Comparison of Space Debris Models in the Centimetre Size Range

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ABSTRACT

In this paper a comparison of the reference populations of current space debris models is made. In order to allow a meaningful comparison, the populations were extrapolated to January 1997. The following space debris models were compared: ORDEM96, EVOLVE (NASA), MASTER (ESA), CHAINEE (TU Braunschweig, Germany), SDM/STAT (CNUCE, Italy), IDES (DERA, UK) and a Russian model by Nazarenko. Most of these models are evolutionary models, i.e. they model the space debris sources like launch traffic, explosion and collision rates and then propagate the created objects. However, they are limited in modelling unknown debris sources which were detected by radar. Therefore, there remain considerable differences between the models themselves and between the models and the radar measurements. These differences are analysed.

1. INTRODUCTION

The earliest space debris environment models covering also undetected orbital debris were developed by Kessler in the 1970's (Ref. [7]). Subsequently in the USA (mainly at NASA), in Europe and in Russia different approaches were followed to model the space debris environment. There are three basic types of space debris models (Ref. [9]): support models, evolutionary models and engineering models. Support models *support* the analysis of the space debris environment and cover specific topics, e.g. traffic models, satellite breakup models, atmospheric drag models and flux models. Evolutionary models consist of a set of support models tied together to predict the changing orbital debris environment. They are based on a historical population which was created by simulating the known on-orbit fragmentations. Examples are EVOLVE (NASA), SDM/STAT (University of Pisa, Italy) and IDES (DERA, UK). The third catagory are engineering models. They combine the outputs of other orbital debris models with measurements of the environment to produce an environment definition model that can be used by spacecraft design engineers.

The first engineering model was developed by NASA in 1985 (Ref. [8]). It underwent a number of changes based on the measurements mainly by the Long Duration Exposure Facility (LDEF) satellite, the Haystack and Goldstone ground radars, and the US Ground-based Electro-Optical Deep Space Surveillance System (GEODSS) telescopes. In November 1996, the latest NASA engineering model, ORDEM96, was published (Ref. [10]). In Russia, a semi-analytical stochastic model was developed by Nazarenko (Ref. [11]). The parameters of this model were recently adjusted to match the Haystack data of 1990 to 1994.

Already in 1992, long before the speculations began about the Sodium-Potassium particles at altitudes around 900 km, it became clear that the evolutionary models fail to generate enough centrimetre and subcentimetre sized objects when simulating the historic on-orbit breakups (Ref. [5]). The flux at that size range which was predicted by evolutionary models was sometimes one order of magnitude or even more below the values predicted by the NASA engineering model of 1989. One possibility to over-

Proceedings of the Second European Conference on Space Debris, ESOC, Darmstadt, Germany, 17-19 March 1997, (ESA SP-393, May 1997)

come these discrepencies were the introduction of scaling factors. However, the question remained, how accurate are our present space debris models?

In the following, the most common space debris models will be shortly described. In order to be able to compare the various models the altitude dependent spatial density of 1 cm objects and their number will be calculated for an epoch of 1 January 1997. (The extrapolation to 1997 covers the breakup of the Pegasus/HAPS vehicle which took place on 3 June 1996 and which created a significant number of 1 cm objects. Since none of the models took into account this breakup, the comparison made in this paper is not affected by that event. But it should be remembered that the populations referred to below are all lacking the fragments of that event.)

2. SPACE DEBRIS MODELS

In this chapter the assumptions will be presented which the various space debris models adopt in order to calculate the spatial density on 1 January 1997. For detailed information about a model the reader is referred to the indicated reference paper which provides a more in-depth description of the model. It must be stressed that the results mainly depend on the initial population rather than on the traffic and explosion models used for the short extrapolation in time. This is especially true for CHAINEE and SDM/STAT, which were designed to model the long-term evolution of the space debris environment. For this purpose, the trackable population is much more important than the centimetre sized objects, because they are normally too small to cause catastrophic collisions, i.e. collisions which lead to a complete breakup of the target satellite. Anselmo (CNUCE) and Eichler (Lockheed/NASA) argue that errors in the assumptions about the 1 cm populations hardly influence the collision cascading effects to be seen in long-term simulations. Likewise EVOLVE was not designed to pinpoint a distribution for a specific year. Nevertheless, these models were included in this analysis, because this shows how different the current 1 cm population is assessed by various modelling groups.

