Determination of the satellite reentry time with allowance for random variations of atmospheric drag

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1. Introduction

The forecast accuracy of LEO satellites motion remains the same during the last decades. Namely, the RMS of the forecast errors is about 10% of the value of atmospheric disturbances.

The necessary requirement for minimizing the forecast errors is **the use of the same satellite motion model for determining the initial data from the measurements and forecasting .**

To determine (update) the initial data based on measurements, the Least Square Technique (LST) has been traditionally used. This technique was developed 200 years ago when the artificial Earth satellites did not exist. **The main feature of the LEO satellites motion is a significant influence of disturbing factors**, which cannot be estimated mathematically with necessary accuracy because of their unpredicted changing in time.

The authors over many years have carried out investigations aimed at improving the accuracy of LEO determination and forecasting [1-6]. Great attention was paid to study of the atmospheric density variations [1-3, 8–12].

2. Problem solution technology

To solve the problem we have to know the data on space weather and Earth orientation parameters. The values of indices of solar activity $F_{10.7}$ and geomagnetic disturbance K_p (A_p) are used as input parameters in the models for calculating the atmosphere density.

As a source of orbital information for calculation we use the JSpOC space-track.org site. **The TLE from this site we transform into the proper orbital form** and save into the database. Furthermore, we consider these orbits as measurements to determine the smoothed orbits and corresponding ballistic coefficients.

For each of chosen orbit determination methods and atmospheric models we calculate the SC reentry time and place after the smoothed orbit calculation.

The numerical and semianalytical methods are used for integration of the motion equations.

The results of calculations for SC "TIANGONG 1"reentry parameters are published regularly on the Internet site **www.satmotion.ru**.

3. Features of the least squares technique application

To forecast the SC motion we use the numerical Everhart method [17] and the Universal Semianalytical Method (USM) [18,19]. To estimate the influence of atmospheric density models on the accuracy of calculations we use **three dynamical models (GOST-1984, GOST-2004 and NRLMSIS-00)** at numerical integration. In the USM predictions, the GOST-1984 atmosphere model is implemented to calculate the density.

To obtain the smoothed orbit three optimization cycles embedded into each other were organized:

- the cycle on searching for the LST functional minimum;
- the cycle on rejecting the anomalous measurements;
- **the cycle on choosing the fit span.**

For searching the LST functional minimum, presented as a sum of squares of nonlinear functions, the rapidly-converging Newton's method is mainly used. The normalized value of the LST functional is used as a criterion of convergence of the optimization process.

4. Allowance for statistical characteristics of atmospheric disturbances

The basic principles of the improved technique (the optimum filtering of measurements, **OFM**) were published about 40 years ago [8]. This technique was implemented in the USSR space surveillance practice for determining and forecasting the orbits of LEO satellites [1]. This technique was improved later [4,5,6,9]. The main feature of the developed methodology **is allowance for statistical characteristics of atmospheric disturbances** on the measurement processing interval and at motion forecasting.

It was assumed that the autocorrelation function of atmospheric disturbances has the form on the right. The correlation matrix (***P***) of interfering parameters (***q***) is constructed with allowance for correlation of atmospheric disturbances and is used to “weight” the measurements without extending the state vector. The value of interfering parameters (noises) is calculated ***after*** constructing the estimate (*x*) on the basis of residual discrepancies.

$$K_q(t,\tau)_0 = \begin{cases} \sigma_q^2\left(1-\dfrac{|t-\tau|}{\Delta}\right), & by \quad |t-\tau|<\Delta, \\ 0 \quad by & |t-\tau| \ge \Delta. \end{cases}$$

