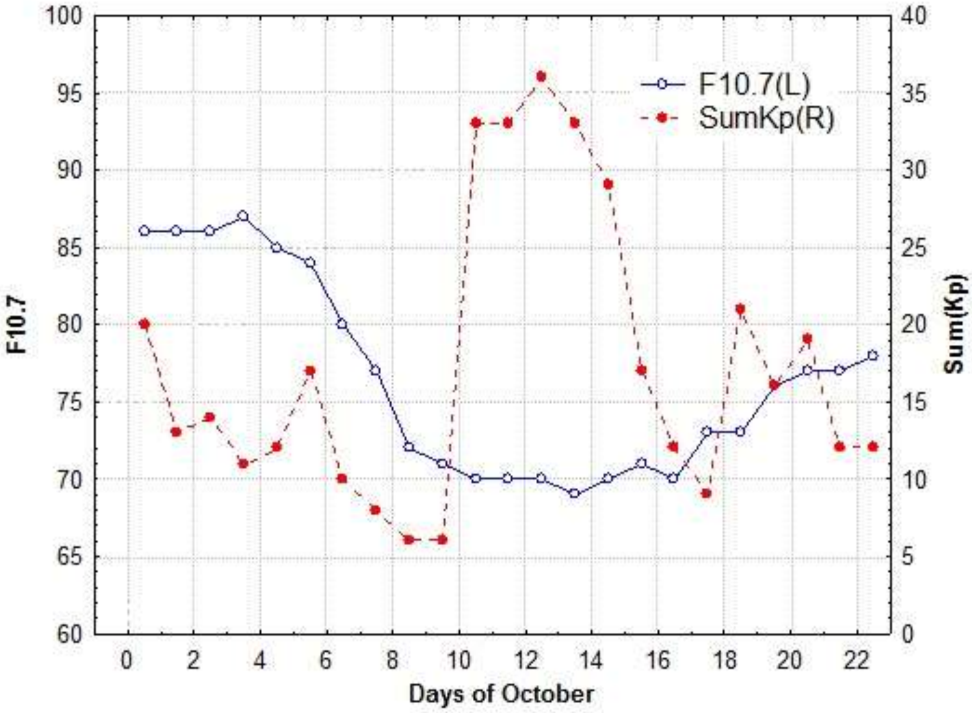


Figure 2. Data on solar and geomagnetic activities.

The Figure 2 shows the data on solar and geomagnetic activity indices (F 10.7 and Kp) in October 2017. We can see from the data that during relatively minor changes in solar activity (index F 10.7) there were strong variations in the geomagnetic disturbance index of Kp. A long magnetic storm was observed at 5-day intervals on October 11 to 15. Significant geomagnetic disturbances were also observed on October 1 and October 18-20.

Comparing Figures 1 and 2 we can see that it is the variation of solar and geomagnetic activity to be the main cause of the observed significant unpredictable changes in atmospheric braking of the spacecraft. The comparison shows the advantages of the OFM method that helps to track real braking variations with less amplitude and phase distortions compared to other measurement methods.

The Figure 3 shows the results of 85 predictions of motion of the spacecraft up to the moment it reached the re-entry altitude (80 km) based on the above-mentioned clarifying results. The estimated entry points are in the range between 12pm on October 21 and 12 pm on October 24. The minimum occurred after the geomagnetic storms on October 1 and 11-15. That is a natural consequence of the increase in actual atmospheric braking. The maximum re-entry time was reached after a minimum of Sb estimates on October 11, just before the beginning of the strong geomagnetic storm mentioned above.

A specific feature of the Figure 3 data is the stabilization of the time of the decay epoch for the time interval after October 19. This area is highlighted with a rectangle. That stabilization is due to a number of reasons:

- As the satellites decay the density of the atmosphere increases and its variability decreases as a result of the influence of different geophysical factors.
- The advantages of the use the OFM method to improve the accuracy of the determination and prediction of orbits result in short-term predictions.

