NEAR REAL TIME CORRECTIONS TO THE ATMOSPHERIC DENSITY MODEL

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ABSTRACT *– Perspective direction of an increasing accuracy of satellite orbit determination and prediction for low earth orbit (LEO) satellites is thepurpose of the upper atmosphere monitoring, i.e. the analog of a weather service in the lower atmosphere. Our idea for upper atmosphere monitoring is based on the usage of the available atmospheric drag data on catalogued LEO satellites for construction of corrections to the atmospheric density model used. The drag data are obtained and operationally updated as a result of regular satellite observations.*

The corrections to the GOST atmospheric density model were estimated since April 2002. The density corrections include a bias term and a term that is linear with the altitude. These corrections are derived from the Two Line Element (TLE) dataset. For these purposes real orbital data for several hundred space objects, with perigee heights below 600 km, were accumulated. More than 200000 TLE sets were processed. Density correctionswere constructed on a one day grid. The effectiveness of density correction under various atmospheric conditions was estimated by comparison of the results obtained with the uncorrected and corrected density models. The corrections to the GOST atmospheric density model increased the fitting and prediction accuracies of LEO satellite motions and obtained more accurate atmospheric density estimates, without development a new model. The considered approach of atmospheric density correction is applicable for any atmospheric model.

INTRODUCTION

The main inaccuracies in the determination and prediction of low-altitude objects' orbits are due to errors in atmospheric density models. Even the modern atmospheric models [1-8] have errors of the order of 10-15% in quiet and 30-60% in highly perturbed conditions. This situation has not changed, virtually, during the last 30 years. Moreover, one cannot expect the appearance, in the near future, of much more accurate atmospheric models and their use for LEO prediction. This is explained by the complexity of the physical and chemical processes occurring in the upper atmosphere. The development of acceptable-in-accuracy mathematical models for these processes is a complicated scientific problem. But even if will be solved, the practical significance of such models for solving operative tasks will be minor, because of large computing efforts required for their realization.

In this connection, it is useful to make an analogy between the problem of density estimation in the upper atmosphere and prediction of weather in the lower atmosphere. Obviously, the application of the averaged climatic model, constructed on the basis of processing long-term observations over an elapsed time span, does not allowto the prediction of current weather accurately enough. Similarly, at satellite flight altitudes the application of empirical and semi-empirical atmospheric density models, constructed on the basis of averaging the experimental data obtained over the time span elapsed long ago, does not provide a possibility for qualitative estimating and forecasting the atmospheric density in the current time neighborhood. The increasing of weather forecasting accuracy (as compared to the climatic model application) is achieved on the basis of a special meteorological service. Similarly, the increasing of accuracy of estimating and forecasting atmospheric density in the upper atmosphere can be achieved only on the basis of establishing a special service for monitoring its current state.

To provide essentially better spatially-temporal resolution of measurement information, as compared to the achieved level, an ideal approach would be to establish a system of spacecraft equipped with special sensors for the upper atmosphere monitoring. However, a very high cost of such a project does not allow hope for its implementation in forthcoming years.

In this respect, an alternative version not requiring high expenses of money and time is the realization of Yu.P. Gorochov's and A.I. Nazarenko's idea, which was first advanced in their paper published at the beginning of the eighties [9]. In that paper it was offered to monitor the current state of the upper atmosphere based on the available drag data for all LEO satellites. The number of such satellites, having altitudes up to 600 km, equals some hundreds, and their orbital elements have been regularly and operatively updated by the Russian Space Surveillance System (SSS). It was offered to use these data for estimating current corrections to the modeled density profile of the upper atmosphere.