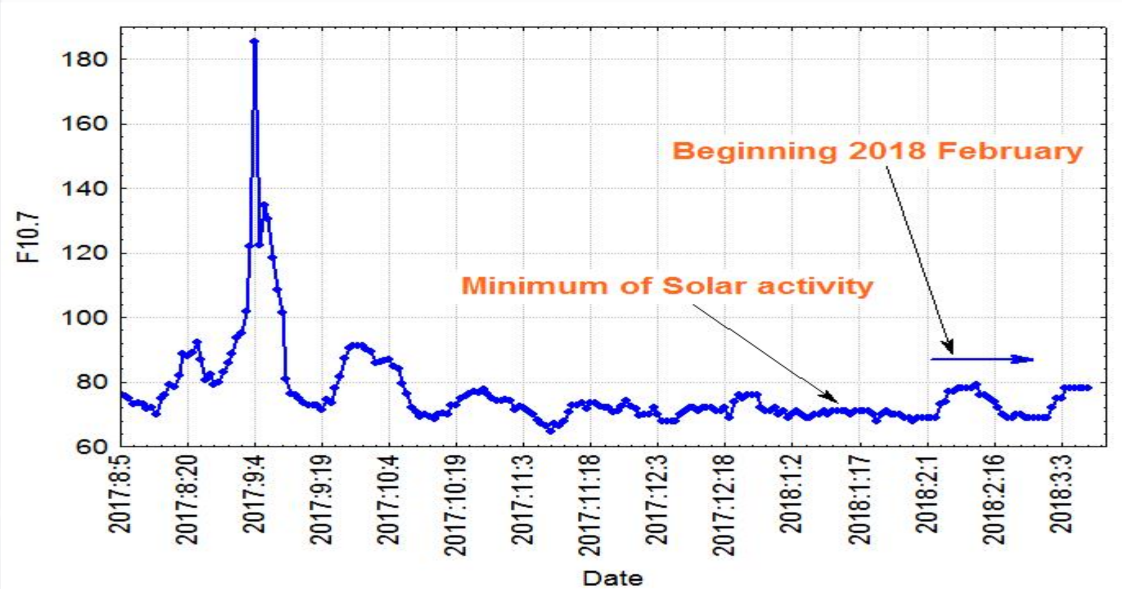
$$\hat{x} = \left(X^T \cdot P \cdot X\right)^{-1} \cdot X^T \cdot P \cdot Z,$$

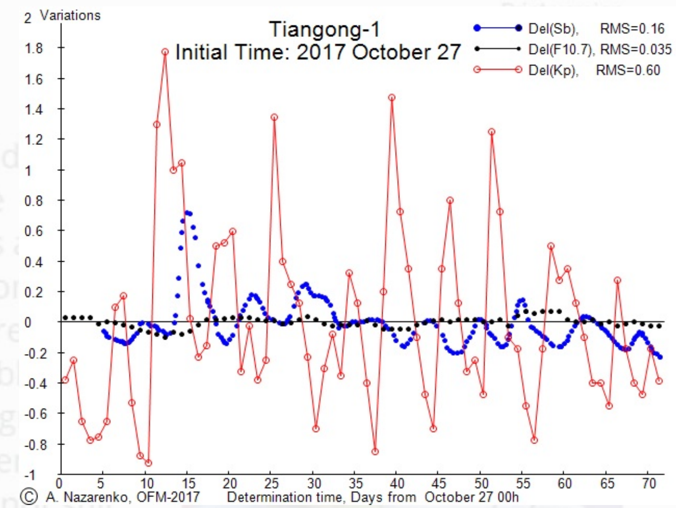
$$P = \left(\frac{\sigma_q^2}{\sigma_z^2} \cdot B \cdot K_q \cdot B^T + E\right)^{-1} = \left(S_n^2 \cdot B \cdot K_q \cdot B^T + E\right)^{-1}.$$

Technique	Numbers of measurements on a fit span						
	k-6	k-5	k-4	k-3	k-2	k-1	k
LST	-	-	0.315	0.712	0.669	0.789	**0.394**
OMF	18.749	14.785	11.460	7.799	5.534	1.751	**0.081**

RMS of residual time discrepancies in time (sec) with using LST and the OFM technique.

5. The geophysical situation at the end of 2017 and at beginning of 2018

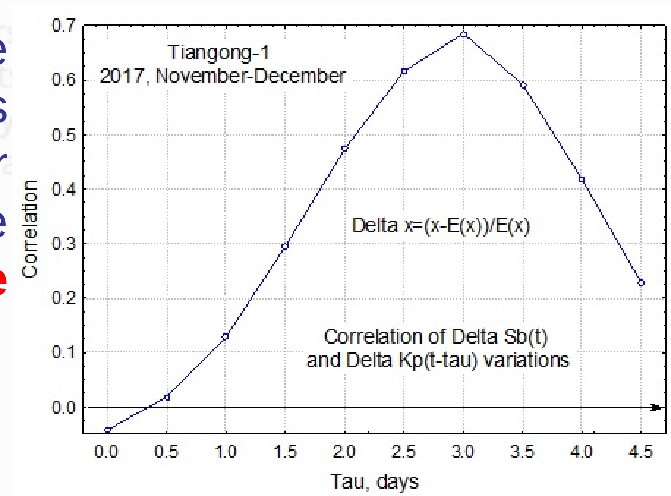




Variations F 10.7 , Kp and Bal. Coef (Sb)

