REENTRY TIME PREDICTION USING ATMOSPHERIC DENSITY CORRECTIONS[1]

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ABSTRACT

Errors in the upper atmosphere density models have a significant influence on the accuracy of orbit prediction and, specifically, on the accuracy of reentry time prediction for space objects (SO). Determination of current time corrections to the atmosphere density and their use in orbit prediction is proposed as a method to increase the accuracy of reentry time prediction. The potential effect of increasing the accuracy of SO reentry time prediction, associated with accounting for the corrections to the NRLMSIS-00 atmosphere density model(Picone et al, 2002), is estimated for SOs having both spherical and nonspherical shapes. The use of the atmospheric density corrections provides visibility into the time variations of individual SO aerodynamic characteristics and allows their use in predicting the reentry time.

1. INTRODUCTION

Atmospheric density mismodeling was, and remains, the dominant error source in the orbit determination and prediction of LEO satellite orbits. To improve the accuracy of motion prediction for these satellites, it has been proposed to track the actual density of the upper atmosphere using the available drag data on the catalogued LEO satellites. The total number of such drag-perturbed SOs reaches several hundred at any given time. The element sets for these SOs are updated as an ordinary routine operation by the space surveillance systems. We use these element sets as the observation data for estimating the corrections between the actual atmosphere density and a chosen atmosphere density model. Recently we obtained the density corrections for the NRLMSIS-00 atmosphere model using the Two Line Element sets (Yurasov et al., 2005). Time series for the density corrections were generated on a one-day grid over a four-year interval from December 1, 1999, to November 30, 2003. Fig. 1 illustrates the time histories of the estimated correction parameters b_1 and b_2 for the NRLMSIS-00 density model. Using these data, everyone can independently estimate the corrections to the NRLMSIS-00 model density and take them into account in orbit calculations by the formula

$$\frac{\delta\rho}{\rho}(h,t) = b_1(t) + b_2(t)(h-400)/200 \qquad (1)$$

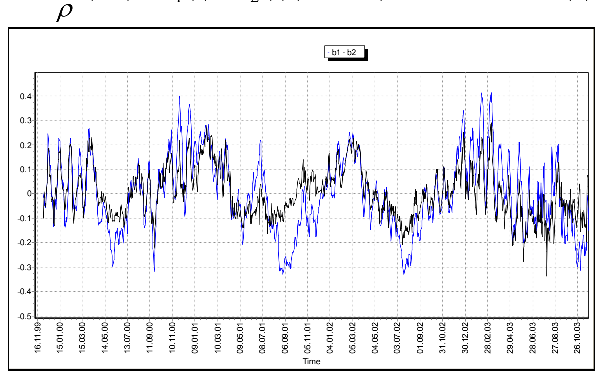

Figure 1. Estimated b_1 and b_2 density correction parameters for the NRLMSIS-00 model

The effectiveness of this process was evaluated by comparing the orbit determination and prediction results obtained without and with the constructed density corrections. The application of density corrections for the NRLMSIS-00 model reduced the scattering of ballistic coefficient estimates from 2 times for eccentric orbits up to 5.6 times – for near-circular orbits. The reduced scattering in the ballistic coefficient values indicates that the various complexities in the physics of the atmosphere are more consistently modeled with the density corrections. For the Russian GOST atmosphere model (Ref. 8), similar results were obtained previously (Yurasov et al., 2004). However, it is necessary to note that these corrections mainly account for un-modeled density variations at altitudes from 300 to 600 km. These estimates of the density correction effects cannot be extended to decaying SOs due to the following reasons:

1. *The deficiency of observation data used for construction of density corrections at low altitudes.* This fact is illustrated by Fig. 2, where the time-altitude distribution of

[1] This work was undertaken under an agreement between the Texas Engineering Experiment Station (ref. #D40005) and Dr. V. S. Yurasov from the KIA Systems, Moscow, Russia.

Proceedings of the Fourth European Conference on Space Debris, Darmstadt, Germany, 18-20 April 2005
(ESA SP-587, August 2005)

the drag observation data is given for all of 16 space objects used for the construction of the density corrections for the NRLMSIS-00 model. It is seen that at altitudes lower than 280 km, no drag measurements were obtained for some time intervals.