THE THECHNIQUE BASIS

Let's represent the real value of atmospheric density at some point of space and at an arbitrary time as the sum of ρ_{model} value calculated by the model, and a current deviation $\delta\rho$ from this computational value

$$\rho(t) = \rho_{model} + \delta\rho = \rho_{model} \cdot \left(1 + \frac{\delta\rho}{\rho_{model}}(t)\right). \tag{1}$$

The problem consists in determining the values of the $\delta\rho / \rho_{model}$ ratio, averaged over some short time interval $(t_j, t_j + \tau)$ as some function of altitude

$$\frac{\delta\rho}{\rho_{\text{model}}}(h)_j = \frac{\delta\rho}{\rho}(h)_j = F(h)_j. \tag{2}$$

During the processing of the measurements, the orbital parameters and ballistic coefficients are estimated to provide the best matching of actual and computational trajectories of satellite motion. Therefore, the following ratio is valid between the atmospheric density variations and estimated values of ballistic coefficients:

$$\left(\frac{\delta\rho}{\rho}\right)_{real} \approx \left(\frac{k - k_{real}}{k_{real}}\right), \tag{3}$$

where k_{real} and $(\rho)_{real}$ are real (true) values of satellite's ballistic coefficient and atmospheric density at the perigee altitude.

If the true value of ballistic coefficient k_{real} is known, then the right-hand part of expression (3) can be considered as a measurement of atmospheric density variation at the perigee altitude of the i^{th} satellite. Taking into account formula (2), the set of these measurements, accumulated over the

$\left(t_j, t_j + \tau\right)$ time interval, is a statistical basis for constructing the altitude profile *F(h)* of atmospheric density variations.

If the altitude profile is represented by a linear function of altitude, then the spatially-temporal function of the density variations is expressed by the elementary formula

$$\left(\frac{\delta\rho}{\rho}\right)(h,t) = a_1(t) + a_2(t)h \tag{4}$$

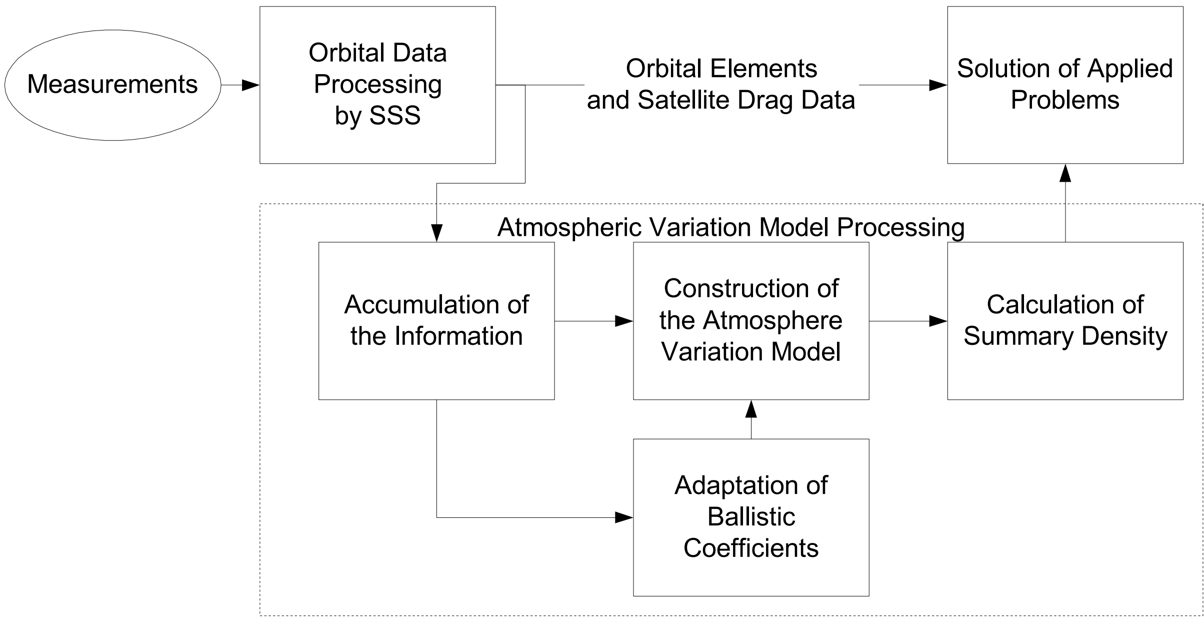

Fig. 1. Atmospheric Density Monitoring Processes

Figure 1 shows the interaction of four main components of the considered technique for monitoring the atmospheric density with sources and users of the information. They are as follows:
"Accumulation of the Information" - operative updating of the orbital data obtained by a space surveillance system for all chosen satellites and storing this information.
"Construction of the Atmosphere Variation model" – the regular (with the time interval τ) operative updating the altitude profile of density variations based on the information accumulated over the indicated time interval.
"Adaptation of Ballistic Coefficients" - periodic (with about a month interval) updating of ballistic coefficients $\overline{k}_i$ ensuring best coincidence of these estimations with accumulated experimental and a priori information.
"Calculation of Summary Density" – calculation of total atmospheric density values at the required spatially - temporal point for using them in satellite motion forecasting algorithms.