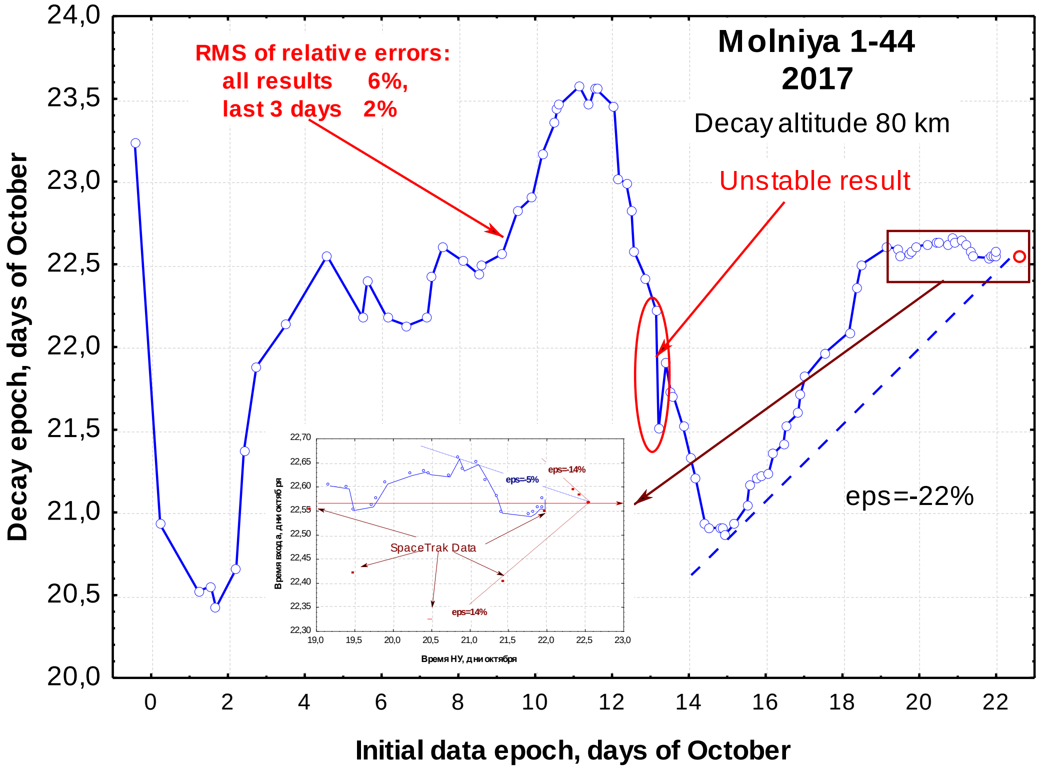


Figure 3. Predictive estimates of the time of entry into the dense layers of the atmosphere

The latest prediction was completed by initial data for 23^h 25^m on October 22. The calculated entry time was October 23 13^h 46^m. The duration of the flight of the spacecraft from the time of ID to the entry point time ≈ 14 hours. The results of calculations at the last 3-day time interval before the reentry will be considered below in details.

Relative error (eps) is an important characteristic of the accuracy of the entry time determination. It is calculated as ratio the difference of the calculated and reference entry time to the remaining lifetime. That estimate was calculated for all 85 predictions under various initial data. The last calculated entry time was used as the reference value. According to all predictions, the RMS of relative error was 6%, and according to the data for the last 3 days it was 2%.

The Figure 3 shows that, in addition to the understandable changes in the estimate of the entry time due to the influence of geophysical factors, there is one bounce change in the estimated entry time for ID on October 14. That area is marked with the red ellipse. Under the initial data at 03^h 21^m on October 14, the expected entry time was 05^h 17^m on October 23. Under the following initial data for 05^h 00^m of the same date, the estimated entry time was 12^h 03^m on October 22, which was reduced by ≈ 17 hours at once. When using next ID the estimated entry time returned to the expected values (smooth changes in estimates). The possibility of appearance of unstable estimates of satellite lifetimes was predicted in the monograph [13] (p. 108). It was proved that this instability occurs with low elliptical orbit satellites, with some values of the perigee argument. The satellite Molnia 1-44 was exactly one of the kind.