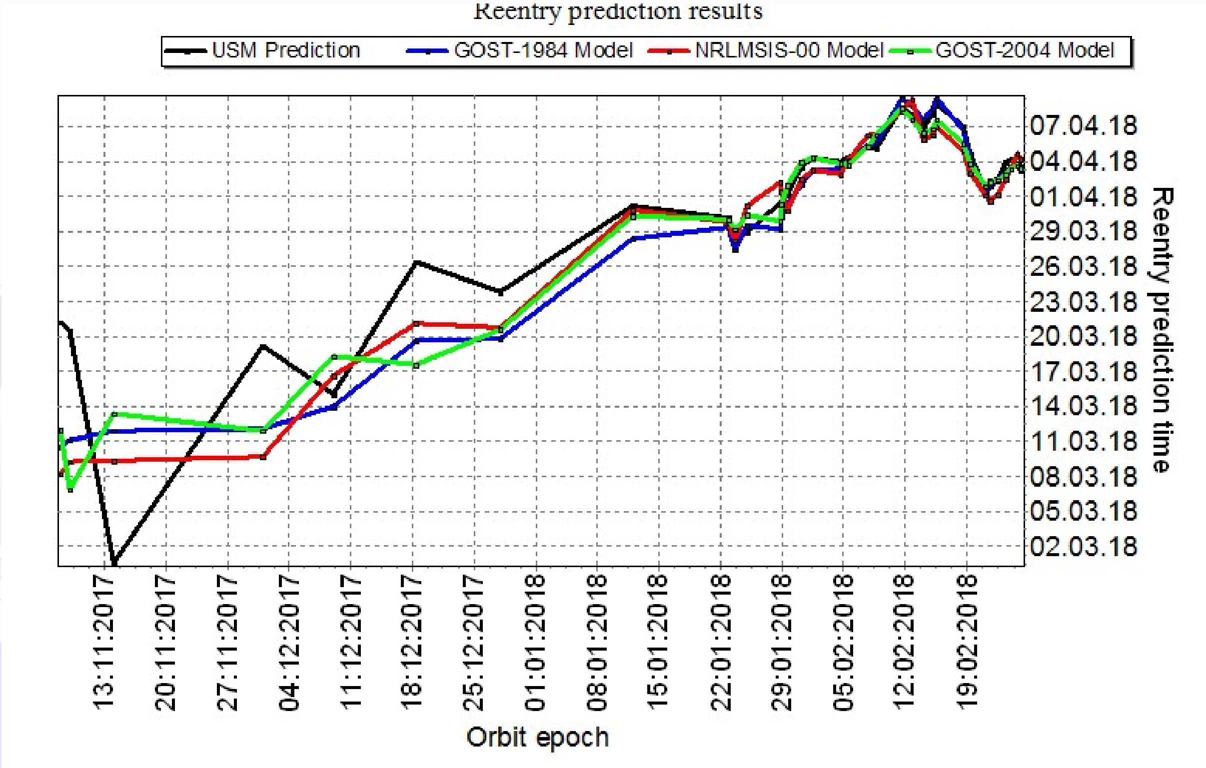
In the late August – early September of 2017 there was a sharp spike of the **solar activity**. After this spike the solar activity has gradually decreased. Over this interval the solar activity level can be characterized as low with moderate variations. **The growth of solar activity began in February 2018.**

The maximum correlation value (for tau = 3 days) is ≈ 0.7. **This confirms very significant relation between the geomagnetic activity variations and the SC atmospheric drag level.**