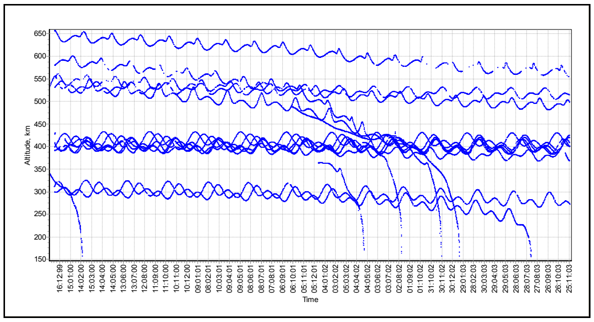

Figure 2. Time-altitude distribution of observation data

2. *The observed tendency of the relative errors in the density models to decrease with lower altitude.* We have obtained the altitude regressions for the RMS of the model relative errors using the constructed corrections at altitudes from 200 to 600 km. For the NRLMSIS-00 model, this regression relationship is as follows:

$$\sigma(h) = 1.04 + 0.0373\ h\,, \qquad (2)$$

where $\sigma(h)$ is expressed in percent and the altitude h is expressed in km.

3. *Increase in influence of the SO's attitude on the accuracy of motion prediction for reentry objects.* For the majority of SOs, at high altitudes this influence is small as compared to the un-modeled atmospheric density variations. However, if the SO orientation is not stabilized along the direction of incident airflow, the amplitude of the ballistic coefficient variations due to the SO rotation around the center of mass cannot decrease with orbit decay, as against the un-modeled atmospheric density variations.

4. *Time dependence of density variations.* It is not improbable, on the time interval corresponding to the final stage of SO orbital flight, that the density corrections have near-zero values. In this case it is senseless to expect any positive effect by accounting for the density corrections.

5. *Non-linear effects.* Unlike high altitudes, the atmospheric drag effect at low altitudes becomes so considerable, that the character of changing of atmospheric density and SO's orbital elements becomes essentially non-linear. At higher altitudes the atmospheric density values in the Orbit Determination fit and predict intervals differ not so significantly, as at lower altitudes. The linear model for density corrections that we have used (Eq. 1) may be unsuitable for the very low altitudes associated with reentry.

This paper studies the influence on the accuracy of reentry predictions of: (1) un-modeled density variations for the NRLMSIS-00 model and (2) variations in specific SOs' aerodynamic characteristics.

2. DESCRIPTION OF THE USED APPROACH

The technique for investigating the reentry objects is combined with the technique for monitoring the atmospheric density variations (Yurasov et al., 2004). The flowchart describing this technical approach is given in Fig. 3.

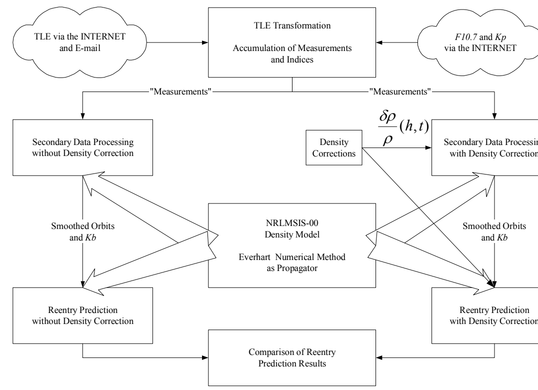

Figure 3. Flowchart describing the used approach

Let us consider the elements of the technical approach in detail.

1. To estimate the influence of un-modeled density variations on the errors of reentry time prediction, it is necessary to have a sufficiently large set of statistical data obtained under various conditions of solution of the given task. Therefore, the acquisition of real orbital data in the TLE format for several tens of space objects that decayed in years 2000-2003 was organized. The element sets for the chosen SOs were downloaded from the NASA OIG and the CelesTrak Web sites (Ref. 9, 10). The TLE sets were transformed into osculating orbital elements, which were considered further as noisy "measurements" during "smoothed" orbit and associated ballistic coefficient calculations.

2. The solar and geomagnetic activity indices were downloaded from the NOAA National Weather Service Space Environment Center (SEC) FTP-server (Ref. 11). All data were saved into the database.