2.1 Nazarenko's model

Nazarenko developed a semi-analytical stochastic model for medium and long-term forcast of the LEO debris environment. It was first presented at the First Europen Conference on Space Debris (Ref. [11]). Meanwhile this model was updated taking into account the Haystack data of 1990 to 1994 (Ref. [17]). The space debris distribution of fragments of various sizes was constructed by modelling the process of technogeneous contamination as observed in the past (1960-1995). The annual increase $q(h,d)$ is assumed to be constant. Here h is the altitude and d is the object size. The annual increase is assumed to be proportional to the number of catalogued objects:

$$q(h,d) = k(d) * q_{cat}(h)$$

where q_{cat} describes the altitude distribution of the catalogued objects. The factor $k(d)$ is derived from experimental data and is 36 for d = 1 cm (Ref. [12]). Since the model parameters were adjusted using the Haystack data this model takes into account non-fragmentational debris sources.

2.2 MASTER

The Meteoroid And Space debris Terrestrial Environment Reference (MASTER) model was developed at TU Braunschweig, Germany under ESOC contract (Ref. [15]). The MASTER reference population refers to an epoch of 1 April 1996 and consists of a sample of about 250 000 objects, which represent a total population of about 400 million objects of 0.1 mm and larger. This population was created by simulating all known breakups that happened before April 1996. To extrapolate in time, the numbers of the reference model were increased by 4 % a year, which means an increase of 3 % during the 9 months of extrapolation to our target epoch of 1 January 1997.

By mere simulation of the historic breakups, the created population is not able to predict a realistic debris flux in the size range below 10 cm because the number of small objects is underpredicted. Therefore, a size dependent correction factor was introduced to bring the MASTER predictions in line with measurements obtained from surfaces returned from space and with radar data. At 1 cm, the factor is 10.2. Overall the total number of objects larger than 1 cm has increased by a factor of 4.4. MASTER can be classified as a hybrid model, with evolutionary features (for building the reference population) and with engineering features (due to its "flux increase factor").

2.3 ORDEM96

ORDEM96 is the name of the computer program for a semi-empirical orbital debris model developed at NASA (Ref. [10]). It combines direct measurements of the environment with the output and theory of more complex orbital debris models. It approximates the environment with six different inclination bands. Each band has a unique distribution of semi-major axis, for near circular orbits, and a unique perigee distribution, for highly elliptical orbits. In addition, each inclination band has unique size distributions which depend on the source of debris. The distributions for smaller sizes are adjusted to be consistent with the flux measured by ground telescopes, the Haystack radar, and the Goldstone radar as well as the flux measured by the LDEF satellite and the Space Shuttle.

The formulae given in Ref. [10] refer to an epoch of Jan. 1995. The extrapolation in time is implemented via a growth factor which is currently fixed at 4 % linear increase per year (w.r.t. the 1995 population) for all inclination bands except for the 7° inclination band where an increase of 8 % per year is assumed.

2.4 EVOLVE

EVOLVE was developed at NASA Johnson Space Center. It uses as input data the historical record of launch traffic and mission model data for future traffic. Breakup models are used to determine the distribution of debris fragments resulting from collisions or explosions occurring in orbit. In 1996 solid rocket motor (SRM) particles and a 65°-inclination population were added.

Before the two populations were added, the number of 1 cm objects as of 1 Jan. 1995 was 50215 (Ref. [3]) which gives 54232 objects as of Jan. 1997 if a linear annual growth rate of 4 % is assumed. In order to give an approximation of the number of 1 cm objects of the new EVOLVE model, a flux curve for Jan. 1995 presented in Ref. [14] was converted to spatial density by assuming an average relative velocity of 7 km/s. By multiplying the spatial density with the volume of the altitude bins and adding 8 % for the two years of extrapolation a number of 104,000 objects was obtained.