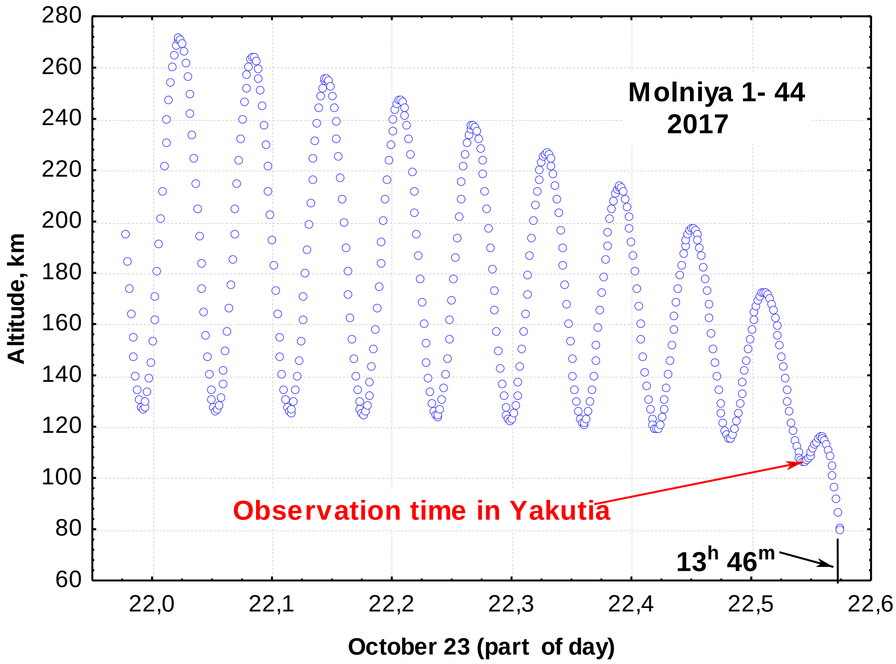


Figure 4. The change of the altitude of a prediction to the entry point

The data from this figure is very useful to explain the results described above. There is a huge difference in the altitude of the apogee and perigee, which that spacecraft had in the latitude ≈ 61°. On the semidiurnal prediction interval, as expected, the altitude of the apogee decreased significantly, by 100 km. At this interval, the altitude of the perigee decreased much slower. At the time of the last passage of the spacecraft in high latitudes before its decay (at the time of ≈ $12^h\ 59^m$), the altitude was 102 km. The rapid decrease in altitude started right away. In 48 minutes, the spacecraft declined to 80 km. The calculations show that after reaching the altitude of ≈ 100 km, satellites do not usually exist long. In most cases, they are destroyed within 20-30 minutes. In our case, this time was much longer, ≈ 50 min. It was due to the position of perigee at high latitudes. The case is that after passage of perigee, the altitude of the satellite changes as a result of the influence of two circumstances:

- the altitude increases due after perigee;
- the influence of the braking effect and the effect of the Earth compression.

The first circumstance leads to an extension of the lifetime. In ours case, however, the second circumstance was more substantial. We can see it in the right part of the graph in the Figure 4.

The accuracy of the estimate decay epoch ($13^h\ 46^m$) is confirmed by the information that on the evening of October 23 ($12^h\ 29^m$ UT), people in Yakutia observed and photographed the satellite's decay. At that time the spacecraft Molnia 1-44 passed moved over Yakutia. The bright glow of the reentering satellites is usually observed when they burn in the upper layers of the atmosphere. Observations of the reentry in Yakutia tells the spacecraft started breaking apart at an altitude of more than 102 km. Some light elements of a large and significant area-to-mass ratio split. Those fragments were observed by witnesses in Yakutia. Heavy fragments of small size could fly farther for tens of minutes more. Thus, the time interval from $12^h\ 59^m$ to $13^h\ 46^m$ on October 23 was the most likely time of the end of life of the spacecraft Molnia 1-44.