3. For each "measurement" epoch, the smoothed orbit and the associated ballistic coefficient K_b were determined based on a least squares fit of the "measurements" created by transformation of the TLE elements. This least squares fit process is called "secondary data processing". A set of "measurements" corresponding to the time interval prior to the epoch of the smoothed orbit was chosen for each fit.

The fit interval used for the estimation of the smoothed elements and the associated ballistic coefficient depends on the satellite lifetime.

4. The complete version of the NRLMSIS-00 density model was used as a baseline model of the upper atmosphere density. The Everhart numerical method was used for the propagation of the satellite motion (Everhart, 1974) and the re-entry time estimation.

5. Similarly to step #3, the smoothed orbit and associated ballistic coefficients are determined a second time for each epoch of the "measurements" by taking into account the density corrections.

6. The influence of un-modeled density variations was evaluated by comparing the re-entry prediction results obtained without and with estimated density corrections. To obtain the comparable error statistics across all satellites and for different prediction intervals, a normalized re-entry error parameter is used. The ratio of the re-entry prediction error to the lifetime value was accepted as the normalized (relative) prediction error parameter

$$\varepsilon = \frac{\Delta t}{Lifetime} = \frac{t_{real} - t_{calc}}{t_{real} - t_0} \tag{3}$$

where t_0 is prediction epoch, t_{real} is the real re-entry time, t_{calc} is the predicted (calculated) re-entry time.

7. The a posteriori model of calculations was used, i.e. both on the measurements fitting interval and on the prediction interval the indices of solar and geomagnetic activity, as well as density corrections, were supposed to be known. In view of this circumstance the obtained results can be considered as potentially accessible or optimistic ones.

8. For the majority of chosen 95 SOs, the reentry time calculation was started, when the remaining lifetime became less than 10-18 days.

9. For altitudes lower than 180 km, the following formula was applied for calculating the density corrections instead of Eq. 1:

$$\delta\rho/\rho = \left[b_1(t) + b_2(t)(h-400)/200\right]\exp\left[(h-180)/30\right] \tag{4}$$

10**.** For determining the "true" values of reentry time for the chosen SOs, the results of reentry estimations obtained from several sources were used (Ref. 10, 12-14).

3. SPACE OBJECTS OF SPHERICAL SHAPE

At low altitudes, prediction errors caused by the attitude motion of a SO may become comparable with and even dominate over the effects related to un-modeled variations of the atmospheric density. In order to avoid mixing these two factors, we shall first consider the influence of density corrections on the motion prediction characteristics for space objects having a spherical shape. It is assumed that rotation around the center of mass does not change the ballistic coefficients of these SOs. Among the chosen SOs, only the satellites of the *Starshine* series had spherical shape. The characteristics of these satellites are presented in Tab. 1.

Table 1. Starshine satellites of spherical shape

SO#	Name	Inclination, deg	"True"decay time (UTC)
25769	*Starshine* 1	51.6	02/18/2000 15^h41^m
26929	*Starshine* 3	67.0	01/21/2003 05^h05^m
26996	*Starshine* 2	51.6	04/26/2002 11^h11^m

Let us consider in detail the results of reentry time predictions obtained for the *Starshine* 1 satellite. The *Starshine* 1 satellite decayed on February 18, 2000. Fig. 4 shows the plots of density corrections for the NRLMSIS-00 model from February 1 to February 19, 2000. These corrections are plotted for the altitude range from 100 to 600 km with a step of 100 km. Fig. 5 shows the plot for the time history of the perigee altitude of the satellite. Fig. 6 presents the estimates of the predicted reentry time for the final stage of the *Starshine* 1 lifetime. These estimates were obtained without and with density corrections for the NRLMSIS-00 model. In this figure, the abscissa gives the predicted orbit epoch, and the ordinate gives the predicted values of the reentry time. The data presented in Figs 4 to 6 indicates that at the beginning of February, 2000, the model density values at the perigee altitude of the *Starshine* 1 satellite were 10% greater than the real values of density. The density corrections were negative over all altitudes at that time. As the *Starshine* 1 orbit decayed, the actual density at its flight altitude smoothly increased. Therefore the reentry time predicted without density corrections gradually approached the reentry time predicted with density corrections (see Fig. 6).

Fig. 7 presents the histogram of the relative error distribution (see Eq. 3) for the *Starshine* 1 satellite. It can be seen from this plot that the application of the density corrections led to a decrease in the root mean square (RMS) of the relative error from 8.1% down to 1.4%.