2.5 IDES

The Integrated Debris Evolution Suite (IDES) was developed at the Space Department of the Defence Research Agency at Farnborough, UK (Ref. [18]). IDES models the debris population greater than 10 microns by simulating the past 133 known fragmentation events and evolving the population containing the generated fragments to an epoch of 1st January 1996. At this date, the launch-related objects in the USSPACECOM catalog are added to the deterministic population greater than 10 cm which is represented by individual objects. The population below 10 cm is represented by a statistical fragment orbit matrix containing the number of objects in discrete bins with dimensions of perigee radius, eccentricity, inclination and mass. The IDES 1996 environment model is then used as the initial conditions for making future long-term debris evolution projections with a detailed future traffic model. Satellite risk assessment is available in current and future predicted environments.

The IDES 1996 centimetre-sized population of 145,000 objects in or intersecting LEO was derived by using a new power law for the mass distribution of high intensity explosions (see Ref. [18]). In order to reach an epoch of 1st January 1997 for this comparison, IDES propagated its 1996 population by a year along with 208 objects added by the future traffic model and fragments from 4 explosions predicted during the one year evolution.

2.6 SDM/STAT

The Semi-Deterministic Model (SDM) and the STochastic Analog Tool (STAT) were developed at CNUCE/CNR, Italy (Ref. [1]). SDM is a pure evolutionary model which simulates individual launches, explosions and mitigation measures based on user defined scenarios and single collisions based on calculated collision probabilities. STAT is a kind of particle-in-a-box model grouping objects in semimajor axis/eccentricity/mass bins, with similar software for the debris sources, but with a different propagation method for the objects. Since they are based on the same initial population of 1 Jan. 1994 (CNUCE 1994.0 Orbital Debris Reference Model, Version 5.1, Ref. [1]), the differences between SDM and STAT are negligible. Therefore, only the results of SDM were used for this paper.

The extrapolation in time comprised three years (Jan. 94 to Jan. 97). The annual launch rate was taken as 90 (although the actual values were 89, 74 and 73 for the years 1994 to 1996). The average explosion rate in LEO was set to 2.8 per year and no catastrophic collision was triggered by the random number generator during these three years.

2.7 CHAINEE

CHAINEE is the European extension of CHAIN which was developed by Eichler at TU Braunschweig, Germany and which is now in use at NASA/JSC. It is a particle-in-a-box model, with 4 altitude bins and 5 mass bins. The original population of 57 972 centimetre-sized objects was replaced by the population of the 1995 MASTER model (without applying the scaling factor). The new population consists of 31 143 centimetre-sized objects and refers to an epoch of 1 Jan. 1995.

The propagation of objects from higher altitude bins to lower bins and the removal from the lowest bin is controlled via functions which describe the mass dependent decay of satellites. Input from launches and explosion are defined by two 4x5 matrices defining the annual increase in the altitude and mass bins. For the two years of extrapolation to 1997, the matrices for business-as-usual were taken as given in Ref. [2]. The components of the "growth matrix" range from 0 to 7.25 % linear annual increase. It must be stressed, that the obtained results have to be mainly attributed to the starting population rather than to CHAINEE because of the very short extrapolation period.

3. MODEL PREDICTIONS

In Fig. 1 the spatial density of the 1 cm objects is given for the seven models for an epoch of 1 January 1997. The spatial densities are direct outputs from the software of the corresponding models except for ORDEM96 and CHAINEE where the spatial density was derived from the number of objects given for specific altitude or perigee bins. For CHAINEE this was straightforward because objects are allocated to one altitude bin only. Therefore, the density can be calculated by simply dividing the number of objects in an altitude bin by the volume of that bin. In the case of ORDEM96 there are objects in eccentric orbits with a fixed apogee altitude of 20 000 km. For these objects, the residence probabilty in 50-km wide altitude bins were calculated and summed up.

