

THE LONG-TERM EVOLUTION OF DEBRIS ORBITS IN VIEW OF SPATIAL OBJECT ACCUMULATION

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ABSTRACT

The long term orbital behaviour of a debris object over decades and centuries decides on its potential collisional threat to other objects. Special orbits are subject to peculiar perturbations, e.g. due to resonances, which may lead to early elimination from space as well as to long term accumulation, posing a collision risk to regions not anticipated. In order to assess such influences, many objects with a variety of orbital elements have to be propagated with adequate precision over a long time. At the IFR a software tool named LOPEX has been developed, combining good short-term prediction results with the capability of very fast propagation over several centuries. Following a brief introduction of the LOPEX tool, some examples are given of long-term behaviour on presently used orbits as well as on orbits planned to be used in the future. The propagator LOPEX has been implemented in the new long-term debris environment model LUCA. This combination enables high resolution projections of the future debris population considering collisions and debris mitigation.

1. INTRODUCTION

Long term modeling of orbital debris is established in a number of research institutes and companies all around the world. This modeling typically covers some decades to about 100 to 200 years in the future. Since there are a number of uncertainties introduced, e.g. by the break up models used or by the traffic assumptions, the orbit mechanics often is applied by a certain degree of accuracy only. The reduced accuracy is considered sufficient, especially due to the small computer time requirements dedicated to it.

In general, the above arguments may apply especially for first order evaluation and analysis. But, if one looks into some details of the long-term behaviour of earth orbits, one can identify a number of cases which are of interest with respect to the evolution of the spatial density with time. In particular, these effects are not stochastic influences on e.g. the orbital lifetimes of debris objects. Stochastic influences do not require specific effort during the modeling process. They can

be treated as some kind of noise. This paper addresses the effects, that can be characterized as bias. Hence, neglecting such effects may lead to systematic uncertainties and miss-interpretation of the results.

Any type of higher order analysis raises the computation time. A tolerable compromise between the accuracy and the computation time need must be achieved in order to obtain analysis tools which can be used on a 'typical work bench' of a space debris analyst. For this purpose it is essential to study the relevant interactions of the orbital perturbations and the parameters of influence in detail with regard to the spatial density. This has to be performed for a number of orbits, starting from LEO and reaching up due the geostationary altitude regime.

In the frame of this paper it will be shown, that the often used debris sub-populations (LEO, MEO, SSCO, GEO, etc.), which appear to be independent from each other, may interact significantly due to orbit mechanics.

2. THE ORBIT PROPAGATOR LOPEX

At IFR TUBS the orbit propagator LOPEX (Ref. 2) has been developed in order to enable time efficient analysis of the long term evolution of debris orbits. All relevant perturbations (forces due to the non-spherical gravitation potential of the earth, atmospheric drag, lunisolar perturbations, solar radiation pressure) and their coupling effects as well as resonance effects are considered. Special efforts have been made with respect to the lunisolar perturbations, since these perturbations have the ability to introduce 'bias' into the orbital evolution.

LOPEX is a stroboscopic code, its flow chart is given in Fig. 1. For the purpose of fast computation a set of analytically derived formulae is implemented. These formulae describe the long periodically and secular perturbations. An example is given in Eq. (1) for the changes of the eccentricity with time due to solar gravitational perturbations. The typical computer time

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need for the calculation of the orbit evaluation is 0.001 to 0.005 s per object and simulated year. The program has been verified and tested and its accuracy has been proven.

3. EXAMPLES FOR LONG-TERM EVOLUTIONS OF DEBRIS ORBITS

In the following some examples obtained by LOPEX are given in order to underline the influence of the long-term evolution of debris orbits in view of the spatial density development. In Fig. 2 the perigee altitude of a low inclined GTO object is given as a function of time. Due to the lunisolar perturbations there is a variation with time depending on the initial conditions. There are two curves given in Fig. 2, valid for objects with different mass to area ratios. One would assume, that the object with the smaller mass to area ratio will have a shorter orbital lifetime.