REALIZATION STAGES

The offered idea of monitoring the upper atmosphere density based on the satellite drag data has been developed in several stages for 20 years. At the first stage (in the eighties) this technology has been tested experimentally [10-16]. The atmospheric density variations have been estimated with a periodicity of 3-hours. Based on processing a large set of real data, the possibility of a 2-fold increase of the accuracy of forecasting LEO satellite motion was demonstrated. The difficulties of further improvement of the technique and its regular operative application had an organizational, rather than a technological, character.

During the second stage (since 1996 to 2000) detailed mathematical modeling of the upper atmosphere density monitoring, based on the satellite drag data, has been carried out [17-22]. The possibility of comparing the modeled density variations with the results of the estimation of these variations has formed the basis for essentially revising the basic algorithms. Besides, some new aspects of monitoring techniques, not considered earlier, were investigated. In particular, the amplitude-phase distortion of density variation estimates was studied. The modeling results confirmed the possibility of estimating short-periodic variations of the atmospheric density in the 200-600 km altitude range with errors, which were, in the majority of cases, 3 to 6-fold lower, than the level of variations themselves.

The results, obtained at preceding two stages of developing the technique for upper atmosphere density monitoring, as well as currently available information possibilities, allowed us to proceed to the third stage, namely, to regularly monitor density variations using the real information. A characteristic feature of the current situation is the accessibility of the orbital data in the so-called "two line element" (TLE) format. These data, obtained by the US Space Surveillance System (SSS), can be received regularly and operatively enough via the INTERNET. These data differ, in quantity, structure and some other characteristics, from the input data used at the preceding stages. So, whereas the Russian SSS updates the LEO orbits at each observable revolution [23], the TLE-orbits are re-calculated for the majority of space objects (SO) 1-2 times a day. And only at the re-entry phase of satellite's lifetime, the TLE are updated at each observable revolution. Therefore, whereas with using the Russian SSS's and modeled data, the variations have been estimated with a 3-hour step, such a time resolution can hardly be achieved using the TLE data.

TLE USE AND DATA DISTRIBUTION

It should also be noted that the satellite drag data, contained in TLE-orbits, can not be directly used for constructing density variations [24]. For this reason some modification of the technique and development of special software for automated processing the data in the TLE-format, and for estimating current variations of atmospheric density based on these data, were carried out.

The following technique was implemented for estimating density variations using TLE-orbits (see Fig. 2).

1. The orbits were re-calculated from the TLE-format into osculating elements and mean elements accepted in the Universal Semianalytical Method (USM) [25, 26]. The results of testing the technique and the data on re-calculation accuracy are presented in [27]. Therefore, this subject is not considered here. All transformed data were stored in a specially constructed database. The re-calculation results were considered further as "measurements" for calculating "smoothed" orbits and related ballistic coefficients of SO.
2. The smoothed orbit and ballistic coefficient were determined a posteriori for each measurement epoch. For this purpose the so-called secondary data processing was carried out. Namely, the USM mean elements and the ballistic coefficient value were estimated by the least square method from the measurements on a particular time interval prior to the epoch of an updated orbit. The fit interval, used in estimating the smoothed USM mean elements and associated ballistic coefficients, was chosen depending on the remaining satellite lifetime. The set of measurements, on a fit interval prior to the epoch of smoothed orbit was chosen for each fitting. To take into account the measurement errors, during the secondary processing, the weight diagonal matrix was used. This 6×6 matrix was identical to all sets of measurements, but the matrix components of a six-dimensional vector of measurements were treated with different weights established empirically.