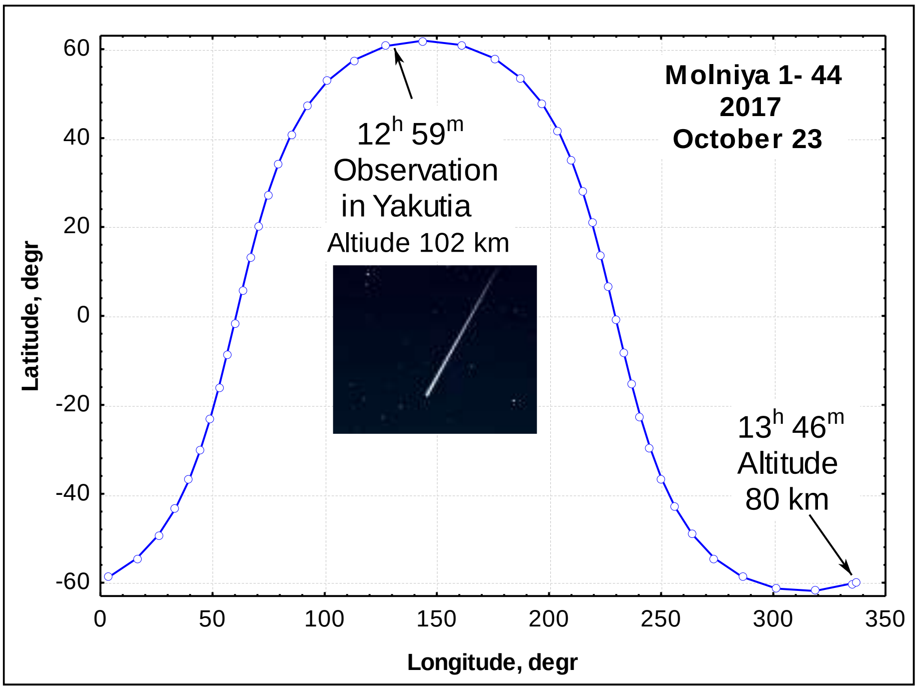


Figure 5. The satellite's subpoint coordinates before the decay

Here is given an 86 minute interval with the orbit trace over the Earth's surface before the estimated decay epoch of the spacecraft at 13^h 46^m on October 23. The right side of the graph (after passage over Yakutia) shows that the most likely area of burning and decay of fragments of the spacecraft. The entire area belongs to the Pacific Ocean and partly to the South-West Atlantic Ocean.

4. Comparison of the results of a decay epoch determination

The comparison of the results of the OFM method with the Table 1 data is shown in the Figure 6.

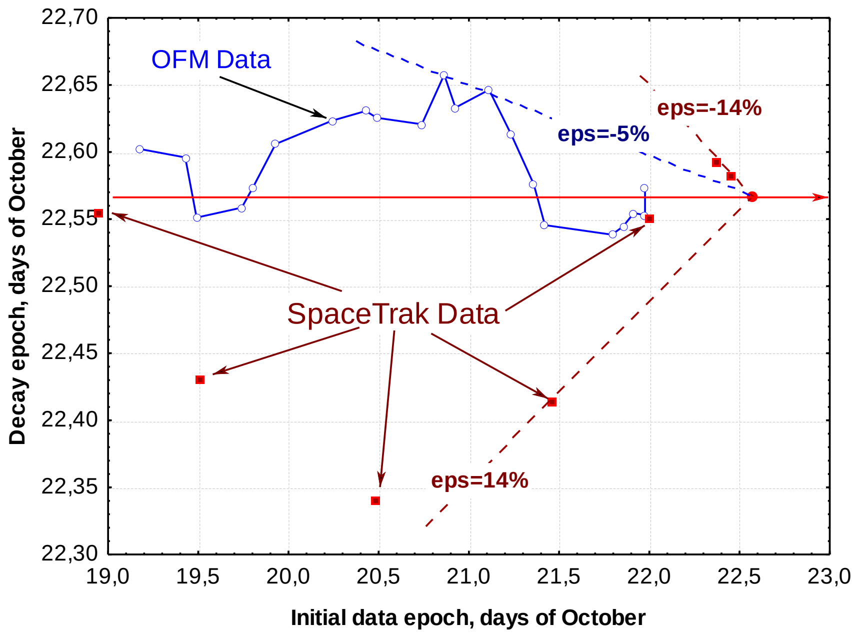


Figure 6. Comparison of estimates of the decay epoch

Data in Table 1 marked with brown squares here. As we can see, in 5 cases our of 7 the results of decay epoch prediction differ a lot from the reference value. The relative error reaches 14%. While using the OFM method, the relative error did not exceed 5% with the RMS relative error equal to 2%.