Cross correlation Kp and Sb

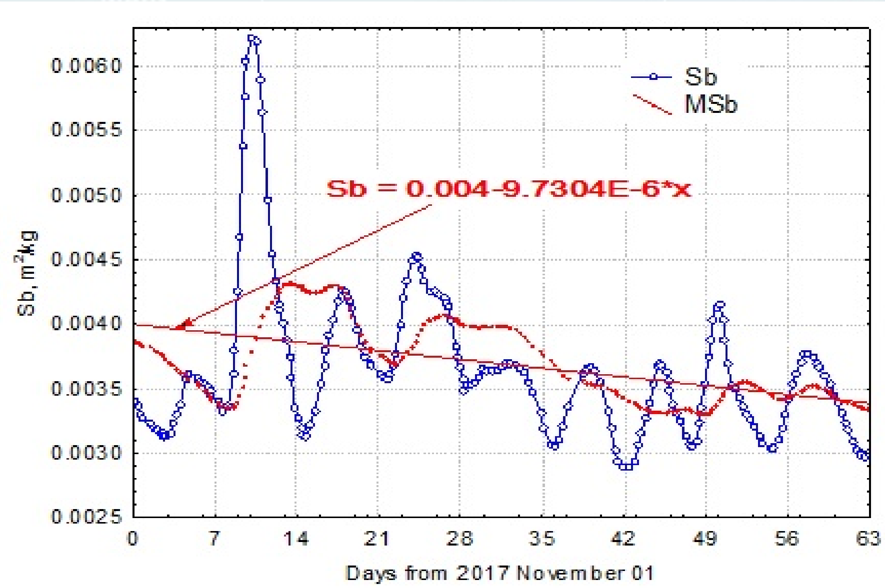
6. Results of application of LST

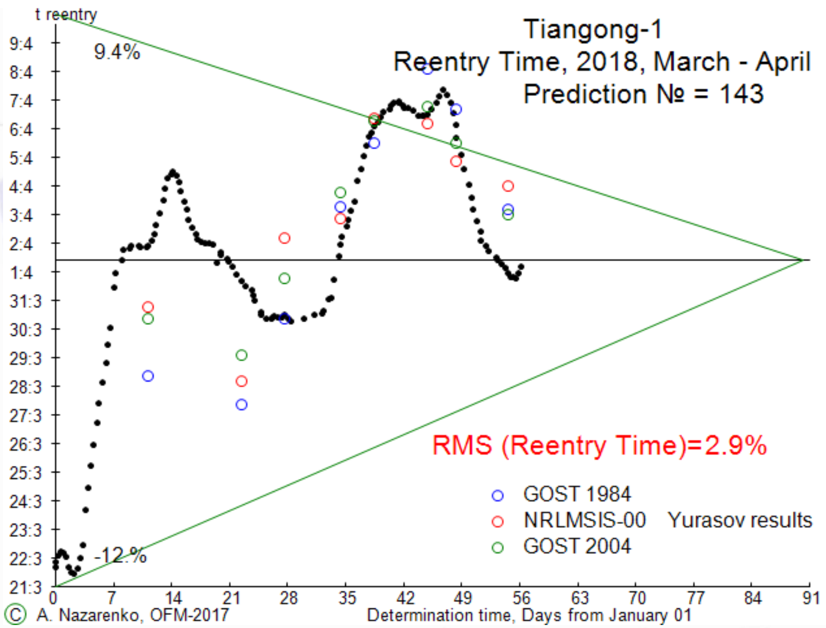


The estimates of forecasted SC reentry times obtained with using various atmospheric models and methods of integration of SC motion equations are generally consistent with each other.

The estimates of the USM prediction are characterized by slightly greater scattering in comparison with the numerical forecasting results. It should be noted however that the time of calculation by means of the USM is two orders of magnitude lower and the distinctions from the results of numerical reentry time calculation do not exceed 5% of the remaining SC lifetime.

7. Using the optimal filtration of measurements





All reentry estimates in 2018

In 2017, significant deviations of the **Sb** estimates from average values are clearly visible. There are secular and periodic changes. The decrease of Sb values amounted to 12% of the initial one. Calculated **average values of reentry time monotonously changed from March 01 to March 20, 2018.** This increase is approximately 16% of the remaining lifetime.

The results of all 143 preceding determinations of SC Tiangong-1 reentry time after January, 01 are presented here. The average value of reentry time is ≈April, 01. **Deviations from the average value do not exceed 12%** of remaining lifetime. The RMS of errors is 2.9%, which is several times lower than the traditional estimates of errors.

Decrease of solar activity ended in January 2018.