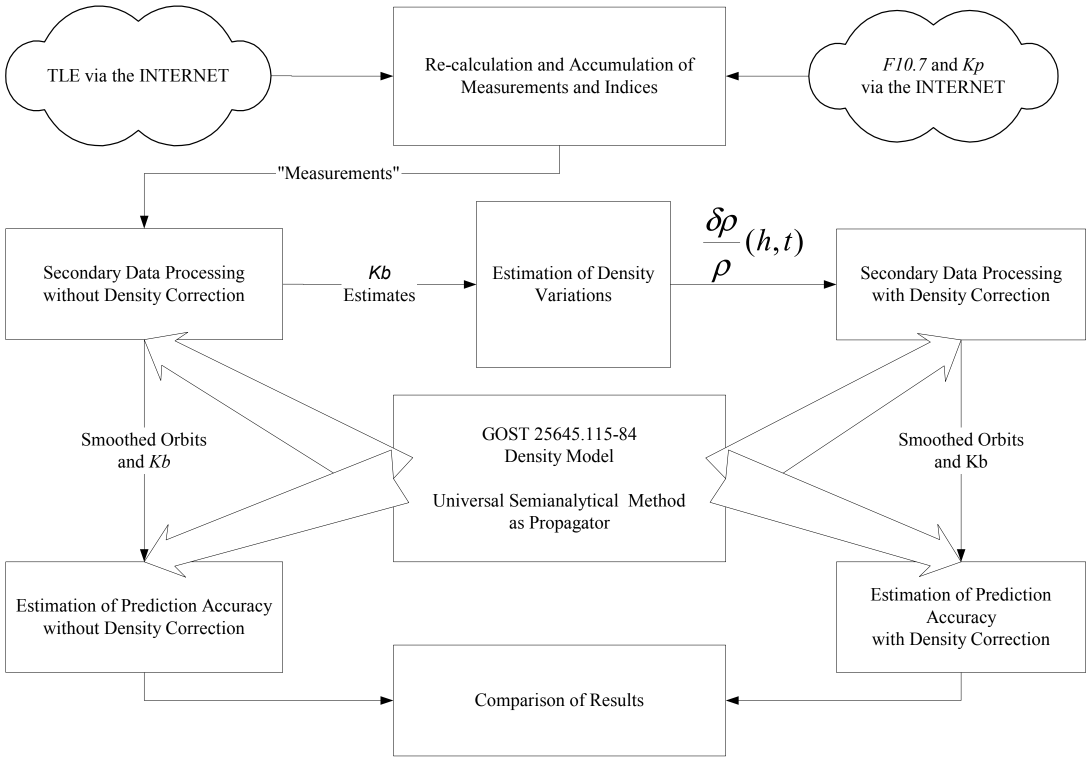

Fig. 2. Flowchart Describing the Technique Used

Usually, the USM was used for satellite motion prediction. And the Everhart numerical method was used for testing only. In these cases the smoothed osculating elements and associated ballistic coefficients were found. The GOST-25645.115-84 density model in the 1990-year version was used for atmospheric density calculations. The current values of solar and geomagnetic activity indices were used in the model. The ballistic coefficient estimate, obtained as a result of secondary processing, was attributed to the middle of the processing interval. The ballistic coefficient was determined as

$$K_b = \frac{C_d S}{2m}, \tag{5}$$

where C_d is the drag coefficient, S is the cross-sectional area perpendicular to the satellite motion, and m is the mass.

3. The atmospheric density fluctuations were constructed using the estimates of ballistic coefficients obtained as a result of secondary processing.

4. Similar to item 2, the smoothed orbits and associated ballistic coefficients were calculated taking into account the constructed atmospheric density variations.

5. Each smoothed orbit, obtained with, and without, density corrections, was predicted forward to the epoch of newer measurements, which have not been used for its updating. Then the prediction errors along the trajectory were calculated by comparing the predicted orbit with measurements. To obtain the comparable error statistics over all satellites and for different prediction intervals, the normalized prediction error parameters were used. Such an error parameter was determined as the ratio of the along-the-track deviation of the orbit, predicted from "measurements", to the value of atmospheric disturbance along the trajectory.