From Fig. 1 it becomes obvious that only ORDEM96, the new EVOLVE and Nazarenko's model describe the sharp peak at 900 to 1000 km altitude which was observed in the Haystack data, because the evolutionary models (except the new EVOLVE) do not include the spherical particles at 65° inclination. At altitudes below 900 km MASTER is close to the two engineering models of NASA and Russia. The four other models are a factor of 2 to 6 below the NASA model. At 1500 km, the two engineering models show a much sharper peak than the evolutionary models. The reason is that the evolutionary models smear out the fragments coming from breakups at that altitude around this peak, which results in flatter spatial density curves.

From the spatial densities it is possible to derive the average number of 1 cm objects in LEO (N_{LEO}). The following summation is done:

$$N_{LEO} = \sum SD(i) \cdot Volume(i)$$

where $SD(i)$ is the spatial density of altitude bin i. The volume of this bin is:

$$Volume(i) = \frac{4}{3}\pi(r_i^3 - r_{i-1}^3)$$

with r_i and r_{i-1} being the limits of the altitude bin i. The results of these summations are given in Table 1:

Space Debris Model	Number of objects
Nazarenko	222 000
MASTER	154 000
ORDEM96	145 000
EVOLVE (new)	104 000
IDES	83 000
EVOLVE (1995)	54 000
SDM/STAT*	47 000
CHAINEE*	33 000

Table 1. Number of 1 cm objects in LEO (0-2000 km) on 1 January 1997 according to different models (*Results depend on the chosen initial population rather than on the programmes themselves).

As it can be seen in Table 1, the number of 1 cm objects in LEO varies from 33 000 to 222 000. This is a factor of 6.7 which describes quite well the result of different model assumptions at this size regime.

The differences in the evolutionary models itself can mostly be explained by the different breakup models. In Ref. [16] the breakup models of MASTER (used for the CHAINEE initial population), IDES, EVOLVE and SDM/STAT are compared. Whereas the models show a good agreement at low-intensity explosions, the differences in the high-intensity explosion models are considerable. Since the 1 cm population is dominated by fragments created by high-intensity explosions, the differences in the total number of simulated objects mainly comes from the fragment-mass distribution function used for high-intensity explosions. MASTER, EVOLVE and SDM/STAT use a similar model. However, IDES simulates many more 1 cm objects. That explains why the IDES population is nearly double as high as the other three evolutionary models. Different assumptions for the delta-velocities and for the mass-to-diameter conversion formula influence the lifetime of the fragments and further increase the differences.

The differences between the evolutionary models and the engineering models cannot fully be explained by the 65° spherical population at 700 to 1000 km altitude. Also below 700 km the evolutionary models are up to a factor 6 below the values which would fit the Haystack data. Zhang [19] came to the conclusion that the current breakup models need to be revised, because measurements on LDEF showed that there are much more small particles (below 1 mm) than can be simulated by explosions. The discrepancies are decreasing towards larger particles, however, still at 1 cm the MASTER model used a scaling factor of 10.2 to correct for these deficiencies of the standard breakup models.

4. ACCURACY OF THE MODELS

The only possibility to assess the accuracy of the presented models is the comparison with measurement data. For the time being the Haystack radar is the only source in the 1 cm size range providing statistically relevant data. The confidence we can place in these measurements depend to a large extend on the number of observation hours. In Ref. [4] a confidence interval was calculated for the estimated number of objects in an altitude bin. The idea is that an unknown number N of objects cross randomly the radar beam. The probability for one object to cross the beam in the time interval is p. The random variable describing the number of detections has a binomial distribution $B(N,p)$, which can be approximated by a Gaussian distribution. Let n be the number of detected objects and c the q-quantile of the Gaussian distribution (c = 1.96 for a confidence level of 95 %, or c = 2.58 for 99 %) then with $b = 2n + c^2(1-p)$ the following confidence interval can be calculated:

$$\left[\frac{b-\sqrt{b^2-4n^2}}{2p}, \frac{b+\sqrt{b^2-4n^2}}{2p}\right].$$

In Fig. 2, the confidence interval for the number of 1 cm objects in the 950-1000 km altitude is depicted as a function of observation time t. The number of detections n was assumed to be 0.5 per hour (see Ref. [13]), and