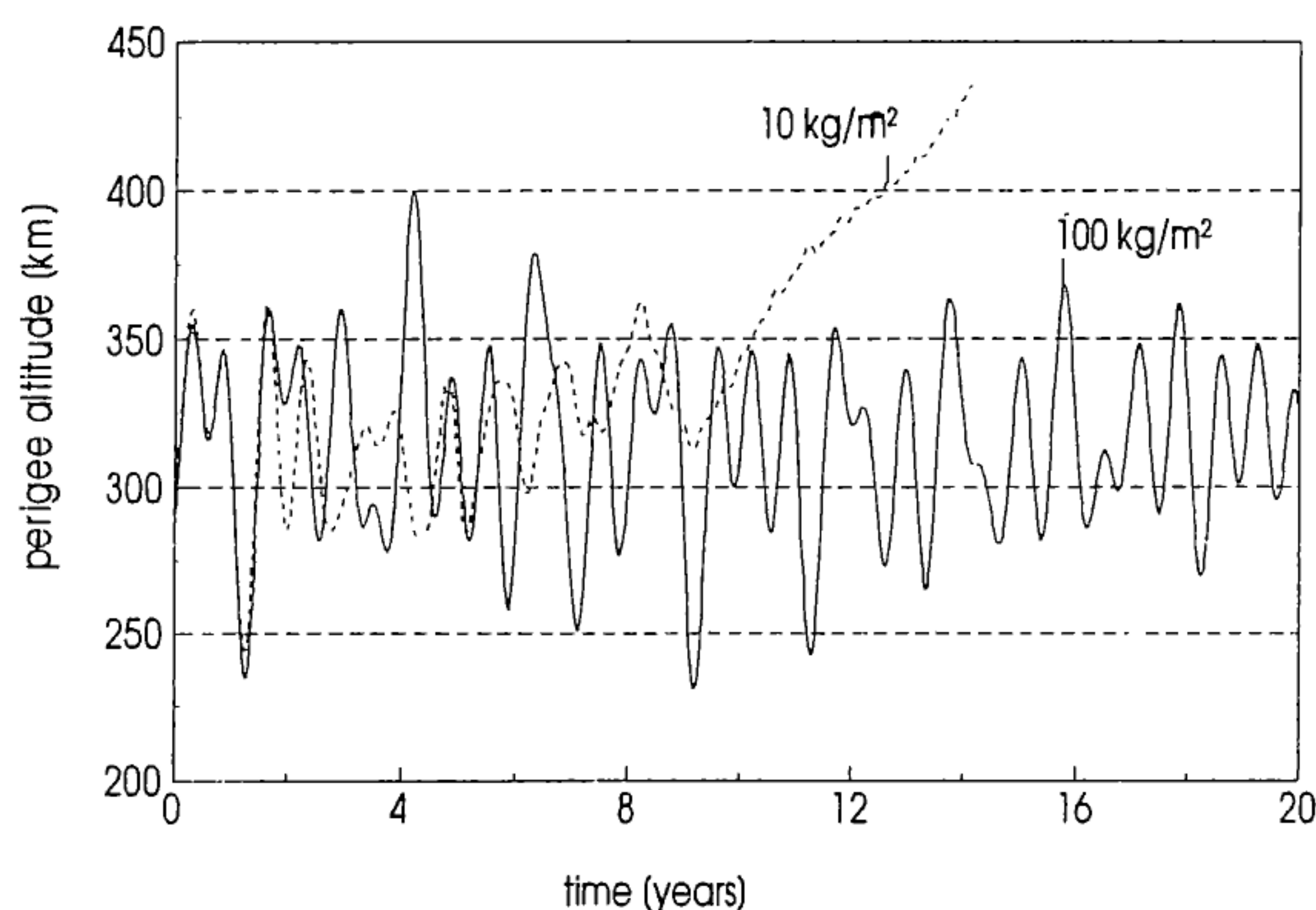


Fig. 2 The perigee altitude of GTO due to lunisolar perturbations as a function of mass to area ratio and time (example: $i=28.5^\circ$)

$$\dot{e}_{so,m} = -\frac{15 \pi K_{so} e \sqrt{1-e^2}}{4 [u_{so}(t0) - u_{so}(t1)]} \left[2\cos(2\omega) \left(\{ \sin^2 u_{so}(t0) - \sin^2 u_{so}(t1) \} \{ c_1 c_6 + c_1 c_3 c_5 - c_2 c_3 c_4 - c_2 c_6 - c_2 c_3 c_5 \} + \{ u_{so}(t1) - u_{so}(t0) \} \{ c_1 c_3 c_4 - c_2 c_6 - c_2 c_3 c_5 \} \right) + \right. \\ \left. + \sin(2\omega) \left(\{ \cos^2 u_{so}(t0) - \cos^2 u_{so}(t1) \} \{ c_1^2 - c_2^2 - c_5^2 - c_3^2 c_5^2 + c_3^2 c_4^2 - 2c_1 c_2 - 2c_3 c_4 c_6 - c_3^2 c_4 c_5 - c_3 c_5 c_6 \} + \right. \right. \\ \left. \left. + \{ u_{so}(t1) - u_{so}(t0) \} \{ c_1^2 + c_2^2 - c_6^2 - 2c_3 c_5 c_6 - c_3^2 c_5^2 - c_3^2 c_4^2 \} \right) \right] \quad (1)$$

