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Prediction of the space debris spatial distribution on the basis of the evolution equations

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ABSTRACT

The numerical–analytical technique for long-term prediction of the space debris (SD) spatial distribution, based on derivation and solution of new evolution equations, is developed. These equations are represented in two forms — difference and differential. In the latter case the problem is reduced to integration of the system of two ordinary differential equations. A high efficiency of the proposed technique, as compared to the traditional approach, is demonstrated.

1. Introduction

It is assumed that two factors have effect on the evolution of the space debris time–spatial distribution during the prediction of space debris contamination in the region of low orbits (LEO) [1–8]: the increment of a quantity of new objects as a result of launches, technological operations, explosions, accidents, etc., and the atmospheric drag that results in lowering the perigee altitude of space objects (SOs) and their reentry.

Two approaches are used for solving the considered problem. The traditional (*deterministic*) approach is widely applied by specialists. For example, NASA's contemporary "EVOLVE" model simulates the after-effect of all known satellites' launching and destruction events, as well as similar events possible in the future. For each object (or a group of objects) the vector of initial conditions is formed. Prediction is performed using the traditional motion models. To estimate the danger of collision of a pair of satellites D. Kessler's methods are used. The results have been summarized for a great number of objects. The distinction in modeling over the future time interval lies in the fact that all fragmentation events are formed according to the Monte Carlo technique. In this case several prediction operations are performed. Obviously, this approach is very labor-consuming; it can be implemented on rather powerful computers only. However, even on the contemporary large computers the traditional approach does not correctly predict the distribution of small-sized space debris fragments. The labor consumption in solving the problem in question can be judged by quotation from paper [8] given below:

> "As one of the more time consuming operations of our model deals with the orbital propagation of the sixth orbital elements for each objects of the population, the code of MEDEE has been designed to take advantage of massively parallel, computer system available at CNES. This means that the orbital propagation module has been parallelized, in order to propagate the population at each time-step over all available cores.
>
> The computer system in which MEDEE is executed is formed by 360 cores summing a total RAM of 24 Go and an overall computing power of 4 Tflops/second."

In spite of its labor-consuming character, this approach does not guarantee the model's adequacy. The accuracy of destruction after-effect modeling is unknown. The model

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tuning according to available measurement data turns out to be a rather difficult task.

Another (*statistical*) approach to formation of Near-Earth Space (NES) contamination sources and to the situation prediction is applied to the Russian Space Debris Prediction and Analysis (SDPA) model. Its main distinction lies in the fact that, instead of the data on particular launches and on SOs destruction events, the model uses the averaged data on SOs spatial distribution and on the number of yearly formed objects of various sizes. This particular approach is substantiated by the following reasons:

- The SD number varies insignificantly (by few percents only) during a year. Therefore, the more detailed (in time) modeling of SD sources is excessive; it highly complicates the model, virtually not influencing the accuracy.
  Note. This statement does not exclude the possibility and expediency of detailed modeling of breakup consequences for short time intervals, when the SD "cloud" remains rather compact. However, the cloud scattering process is known to proceed rather quickly, as a rule. The duration of this process is about 1 month.
- The reasons and conditions of satellites' fragmentations, which resulted in forming the majority of small-sized SD fragments, are extremely diverse. Therefore, one can hardly expect that results of modeling the consequences of all known fragmentations (the number of particles, the fly-away velocity) are accurate enough. The level of errors of such modeling is unknown. Hence, the approach, based on the averaged data, does not seem to be worse, but looks even more preferable.
- The previous statement is even more valid for the future time instants, where reasons and circumstances of fragmentations are unknown. The use of the averaged data on the intensity of new SD formation seems to be optimal for performing the predictions.
- One more reason in favor of applying the averaged data on new SD formation intensity is based on the fact that the averaged data contain a smaller number of parameters in comparison with the detailed data. It is known that the minimum number of any prediction model's parameters to be updated on the experimental data basis is desirable under conditions of limited measurement information. Therefore, the model having a smaller number of parameters to be tuned will provide better prediction accuracy as compared to models having a larger number of such parameters.

In the Russian SDPA model, during the situation prediction with allowance for atmospheric drag of SOs, various objects with perigee altitude <2000 km are considered. We shall suppose that among all variable SO parameters only the perigee altitude essentially influences the evolution of altitude distribution of SO number. The other orbital elements will be designated by *Э*. We subdivide the whole set of objects with different elements *Э* into some finite number of sub-sets (groups) with elements $Э_l$, $l=1,2,\ldots,l_{max}$. Let $p(t,h)$ be the density of the perigee altitude distribution for objects from the selected group at time t. Then we state the problem of studying the laws of density variation in time. Index l will be omitted hereafter in analyzing the distribution evolution for some particular SO group.

In calculating the evolution of altitude distribution of SO number the following factors are taken into account: the atmospheric drag at altitudes of up to 2000 km; the sub-division of all SOs in parameters into the groups which differ in size d, eccentricity e and ballistic factor k_b; the initial altitude distribution of SOs of various types; the expected intensity of formation of new SOs of various types as a result of launches and explosions: $p(h,t)_{new}$ is the increment of SO number at various altitudes per time unit; the non-stationary character of factors is taken into account; namely, the atmospheric density in connection with solar activity variation during the 11-year cycle.

The perigee altitudes are of special importance among the listed orbital parameters taken into account. While rendering the basic influence on orbit lowering, it changes (the perigee altitude is finally lowered resulting in SO reentry). Therefore, the perigee altitude is one of the arguments of evolution equation and it does not enter the partition. The ballistic factors and SO size have absolutely different character of influence: they do not virtually change during the orbital evolution process. The eccentricity has intermediate character of influence: it changes, generally speaking, under the atmospheric drag effect, but this change does not play an essential part, because large parts of SOs have orbits with low eccentricities.

2. Derivation and solution of evolution equations

Let us consider the technique for prediction of the distribution of SOs $p(h,t)$ in the perigee altitude. We will derive the relationship for determining this density at various altitudes at the time instant $t+\Delta t$. In the discrete partition of argument h over some specified interval with the step Δh the initial distribution $p(h,t)$ is specified on this grid of the values of arguments.

Fig. 1 depicts the values of distribution $p(h,t)$ for two values of argument h and $h+\Delta h$. The number of objects in

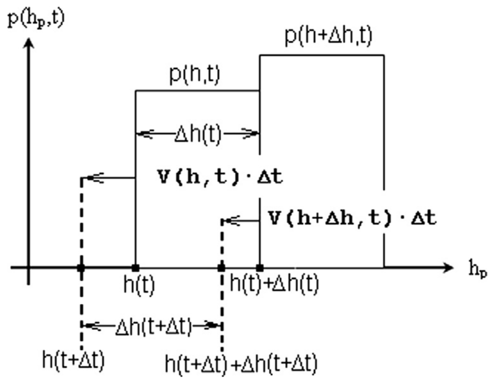

Fig. 1. Scheme of change of SO distribution in the perigee altitude. Scheme of change of SO distribution in the perigee altitude.