8. Development of special public service

In February 2018, the development of a public service COSMODYNAMICS for forecasting the parameters of satellite orbits was started. The initial data could be downloaded online and get the result in a few minutes on the screen, in the account and by email. In the online settlement system, the following modules are provided:

- Uploading input data via web-interface;
- Checking of input data and results;
- Amending of the algorithm options;
- Calculation on server;
- Visualization of the result;
- Sending results to the customer.

The beta version of the system will be open to a wide range of users in 2018.

Cosmodynamics LLC (Innovation Center Skolkovo resident) was established in 2017 in order to develop an open service and algorithms for accurate calculations of forecasts of satellite incidence and dangerous approaches as well as for solving a number of other applied problems where the accuracy of forecasts is a crucial factor. First we plan to distribute our software application and to teach how to use it.

9. Conclusion

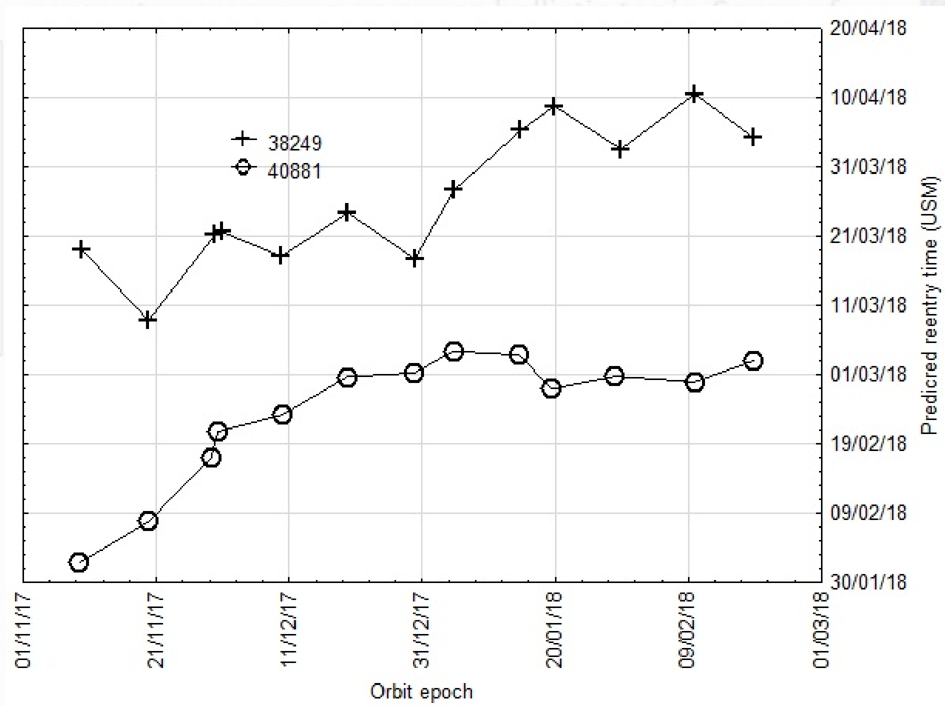
The influence of various options on the accuracy of SC Tiangong-1 reentry prediction is considered: atmospheric density models, methods for integrating the motion equations and orbit determination methods on measurements. On the average the differences between various results **do not exceed 5% of the remaining lifetime**.

The calculations over the time interval **since November** 1, 2017 to mid-February 2018 show the long time increase of the SC lifetime, by approximately up to one month. **This fact can be explained by the long-term decline in the upper atmosphere density during a minimum of 11-years cycle of solar activity, not accurately predicted by the used atmosphere models.**

The minimum of solar and geomagnetic activity was reached in January 2018. Therefore, it is expected that in March-April 2018 the reentry time estimates will not have secular component and will fluctuate in accordance with variations of geomagnetic activity. The errors of SC Tiangong-1 reentry time prediction **will not exceed 10% of the remaining lifetime by using the considered methods.**

Addition

To confirm the correctness of our conclusion concerning long time increase of the SC Tiangong-1, additional reentry predictions for objects 12017B (38249) and 15041B (40881) were accomplished. The consistency of all prediction results shows that **there is the general nature for the observed long-term decrease of atmospheric density** at low altitudes from November 2017 to February 2018. All used atmospheric density models could not accurately predict the specified reduction in density.