where:

$$c_1 = \cos \Omega ; c_2 = \sin \Omega \sin \epsilon ; (\epsilon = 23.4524^\circ) ; c_3 = \cos i$$

$$c_4 = \sin \Omega ; c_5 = \cos \Omega \sin \epsilon ; c_6 = \sin i \sin \epsilon ; c_7 = \sin i$$

$$c_8 = \sin \epsilon ; K_{so} = \frac{\mu_{so}}{r_{so}^3(t0)}$$

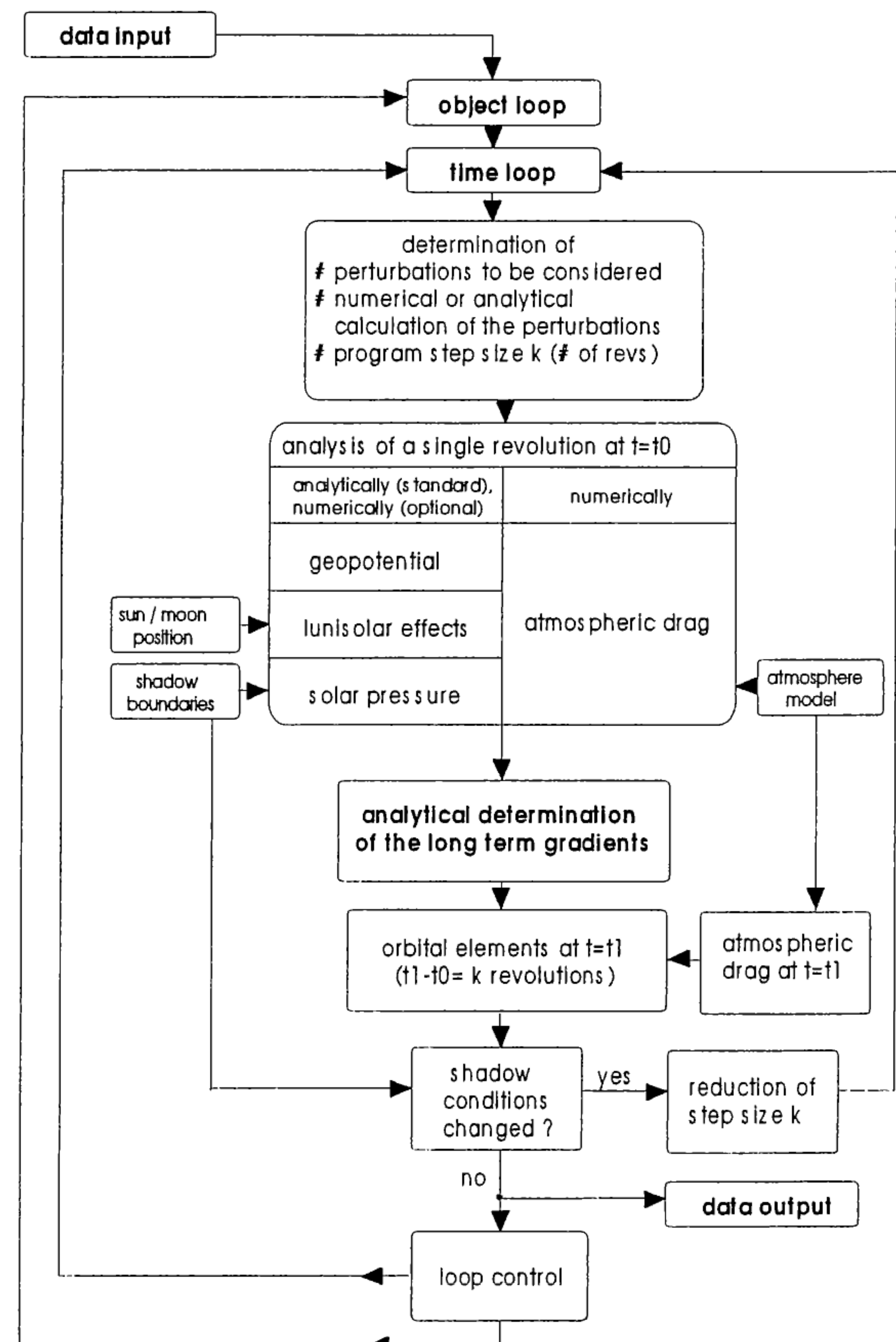


Fig. 1 The structure of the orbit propagator LOPEX

But in fact, the object with the larger mass to area will decay first. This is due to the coupling effect of the lunisolar perturbations and the aerodynamic forces.