To support this experiment 257 LEO space objects (SO) were chosen, whose element sets were regularly updated in the US Space Catalog. All of the chosen space objects have a perigee height lower than 600 km and apogee height lower than 2000 km. Since April 2002, all chosen SO and all daily US SSS TLE's, available over the INTERNET, have been collected. Some of the chosen SO were decayed during the experiment due to the atmospheric drag. By this reason in November, 2002, the list of chosen SO was supplemented by 220 new objects. Thus, the total number of SO, used during the experiment, was equal to 477.

Fig. 3. Solar Flux

Fig.4. Daily Averaged Geomagnetic Index

The solar and geomagnetic conditions during the experiment are characterized by the plots of solar and geomagnetic activity indices presented in Figs. 3 and 4. With respect to the 11-year cycle of solar activity, the given time interval may be characterized as the period of decreasing solar activity after its maximum. It can be seen from Fig. 3, that over an indicated time interval essential drops of the solar flux took place, reaching 100 units for the $F_{10.7}$ index. As to geomagnetic disturbances (see Fig. 4), no strong geomagnetic storms have been recorded during this interval.

Figure 5 presents the histogram of distribution of a diurnal number of ballistic coefficient estimates obtained from secondary data processing, and used for constructing density variations. It is seen that the realizations are distributed rather uniformly in time. The mean diurnal number of realizations has varied basically from 200 up to 300 until November 2002, and from 400 up to 600 – since November, 2002. This is in a good agreement with the number of SO used in the experiment during corresponding periods. The total number of realizations exceeded 200,000 to the present time.

Fig.5. Diurnal Number of Ballistic Coefficient Estimates

The insufficient volume of diurnal data, as well as a great fitting interval used for estimating satellites' ballistic coefficients, does not allow us to hope to obtain good, time-resolving density fluctuations. Recall that in the modeling experiments the step of calculations of density fluctuations was equal to 3 hours; that is, our goal was to detect short-period density variations correlated mainly with changes of geomagnetic conditions. During the given experiment, however, this step was chosen to be equal to one day. Thus, the main task here was to construct atmospheric density fluctuations caused by changes of solar activity.

The temporal-altitude distribution of estimates of ballistic coefficients is presented in Fig. 6. It is seen that the estimates are distributed non-uniformly in altitude. Their greatest density corresponds to the altitude of about 600 km. For lower altitudes the number of estimates decreases. For some time intervals no realizations were obtained at altitudes lower than 250 km.

Figure 7 shows a similar distribution of ballistic coefficient estimates for a subgroup of standard SO. The standard SO are SO having known values of ballistic coefficients, which change insignificantly during the motion. The data on standard SO are used for determining and eliminating the biases, which can probably be present in the atmospheric density model used. It is desirable that the standard SO were distributed uniformly over a considered altitude range. In our case this range is more narrow – from 400 to 600 km. The total number of standard SO was equal to 53, and the number of realizations on them was about 14000.

Fig.6. Temporal-Altitude Distribution of Estimates (all SO)

Fig.7. Temporal-Altitude Distribution of Estimates (Standard SO)

VARIATIONS ESTIMATION RESULTS

The time dependency of variations of ballistic coefficients, constructed for all chosen satellites, and the plots of solar flux are presented in Fig. 8. The long-periodic character of changing these variations is clearly traced. The greatest-in-magnitude variations have been observed in the period from August 17 to August 22, 2002. The solar flux plot indicates that the local solar activity maximum corresponds to this time interval. This maximum repeats with a monthly period and reaches various levels in each particular case. The highest levels of atmospheric density variations, correlated with these events, were exhibited in August, September and December of 2002. This is seen from the plots of atmospheric density variations constructed for altitudes of 200, 400 and 600 km, which are presented in Fig. 9. Over the time interval of the experiment the maximum values of atmospheric density variations lie in the range from 25 % at 200 km altitude to 50 % at 600 km altitude.