Reentry time predictions for objects #38249 and #40881

10. References

1. A.I. Nazarenko. Determination and Prediction of Satellite Motion at the End of the Lifetime. *International Workshop on Salyut-7/Kosmos-1686 Reentry,* ESOC, (G), April 9, 1991.
2. A.I. Nazarenko, P.J. Cefola, V.S. Yurasov. Estimating Atmosphere Density Variations to Improve LEO Orbit Prediction Accuracy. AAS/AIAA Space Flight Mechanics Meeting, Monterey, CA, February 1998. AAS 98-190.
3. V.S. Yurasov, A.I. Nazarenko, K.T. Alfriend, and P.J. Cefola, , “Reentry Time Prediction Using Atmospheric Density Corrections,” Fourth European Conference on Space Debris, Darmstadt, Germany, March 2005.
4. A.I. Nazarenko. Increasing the accuracy of orbit forecasting on the basis of improvement of statistical methods for processing measurements // Fifth European Conference on Space Debris, Darmstadt, Germany, ESA SP-672, 2009.
5. A.I. Nazarenko. Application of the Method for Optimum Filtering of Measurements for Determination and Prediction of Spacecraft Orbits. Solar System Research, 2013, Vol. 47, No. 7.
6. A.I. Nazarenko. How can we increase the accuracy of determination of spacecraft’s lifetime? Acta Astronautica, 115 (2015), p.p. 229-236.
7. http://www.space-track.org
8. A.I. Nazarenko, L.G. Markova. Methods of determination and forecasting the AES orbits in the presence of errors in the mathematical description of motion //Applied problems of space ballistics: collection. M.: Nauka, 1973. pp. 36-67.
9. Nazarenko A.I. Determination and Prediction of Orbits with Due Account of Disturbances as a «Color» Noise // AAS/AIAA Space Flight Mechanics Meeting. CA, February 1998. AAS 98-191.

10 Yurasov, V.S., Nazarenko, A.I., Alfriend, K.T., Cefola, P.J. Direct Density Correction Method: Review of Results. 57th International Astronautical Congress, October 2006, IAC-06-C1.5.2.

11. Yurasov, V.S., Nazarenko, A.I., Cefola, P.J., Alfriend, K.T. Results and Issues of Atmospheric Density Correction. 14th AAS/AIAA Space Flight Mechanics Conference, Maui, Hawaii, Feb. 2004. AAS 04-305.

10. References (continuation)

12. www.satmotion.ru.

13. www.celestrak.com.

14. Earth's Upper Atmosphere. Density Model for Ballistic Support of epy Flight of Artificial Earth Satellites GOST 25645.115-84, Publishing House for the Standards, Moscow, 1985.

15. Earth′s Upper Atmosphere. Density Model for Ballistic Support of the Flight of Artificial Earth Satellites. GOST R 25645.166-2004. Publishing House for the Standards, Moscow, 2004.

16. Picone, J.M., Hedin, A.E., Drob, D.P., Aikin, A.C. (2002-12-01). "NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues". Journal of Geophysical Research: Space Physics. 107 (A12):1468. Bibcode:2002JGRA..107.1468P. doi:10.1029/2002JA009430. ISSN 2156-2202.

17. Everhart, E. 1974. Implicit single sequence methods for integrating orbits.- Gelest. Mech., vol.10, pp.35-55.

18. Yurasov, V.S. Application of a semi-analytical method for motion forecasting of artificial satellites in an atmosphere. Observation of Artificial Celestial Bodies, Astronomical Council of USSR Academy Sciences, Moscow, № 82, 1987.

19. Yurasov, V.S. "Universal Semianalytic Satellite Motion Propagation Method," Proceedings of the Second U.S.-Russian Space Surveillance Workshop, Poznan, Poland, July 1996.