In Eq. 1 it can be seen that the eccentricity change with time due to third body perturbations is a function of the initial eccentricity. In particular, this change is proportional to $e \sqrt{1-e^2}$. A larger initial eccentricity leads to a larger amplitude of the eccentricity variation with time. Hence, if the eccentricity is lowered by aerodynamic forces, the subsequent lunisolar perturbations lead to minor changes of the eccentricity. The consequences of such effects are the following:

- due to the varying perigee altitude an object may appear or not appear in the beam of a ground based radar antenna. A continuous tracking and identification of this object is difficult.
- the dependency of orbital lifetime and mass to area ratio can be reversed.
- a re-entry of a object may be forced by a very low perigee (< 100 km) due to lunisolar perturbations and the resulting aerodynamic forces in the atmosphere. This effect can be used for debris mitigation purposes.

Fig. 3 gives, as an example, the mean perigee altitudes within the next 100 years as a function of the initial conditions (orbital plane with respect to the constellation earth, sun, moon). In case of a low inclined GTO ($i=28.5$ deg) there are distinct maxima and minima as a function of launch date and initial right ascension of the ascending node. In case of higher inclined high eccentric orbits ($i=63.4$ deg, MOLNIYA type) there is no influence of the launch date.

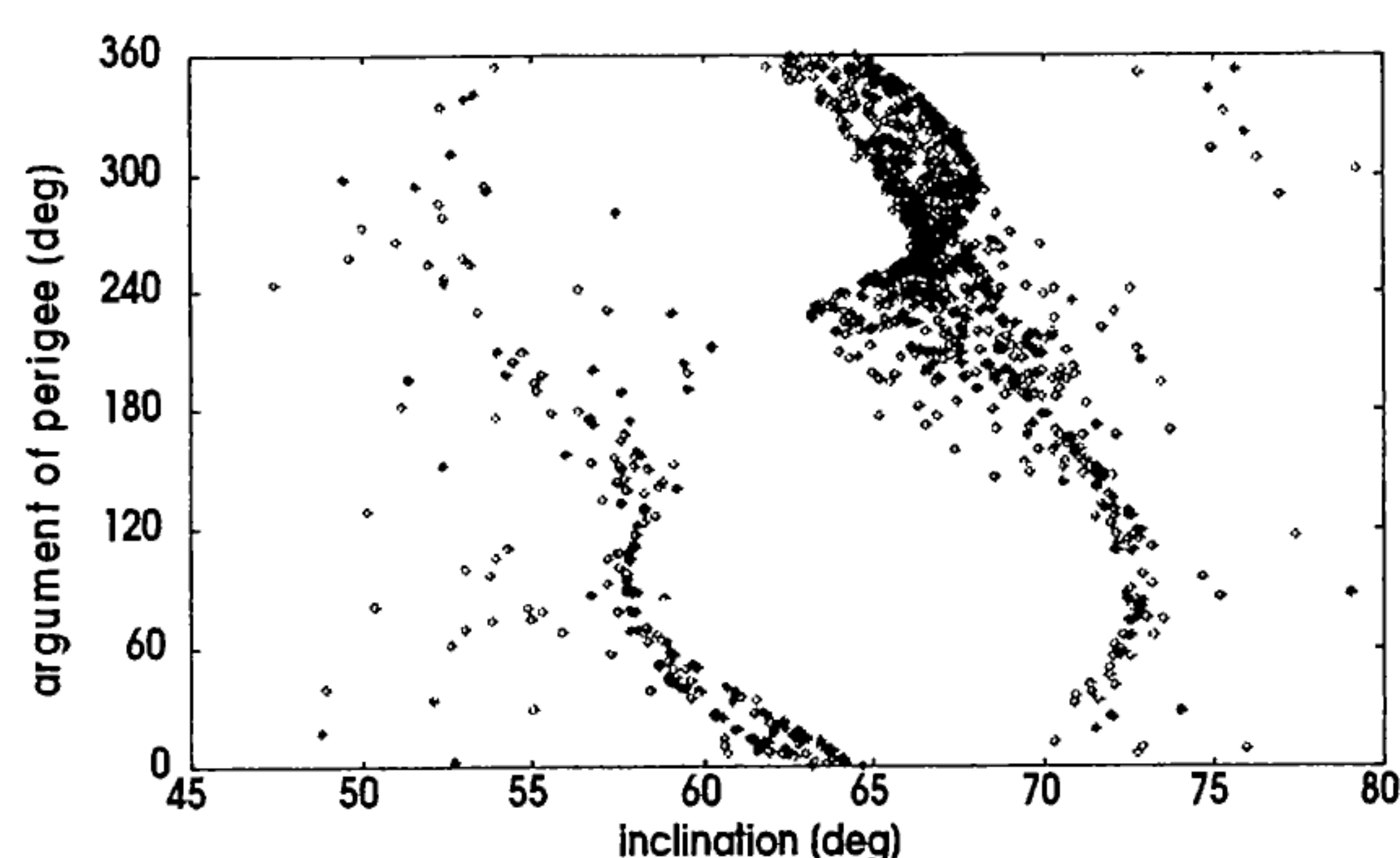


Fig. 4 The distribution of argument of perigee 10 years after a simulated break up on a MOLNIYA type orbit

For orbits of the MOLNIYA type the line of apsides is fixed ($\omega=270$ deg) due to the inclination of 63.4 deg. Hence, these orbits do not interact with the low inclined GEO region. But if a break up occurs in the apogee region of a high eccentric MOLNIYA type orbit (this is the most probable break up due to the high residence

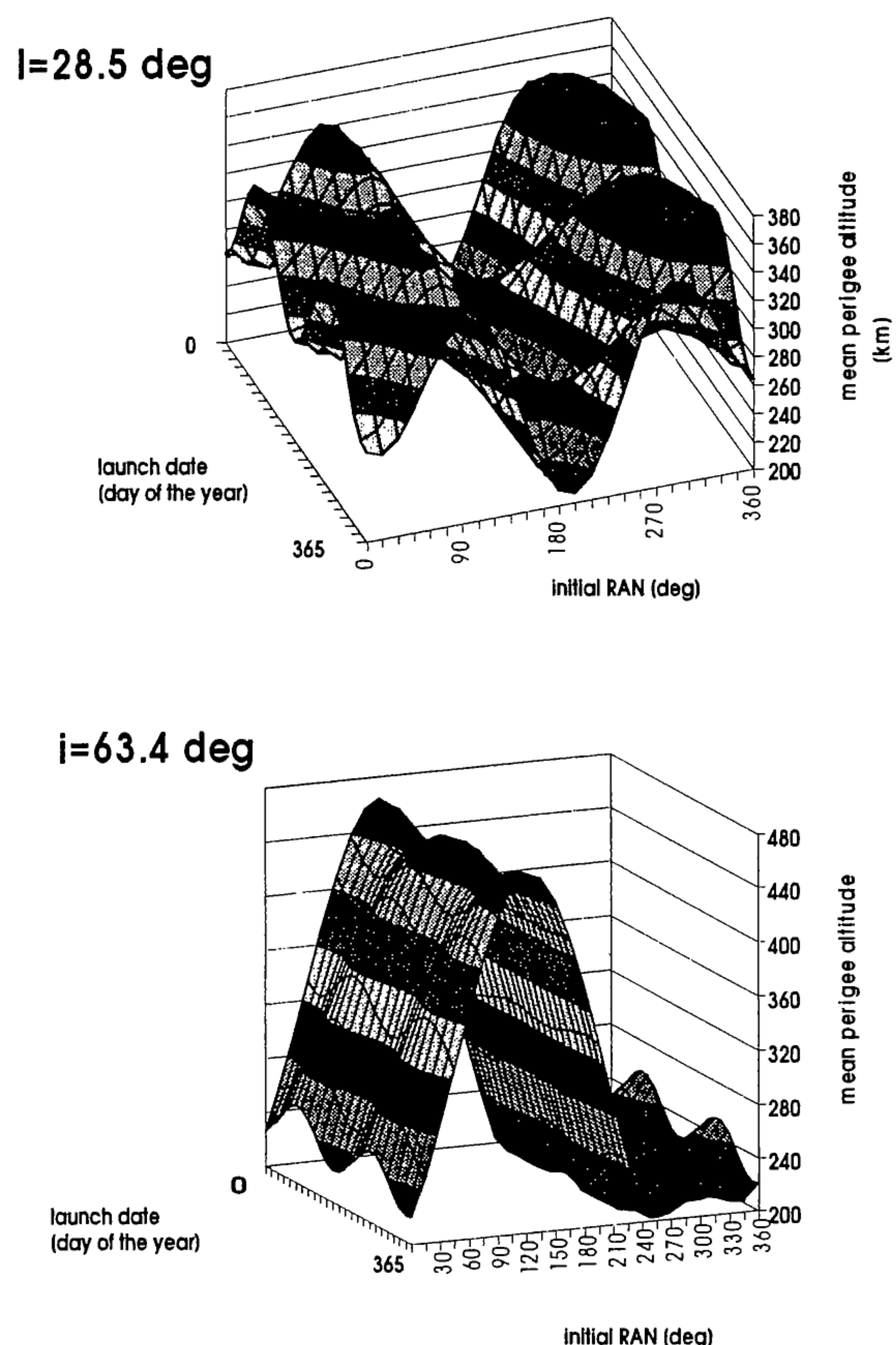


Fig. 3 The mean perigee altitude as a function of launch date and RAN (examples)