Tab. 2 generalizes the data characterizing the influence of the density corrections to the NRLMSIS-00 model to include all the *Starshin*e satellites. It follows from the data of Tab. 2 that:

1. The application of density corrections to the NRLMSIS-00 model decreased the reentry time prediction errors for satellites of the *Starshine* series by factors of 5.7, 3.0 and 1.6.

2. The RMS values of the reentry time prediction errors were in the range from 4.9% to 8.1% before density corrections. These results are in good agreement with our estimates of the errors for the NRLMSIS-00 atmosphere

model expressed by Eq. 2.

3. The residual level of the RMS errors after density correction ranged from 1.4% to 3.1%; that is comparable to the errors in the density correction estimates for the NRLMSIS-00 model. This result is in good agreement with similar estimates for the spherical satellite 1980-37A (Nazarenko et al., 1991).

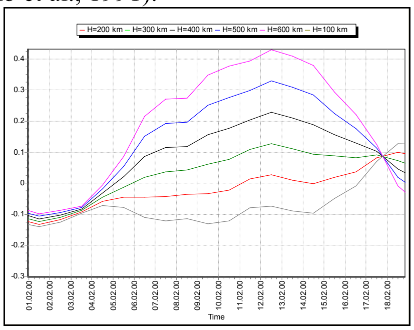

Figure 4. Density corrections for February, 2000

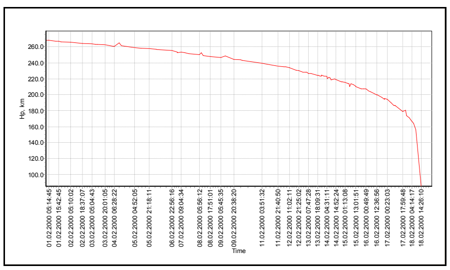

Figure 5. Perigee altitude vs time for Starshine 1

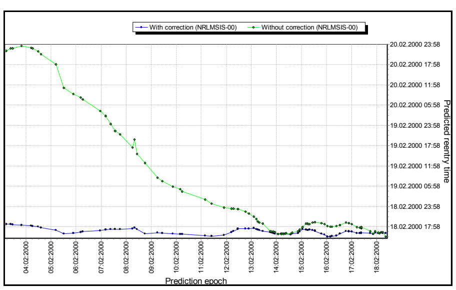

Figure 6. Reentry time estimates for Starshine 1

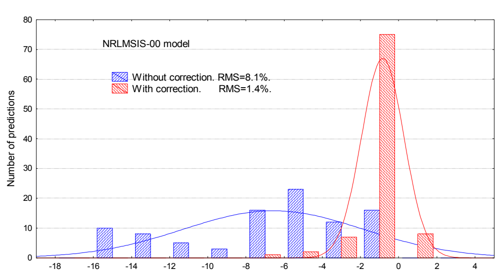

Figure 7. Distribution of relative errors for Starshine 1

Table 2. Statistics for reentry prediction errors for Starshine satellites

SO #	Number of predictions	RMS for relative errors of reentry prediction, %		Ratio of RMS
		Without density correction	With density correction	
25769	91	8.1	1.4	5.7
26929	65	6.5	2.1	3.0
26996	68	4.9	3.1	1.6

4. SPACE OBJECTS OF ARBITRARY SHAPES

In addition to the satellites of the *Starshine* series, estimates of the effect of density corrections on the reentry time prediction accuracy were carried out for 95 LEO space objects having arbitrary shapes. For the majority of these objects, the prediction interval was limited to 10 days. The average number of predictions for SOs in this group was equal to 31. The average value of the RMS errors in the reentry time for the case of predictions without density corrections is equal to 9.1%. The corresponding value of the RMS after density correction equals 6.9%, i.e. it decreased by 32%.

Fig. 8 shows the distribution of the ratios of the RMS of errors calculated for each SO without density correction to those calculated with density corrections. This distribution characterizes, in a generalized form, the effect of the application of the density corrections. A value of the ratio greater than one on this plot signifies that the accounting for the corrections resulted in an increase in the accuracy of the reentry time prediction. A value of the ratio less than one implies that the density corrections resulted in a decrease in the accuracy. It is seen from this plot that improvement of reentry time prediction accuracy took place for 72% of the SOs. On the average, the density corrections resulted in increasing the prediction accuracy by a factor of 1.66.