20. http://alglib.sources.ru/optimization/levenbergmarquardt.php

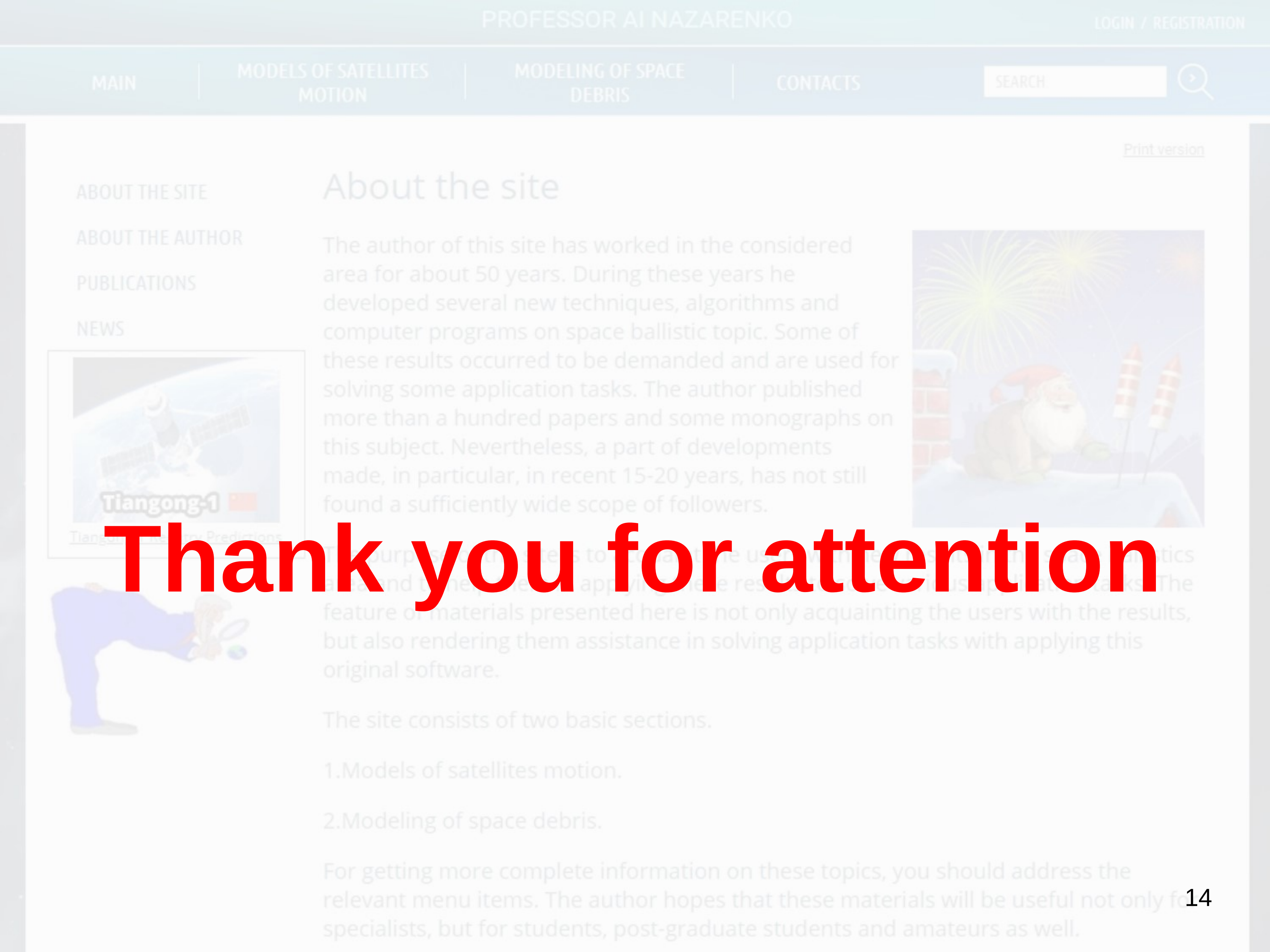
21. A.G. Klimenko, A.I. Nazarenko. Development of the program for numerical integration of the motion equations. Private report, 2006, 38 (p).

22. http://www.swpc.noaa.gov/

23. 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

24. A.I. Nazarenko. Stochastic astrodynamics tasks. Mathematical methods and algorithms for solving. Moscow, URSS, 2017, 352 (p).

Thank you for attention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Tiangong-1 Reentry Predictions

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[illegible] feature of materials presented here is not only acquainting the users with the results, but also rendering them assistance in solving application tasks with applying this original software.

The site consists of two basic sections.

1.Models of satellites motion.

2.Modeling of space debris.

For getting more complete information on these topics, you should address the relevant menu items. The author hopes that these materials will be useful not only for specialists, but for students, post-graduate students and amateurs as well.