probability in the apogee region) the fragments no longer remain on orbits with $\omega=270$ deg=const. This is due to the slightly changed inclination as consequence of the extra velocities introduced by the break up. Fig. 4 shows the arguments of perigee versus the inclinations of the fragments after 10 years. Now the fragments pass the low inclined GEO region and represent collision risk for satellites operating in GEO

4. ANALYSIS OF IGSO, SSCO AND GEO ORBITS

The high efficiency of the LOPEX software resulting from the basic stroboscopic approach especially enables the analysis of orbital evolution over decades and centuries. Application of these long-term capabilities to a satellite in Inclined Geosynchronous Orbit (IGSO) or in Semi Synchronous Circular Orbit (SSCO), respectively, reveals an essential increase of the orbital eccentricity of these bodies after having been resting at constantly low values for decades initially. Similar effects can be observed for the intended medium eccentric synchronous Tundra orbits as well.

In all these cases the symptoms can be described as follows:

1. Dramatical increase of orbital eccentricity after some decades.
2. Oscillation of the eccentricity on a considerably high level, i.e. with an amplitude approaching the critical value for atmospheric reentry in case of synchronous semi major axis.

Mainly the initial eccentricity in combination with the position of the orbital plane determines the point in time when the eccentricity actually starts to rise. But while these parameters only control the temporal course of the effect it seems to be the orbital inclination as well as the semi major axis determining if and to what extent it occurs.

The reason for the above mentioned perturbation phenomenon is the presence of distinct inclination bands, where the perturbations due to the geopotential result in a relative orientation of the orbital plane towards other perturbing bodies (especially the moon) remaining nearly constant for longer periods of time. Hence, the normally alternating character of the disturbing accelerations is changed towards a lasting single-sided effect, leading to strong deviations in terms of eccentricity as well as of inclination. This kind of resonance can be found at inclinations around $46.4^\circ/106.8^\circ$, $56.1^\circ/111.0^\circ$, $63.4^\circ/116.6^\circ$, $69.0^\circ/123.9^\circ$ and $73.2^\circ/133.6^\circ$ (Ref. 1). Orbits of an inclination of about 45° up to 135° are sensitive to the influence of these resonance bands, the maximum is at about 70° or 110° , respectively.

On the one hand this natural mechanism can, of course, be used to reduce the orbital lifetimes of bodies in highly inclined orbits with large semi major axis, normally accounting for millions of years, to only hundred years or even less. As well there would be a kind of self-cleaning effect in case of any breakup in those orbits. On the other hand, one of the major consequences of this wide-scaled deviation of eccentricity is a considerable descent of the perigee and, hence, a contamination of altitude regimes never been anticipated to be exposed to a threat from such a source. Just in case of fragmentation this would, corresponding to the self-cleaning in the altitude where the event originally occurred, lead to an increase in spatial object density in MEO and even LEO.

In Fig. 5 the object densities resulting from simulated low-intensity fragmentation in IGSO, GEO and SSCO are plotted versus time after the break-up and altitude. It can be seen that there is a significant number of fragments passing LEO from this high altitude events due to the above mentioned resonance effects in IGSO ($i=70^\circ$) and SSCO ($i=65^\circ$). The GEO event does not cause any relevant object densities in LEO.