$$p = \sqrt{\frac{\mu}{(h+R_E)^5}}\frac{h\cdot\tan(0.058°/2)}{\pi^2\cos 42.6°}\cdot t$$

with the mean altitude $h = 975$ km (see Ref. [4]). It can be seen, that measurement campaigns of a few days give only coarse estimates of the actual number of objects. With the Haystack radar about 500 hours of data in Zenith mode were collected until 1993 (Ref. [17]), and thus it can be inferred with 99 % confidence that the number of objects in this altitude bin was between 12900 and 17800. For a confidence level of 95 % the width of the interval is reduced to 3700. The relative uncertainty (width of the interval divided by centre of the interval) can be approximated by $2c/\sqrt{n}$. Thus, the uncertainty in the estimated number of objects based on 500 hours Haystack data is about ± 15 % at that altitude ($n = 250$, $c = 2.58$). At 600 km altitude the uncertainty increases to ± 65 % ($n = 15$). On top of these statistical uncertainties, those inherent in the radar measurements (e.g. conversion from RCS to debris size) and those in the assumptions on detectability (which influence the probability p) have to be considered. Therefore, the quoted error bars of ± 15 % and ± 65 % are a bit too optimistic.

ORDEM96 agreed nearly perfectly with the Haystack data for the 950-1000 km altitude bin in 1993 [17]. If we neglect the errors introduced by the extrapolation to 1997, then the number of 1 cm objects in that bin is between 15500 and 20900 which corresponds to a spatial density between 4.5 and $6.1 \cdot 10^{-7}$ objects per km^3. Because no evolutionary model except the new EVOLVE takes into account the 65° spherical population, they are all underpredicting the spatial density at that altitude. At an altitude of 700 to 750 km, ORDEM96 overpredicts the Haystack results by about 50 % (Ref. [10]). Again neglecting extrapolation errors, the confidence interval for the spatial density in that altitude bin extends from 1.0 to $1.7 \cdot 10^{-7}$ objects per km^3. In Fig. 1, it can be seen that only EVOLVE and IDES are inside this interval, whereas MASTER and ORDEM96 are about 20 % above. The other models reveal larger discrepancies at that altitude.

Conclusions about the accuracy of the presented models at altitudes above 1300 km become speculative because at that altitude neither sufficient radar data nor material retrieved from space is at hand to verify the models. The Haystack data (except the 81 hours of 90° extended range) covers only altitudes up to 1250 km. In ORDEM96 the sharp peak at 1500 km observed for trackable objects was extrapolated to smaller objects. However, since the 1 cm population is mainly created during high-intensity explosions, where high delta-velocities are imparted to the fragments, it is more likely that the flatter distributions of the evolutionary models give a better approximation of the real situation.

5. CONCLUSIONS

The number of objects larger than 1 cm in low Earth orbit in January 1997 varies between 33 000 and 220 000 according to the major debris models in use world wide. When the spatial densities are compared, differences of up to a factor of 10 can be found (Fig. 1). Since there are more than 500 hours of Haystack data (Zenith mode) available for altitudes up to 1250 km, the accuracy of the debris models can be judged with a certain confidence. Spatial densities derived from Haystack data have error bars of only about ± 65 % (at 600 km altitude) to ± 15 % (950 km).

In general, the evolutionary models which are based on simulations of the known on-orbit breakups show a considerable lack of centimetre and sub-centimetre sized objects. The breakup models which fail in providing enough small fragments are a main reason (see Ref. [6]). A second reason is that non-fragmentation debris sources like the 65° spherical population at 700 to 1000 km altitude and SRM slag particles are not yet considered. Upgrades in this respect are planned or already implemented in new versions for all the models. Beyond 1250 km firm conclusions are difficult to draw. However, it seems likely that the peak at 1500 km is not as prominent for the 1 cm population as predicted by the engineering models.

6. ACKNOWLEDGEMENTS

The authors would like to thank Alessandro Rossi and Peter Wegener for supplying the spatial density data for the SDM and MASTER model. Likewise they thank Nicholas Johnson, Don Kessler, Luciano Anselmo, Peter Eichler and Jörg Bendisch for their useful comments.