Fig. 8. Variations of Ballistic Coefficients before Correction of Density Model (all SO)

Fig. 9. Constructed Atmospheric Density Variations for GOST Model

The quality of constructed density variations is characterized by scatter plots of estimates of ballistic coefficient variations obtained using the corrected densities. Fig. 10 presents the scatter plot corresponding to all SO with account taken of the density fluctuations. Fig. 11 presents the scatter plots of ballistic coefficient variations for standard SO obtained before and after correction of the density model. It is seen that the use of corrected atmospheric density for orbit determination eliminated the long-periodic variations in estimates of ballistic coefficients, caused by errors in the atmospheric density model. Figure 12 presents the altitude distribution of ballistic coefficient estimates obtained with and without correcting the atmospheric density. It follows from these plots that the density corrections are efficient for all altitudes from 200 to 600 km.

Fig. 10. Variations of Ballistic Coefficients after Correction of Density Model (all SO)

Fig.11. Variations of Ballistic Coefficients Obtained without and with Corrections of Density Model (standard SO)

Fig. 12. Altitude Distribution of Estimates of Ballistic Coefficients Obtained with and without Correction of the Atmospheric Density (all SO)

The statistics for distribution of ballistic coefficient estimates, obtained before and after correcting the GOST model over the 10-month interval, is presented in Table 1. The values of standard deviation (SD) for variations of ballistic coefficient estimates, obtained with and without taking into account calculated fluctuations of atmospheric density, are equal to 16.69% and 10.11%, respectively. For standard SO the corresponding SD values are 12.56% and 3.56%. Thus, the correction of density decreases the scatter of ballistic coefficient estimates by a factor of 1.6 for all SO, and by a factor of 3.5 for standard SO.

Table 1. Statistics for Distribution of Ballistic Coefficient Estimates

Secondary data processing mode	All SO		Standard SO	
	Number of estimates	SD	Number of estimates	SD
Without density correction	106706	16.69%	14418	12.56%
With density correction	107852	10.11%	14453	3.56%

The presented indicators of the density effect are not full enough, since they were obtained by averaging the data over all SO. The comparison of characteristics of scattering of variations of ballistic coefficient estimates, obtained with and without atmospheric density correction, was additionally performed for each of the chosen SO. For this purpose the ratio of SD for variations of ballistic coefficient estimates, obtained without atmospheric density correction to those obtained with the density correction, was calculated for each of the chosen SO. The histogram of distribution of these ratios is plotted in Fig. 13. Only for 13 objects from 477 (or for 2.7 %) the density correction has not resulted in decreasing the scatter of variations of ballistic coefficient estimates. The SD value, obtained after density corrections over all SO on the average, was found to be 2.2 times lower, than that obtained before density correction.

Fig. 13. Distribution of SD Ratios for Variations of Ballistic Coefficient Estimates

As an obvious example, Figure 14 presents the comparative estimates of ballistic coefficients for the STARSHINE 3 standard satellite (NSSC#26929, 2001-043A), obtained with and without density corrections for the GOST model. The same figure gives the plots of ballistic coefficient estimates, obtained using the NRLMSISE-00 model [28] and for the true value of the satellite's ballistic coefficient. Statistics for these estimates are presented in Table 2.

STARSHINE 3 satellite has a spherical shape about a meter in diameter (0.94 m) and weight of 91 kilograms [29]. The theoretical value of ballistic coefficient for this satellite, calculated by formula (5) for the drag coefficient C_d =2.2, is equal to 0.00839 m^2/kg. According to the GOST model, the mean values of ballistic coefficient, obtained as a result of secondary data processing with and without correction of atmospheric density, are equal to 0.00828 m^2/kg and 0.00842 m^2/kg, respectively. These quantities agree well with the theoretical value. Since STARSHINE 3 satellite has a spherical shape, the changes of its K_b estimates are mainly explained by errors in the applied atmospheric density model.

If the atmospheric density variations are determined correctly, the scattering of ballistic coefficient estimates should essentially decrease, when these variations are taken into account. The plots in Fig. 14 confirm this conclusion. So, the standard deviations of ballistic coefficient estimates for STARSHINE 3 satellite, calculated without and with allowance for the atmospheric density variations, were equal to 10.6% and 2.8%, respectively. Thus, the scattering of K_b estimates decreased by a factor of 3.7 due to density corrections for the GOST model. So, the effect of taking into account the fluctuations is obvious for this satellite.