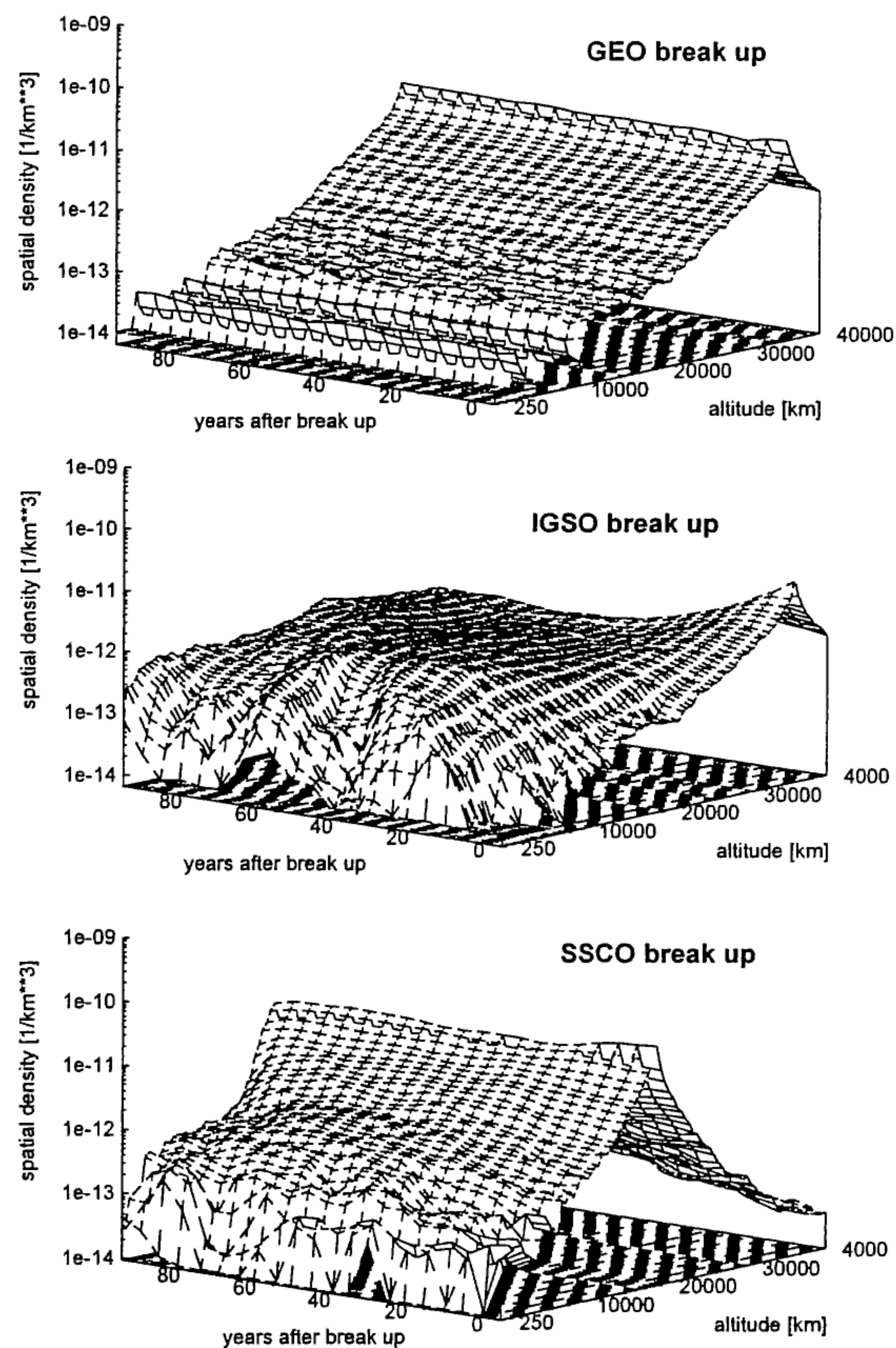


Fig. 5 The objects density due to low-intensity break ups in GEO, IGSO and SSCO as a function of altitude and time

Fig. 6 gives a somewhat closer impression of the time dependent object density at 750 km and 1750 km altitude caused by an IGSO and SSCO break up. The amplitude covers an order of magnitude. For the given IGSO example, a period of about 20 years (750 km) and 40 years (1750 km) occurs. In terms of the related consequences the above effect is comparable to the GTO example given in para. 2. In both cases the spatial densities due to fragments resulting from a low-intensity break up in GEO do not appear above the 10^{-14} objects/km³ threshold.

5. ENHANCED LONG-TERM MODELLING OF THE DEBRIS ENVIRONMENT

From the above examples it can be derived, that enhanced long term modelling of the debris environment has to consider higher order orbit mechanic effects also in order to avoid bias in the analysis. For this purpose the orbit propagator LOPEX has been implemented in the high resolution long term model LUCA.