It is important to point that in the American SSS, the last clarification of the orbital parameters by measurements was performed in $11^h\ 45^m$, e.g. 2 hours 17 minutes before their estimated decay epoch in $14^h\ 00^m$ on October 23. In addition, they also performed measurements on one of the previous orbit passage. The declared window (± 29 min) does not contradict our data, as the time $14^h\ 00^m - 29^m = 13h\ 33^m$ is less than our estimate of decay epoch at $13^h\ 46^m$.

Thus, despite the significantly better information capabilities of the American Space Surveillance System, the level of relative errors in their data (14%) was ≈3 times greater than the results of the OFM method.

The Figure 7 shows the results of all the determinations of the time and area of the decay discussed above. Red color marks the application of the OFM method.

Рисунок 7. Information about possible decay regions

Таблица 2. Main results

Source	Decay epoch	Longitude	Latitude
OFM	$12^h\ 59^m$-$13^h\ 46^m$	327.8°	- 61.2°
SSS	$14^h\ 02^m \pm 29^m$	23.5°	-28.6°
Aerospace	$14^h\ 45^m \pm 60^m$	197.6°	19.8°

As shown above, the OFM method determined the time interval from $12^h\ 59^m$ to $13^h\ 46^m$ on October 23 is the most likely time of the end of life of the spacecraft Molnia 1-44. According to the American data, the left border of the possible decay interval is almost identical to the result of the decay epoch prediction based on the application of the OFM method ($13^h\ 46^m$). However, the results are not consistent with the reliable data on observing the reentry over Yakutia at $12^h\ 59^m$ on October 23.

Conclusions

1. The reentry of the large Russian satellite Molnia 1-44 on October 23, 2017, drew the attention of the public. Many materials on the expected time and location of the reentry have been published. Those materials were controversial and in many cases dilettantish.
2. In accordance with international law, the country that owns a satellite is responsible for possible damage caused by its reentry. The country must inform the world community on possible danger.

3. There are only two organizations in the World that rapidly maintain the catalog of space objects and regularly determine the time and place of the decay of all satellites. It is the Russian and American Space Surveillance Systems. These organizations belong to the relevant military agencies and, therefore, distribution of information about their work is restricted.
4. There are several organizations that periodically and selectively offer solutions on the basis of open information. One of them is Aerospace Corporation (USA). The data of the catalog of the American Space Surveillance System are publicly available in the form of Two Line Orbital elements.
5. The methodology for determining the time and place of the decay of satellites is based on the integration of the motion equations, taking into account known disturbing factors. The initial data are determined by applying the classical least squares technique. Numerous previous works demonstrate that the error of determining the reentry time is ≈ 10% of the remaining lifetime. The main errors in predictions caused by unpredictable variations of atmospheric braking force.
6. Based on the accumulated experience, the author created an improved method for determining and predicting orbits considering the influence of random perturbations developed, called the Method of Optimal Filtration of Measurements (OFM). It is proved that the application of the method provides greater precision than the traditional approach. A number of examples demonstrates that the application of the OFM method leads to several times less errors in determining the decay epoch.
7. The OFM method was applied to determine the time and place of the decay of the spacecraft Molnia 1-44. It was determined the **time interval from $12^h\ 59^m$ to $13^h\ 46^m$ on October 23 is the most likely time of the end of life of the spacecraft Molnia 1-44.** The area belongs to the Pacific Ocean and partly to the South-West Atlantic Ocean. According to 20 predictions within in the last four-day interval, the relative error did not exceed 5% before the decay, with a relative RMS error equal to 2%.
8. Results of American Organizations:

Source	Decay Epoch	Longitude	Latitude
SSS	$14^h\ 02^m \pm 29^m$	23.5°	-28.6°
Aerospace	$14^h\ 45^m \pm 60^m$	197.6°	19.8°

The possible dispersion of estimates is defined as ± 20% of the remaining lifetime. According to the data provided the left border of the possible decay interval is almost identical to the result of the decay epoch prediction based on the application of the OFM method (13^h 46^m). However, the results are not consistent with the reliable data on observing the reentry over Yakutia at 12^h 59^m on October 23.

9. ***Thus, it was demonstrated once again a significant (several times) increase in the accuracy for the task with the used of the OFM method.***
10. ***The introduction of the optimal filtration of measurement in the practice of regular calculations is a matter of current concern.***

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