The mean value of the ballistic coefficient, obtained using the NRLMSISE-00 atmospheric model in secondary data processing, was equal to 0.00755 m^2/kg. This value differs by 10 % from theoretical one. This could be due to two reasons: 1) the real value of drag coefficient for STARSHINE 3 satellite is equal to 2.0 (rather than 2.2), and in this case the GOST model estimates should be biased by +10%; 2) there exists some bias in the NRLMSISE-00 model. As to the standard deviation, its value for the NRLMSISE-00 model estimates is close to the GOST model estimates, obtained without density corrections. The execution time required for secondary data processing using the NRLMSISE-00 model was one hundred times greater than that for the GOST model. So, the execution time for the STARSHINE 3 satellite was, respectively, 36 hours and 10 minutes for the NRLMSISE-00 and GOST model. Therefore, the density variations have not still been constructed for the NRLMSISE-00 model.

Fig.14. Comparison of Estimates of the Ballistic Coefficient for STARSHINE 3 Satellite

Table 2. Statistics for STARSHINE 3 Satellite Estimates

Statistics	GOST model No corrections	GOST model With corrections	NRLMSISE-00 model No corrections
K_b mean, m^2/kg	0.00828	0.00842	0.00755
K_b SD, m^2/kg	0.00088 (10.6%)	0.00023(2.8%)	0.00086(11.4%)
Execution time	≈10 min	≈10 min	≈36 hours
Propagation method	The USM propagator	The USM propagator	The Everchart numerical propagator

ESTIMATION OF PREDICTION ERRORS

Consider now the influence of atmospheric density corrections on the orbit prediction accuracy. The normalized along-the-track errors of orbit prediction for the STARSHINE 3 standard satellite, obtained with and without allowance for density fluctuations over the 9-month interval, are plotted in Fig. 15.

The standard deviation of the normalized prediction errors for STARSHINE 3 was equal to 17.35 % , for the case where the density corrections were not taken into account, and 8.89 %, where density corrections were allowed for. Thus, applying density corrections for this satellite has resulted in decreasing the errors twice.

Similarly to the STARSHINE 3 satellite, the ratios of standard deviations of prediction errors, obtained without density corrections, to standard deviations of prediction errors, obtained with density corrections, were calculated for all SO over the 10-month interval.

Fig. 15. Normalized Prediction Errors for the STARSHINE 3 Satellite

Fig. 16. Distribution of SD Ratios for Prediction Errors

The histogram of distribution of these ratios is presented in Fig. 16. We can see that the density corrections have increased the prediction accuracy by a factor of 1.6, on the average. And only for 1.3% of SO, this procedure has not resulted in decreasing prediction errors.

CONCLUSIONS AND RECOMMENDATIONS

1. The main source of errors in orbit determination and prediction for the LEO space objects is the inaccuracy of the upper atmosphere density model. The existing models do not estimate the current density variations to an acceptable accuracy.

2. The considered technique for monitoring the atmospheric density variations is based on using all available data on LEO satellite drag. At present, the daily number of accessible sets of orbital data equals some hundreds.

3. From April 2002 through January 2003, the orbital TLE data for several hundred LEO satellites catalogued by the US SSS, and also both the geomagnetic and solar activity indexes, have been gathered.

4. By secondary data processing of the accumulated data, smoothed orbits and the associated ballistic coefficients were determined.

5. The density fluctuations to the GOST model over the 18-month interval were constructed with a one-day step.

6. The comparative a posteriori analysis of orbit fitting and prediction accuracy for the chosen space objects without, and with taking into account the constructed fluctuations of density, has been carried out.

7. The applied technique and obtained results can be useful for the solution of a number of tasks connected with increasing the orbit determination and prediction accuracy of LEO satellites, for an estimation of errors of the upper atmosphere models and their improvement, and for analysis of physical processes in the upper atmosphere.

8. Construction of the density correction data over longer time intervals, including multiple 11-year solar cycles, is considered as the direction of future work.

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