For 27% of objects, the accuracy worsened after the density corrections. Let's consider the objects of this subgroup in more detail. Fig. 9 presents a more detailed histogram of the distribution of the ratios for RMS lower than 1.0. For 40% (10 from 25) of the SOs of this subgroup, the RMS errors were virtually identical before and after the density correction. The main source of the reentry time prediction error for some of these SOs is the other factors, rather than the errors in the atmosphere density models. In particular, such a reason can be variations of the ballistic coefficient of the SO due to its rotation around the center of mass. The analysis of the effect of this factor and techniques for taking it into account are considered below.

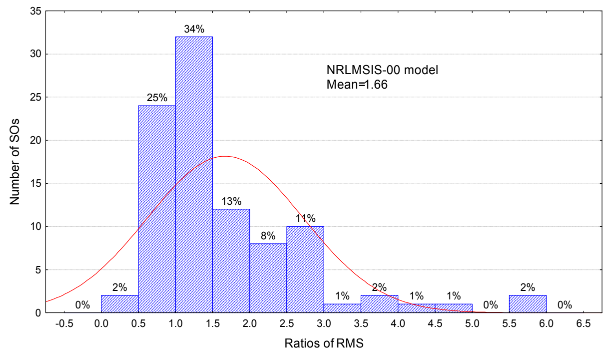

Figure 8. RMS ratios distribution for 95 SOs

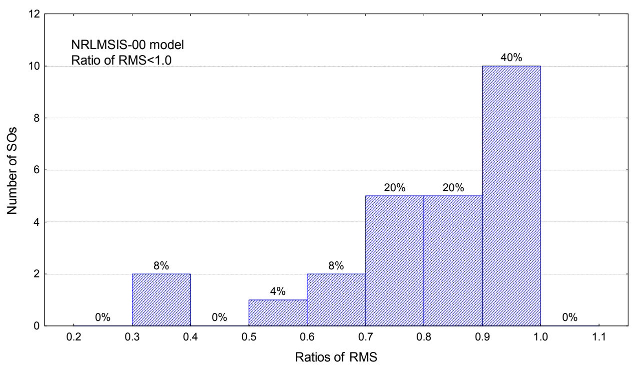

Figure 9. RMS ratios distribution for subgroup of 25 SOs

The analysis of the results for SOs having a ratio of RMS values less than 0.7 has shown that these objects have RMS values of errors before the density corrections that did not exceed 3%. This means that the reentry prediction accuracy was already very high for these SOs. A few percent decrease in the prediction accuracy after density corrections resulted in observable change in the ratio of the RMSs in these cases. One of the probable reasons for this can be the errors in the determination of the density corrections at low altitudes over the time intervals corresponding to reentry time of these SOs. This hypothesis requires additional verification, which can be a subject of a future investigation.

In conclusion, we should note that the obtained estimates of the influence of density corrections on the accuracy of reentry time predictions should be considered as potentially achievable. They were calculated under the condition that we know the corrections to the density over the prediction interval. Under real conditions these corrections are unknown. Therefore, the real effects obtained in a routine mode will be less. In this connection, one direction for improving the estimates in this mode can be the development of algorithms for forecasting the corrections to density and the improvement of atmosphere models.

5. SPACE OBJECT INDIVIDUAL FEATURES

One of the reasons that accounting for the density corrections may not increase the reentry time prediction accuracy is that the SO's aerodynamic characteristics are changing. Such features can be caused, for example, by long term character of the SO attitude motion. Variations of the ballistic coefficient value in some SO cases can become the main reason for motion prediction errors in the upper atmosphere. Analysis has shown that detection of such SOs is possible by comparison of their ballistic coefficients variations, obtained without and with density corrections.

Figure 10 presents the ballistic coefficient variations scatter plot obtained without and with the density corrections for the *Starshine* 3 satellite. The comparison of these data sets indicates that the application of density corrections to the model has eliminated the long-periodic variations in the ballistic coefficient estimates caused by the errors in the atmospheric density model. Before density corrections, the standard deviation (SD) of the ballistic coefficient values was 12.8% for this satellite. After application of the density corrections, the SD decreased down to 2.8%.