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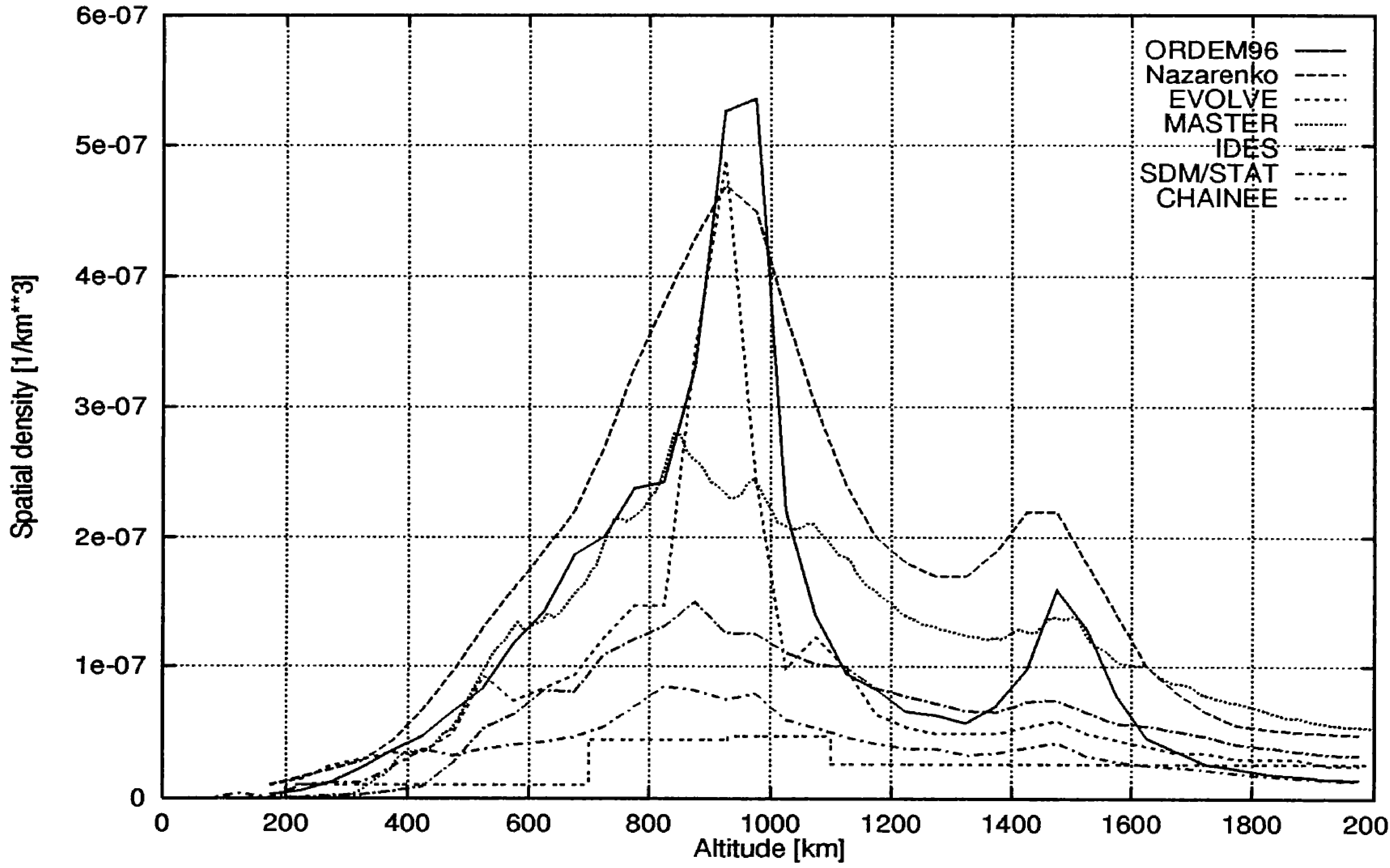

Figure 1: Spatial density of 1 cm objects on 1 January 1997 according to different space debris models.

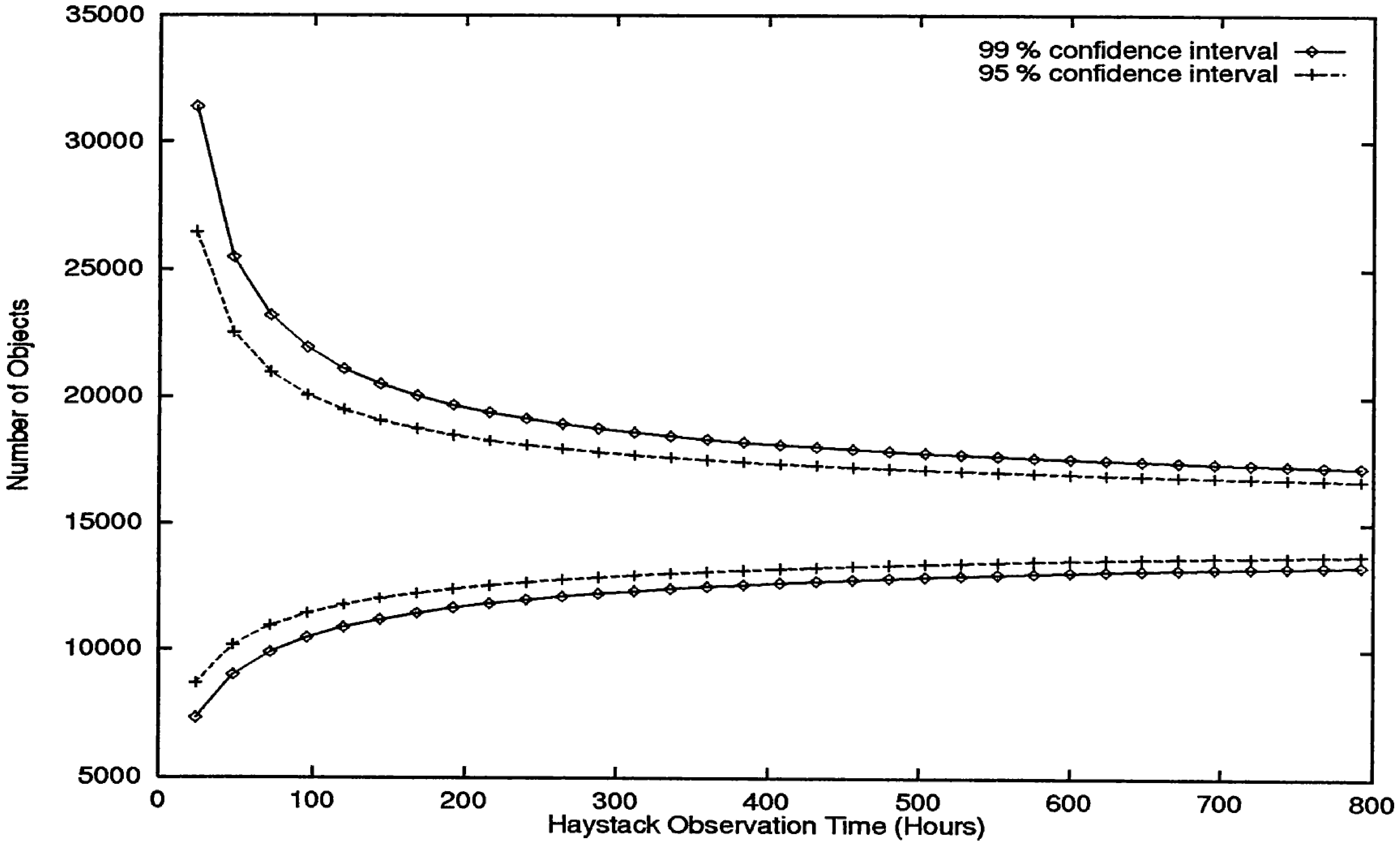

Figure 2: Estimated number of objects in altitude bin 900-950 km in 1993 as a function of Haystack observation time. The intervals are given for two confidence levels (markers are in steps of 1 day).