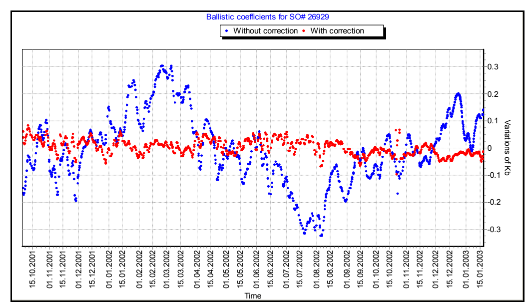

Figure 10. Ballistic coefficient variations obtained for Starshine 3 without and with density corrections

Fig. 11 shows the plots for estimates of the ballistic coefficient variations obtained with and without the atmospheric density corrections for SO #26124; this SO decayed on January 9, 2003. For this SO, the maximal estimates for the ballistic coefficient differ by a factor of five (5) from the minimal ones both before and after density corrections. The ballistic coefficient variation has a period of about 5.6 months.

Analysis has shown that all the decayed SOs of this kind were light-weight space debris and that they have large ballistic coefficient values (see Tab. 3). The common regularity in the ballistic coefficient variations of these SOs was their prominent periodicity with high amplitude, whose value was commensurable with the mean value of Kb. Along with the basic harmonic, whose period was different for various satellites and ranged from 8 days to 6.5 months, other periodic components were also present. The aerodynamic characteristics of individual SOs can be revealed by analysis of the histories of the ballistic coefficients obtained with density corrections. Further, these regularities can be used for forecasting the SO's ballistic coefficient variations and for the SO's reentry time prediction. The obtained results in this area show that prospective methods for the solution of this task can be an auto regression and ARIMA time series analysis and forecasting methods (Nazarenko et al., 1991, Kravchenko et al., 1992, Box & Jenkins, 1970).

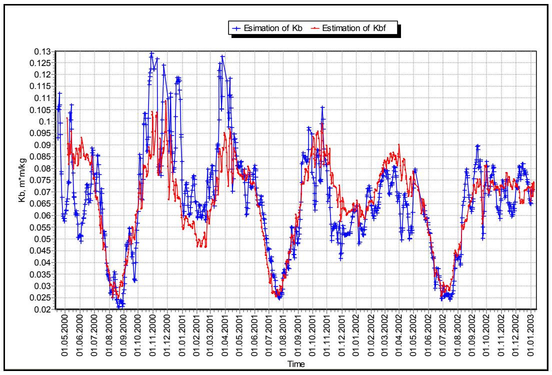

Figure 11. Ballistic coefficient variations obtained for SO#26124 without(Kb) and with(Kbf) density corrections

Table 3. SOs with large variations of ballistic coefficients

SO#	Decay date	*Kb*, m^2/kg	Number of realizations	SD of *Kb* variations, %	
				before corrections	after corrections
17131	08.12.2002	0.0638	424	24.5	32.6
24124	01.04.2003	0.1739	1955	30.4	26.3
24977	11.10.2002	0.7813	1539	33.4	32.5
26124	09.01.2003	0.0656	910	32.6	28.0
26428	20.05.2002	0.3214	835	40.3	28.9
27081	05.09.2002	0.0624	300	37.5	37.9
27113	23.05.2003	0.0737	567	36.5	34.4
27145	05.09.2003	0.0833	893	28.6	29.6

6. CONCLUSIONS

Increasing the accuracy of satellite reentry time prediction is a complicated scientific and technological problem. To solve this problem, it is necessary to use a comprehensive approach to account for all the significant factors.

The error in the upper atmosphere density model used in the satellite motion models influences the reentry time of all space objects (SO). One of the methods for decreasing the influence of this factor is the determination of current time corrections to the atmospheric density and the inclusion of these corrections in predicting the space object's reentry time. Analysis of changes of ballistic coefficient estimates, obtained with density correction, and finding the individual features of the evolution of the SO's aerodynamic characteristics also represent a direction for increasing the accuracy of SO reentry time prediction.

The directions of future work are connected with:

- Forecasting the atmospheric density corrections and their inclusion in the SO's reentry time determination
- Forecasting of SO's ballistic coefficient variations on the basis of revealed individual time regularities and their inclusion in the SO's reentry time determination

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