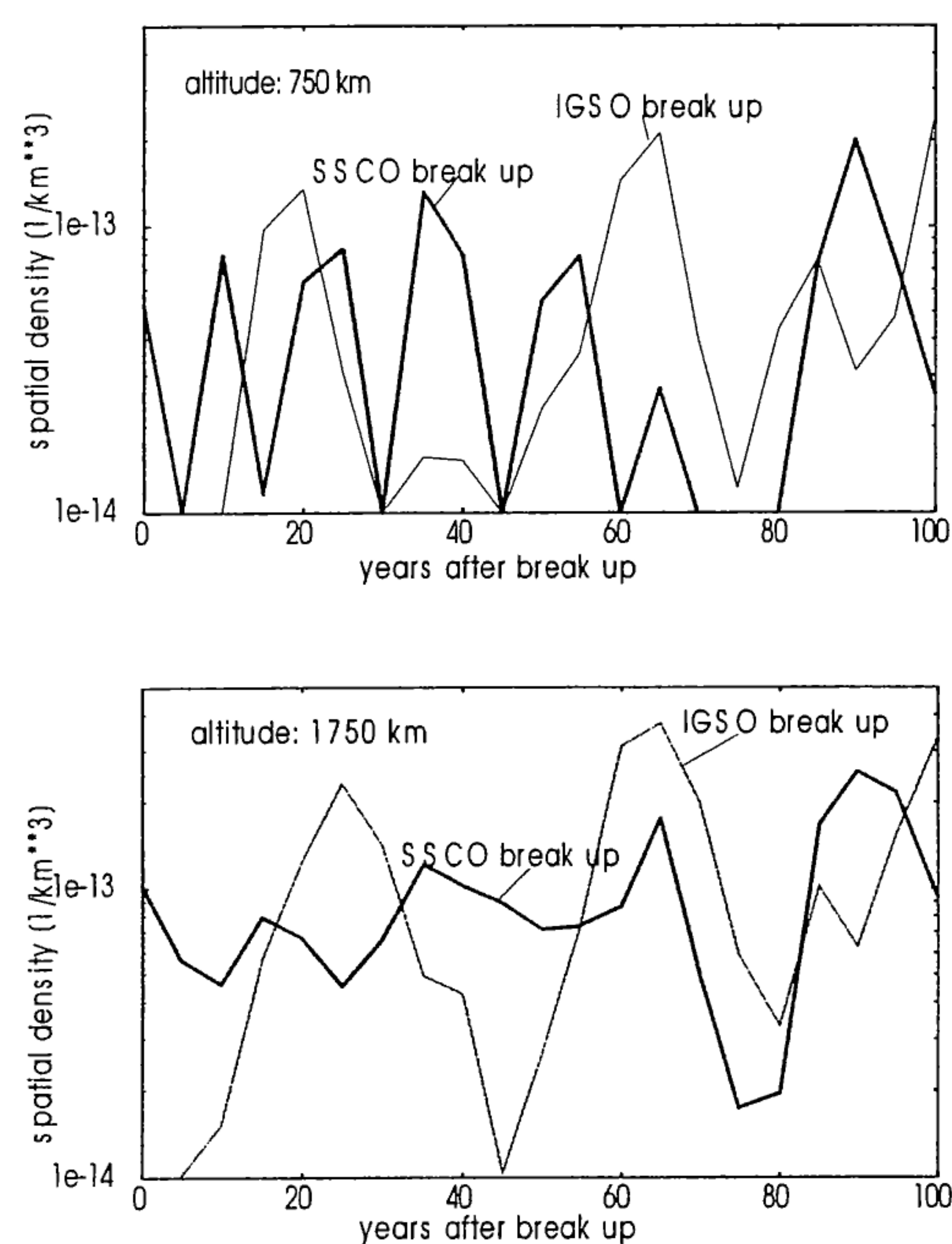


Fig. 6 The object density in 750 km and 1750 km altitude due to low-intensity break ups in IGSO and SSCO as a function of time

LUCA has been recently developed by IFR TUBS and is characterized in Fig. 7. It combines the advantages of a high spatial resolution and of a tolerable computer time need. In order to calculate the time dependent collision risk, a special tool has been implemented. This tool analyses the geometry of the orbits of all population members and determines the probability that members of the population will have a collision. The tool is used once in one year of simulated time and guarantees that changes in the population properties are reflected in the collision probabilities. This ability also is an enhancement with respect to the model methodology compared to the former used programs. These probabilities are used to trigger individual collisions, a few in the first years of the simulation, much more after some decades.

Fig. 8 gives the number of objects > 1 cm lower than 2000 km altitude for the next 100 years as a function of altitude and time. For this example analysis performed by the program LUCA a moderate growth of the so called basic population, i.e. the population due to launched objects and explosions, of 1.7 % related to 1996 was assumed. The three scenarios have the same probability, they only have been obtained by different seed values of the random number generator. This leads to different types of collisions and different points in time when the collisions are triggered. Future reality may be any one of such scenarios.

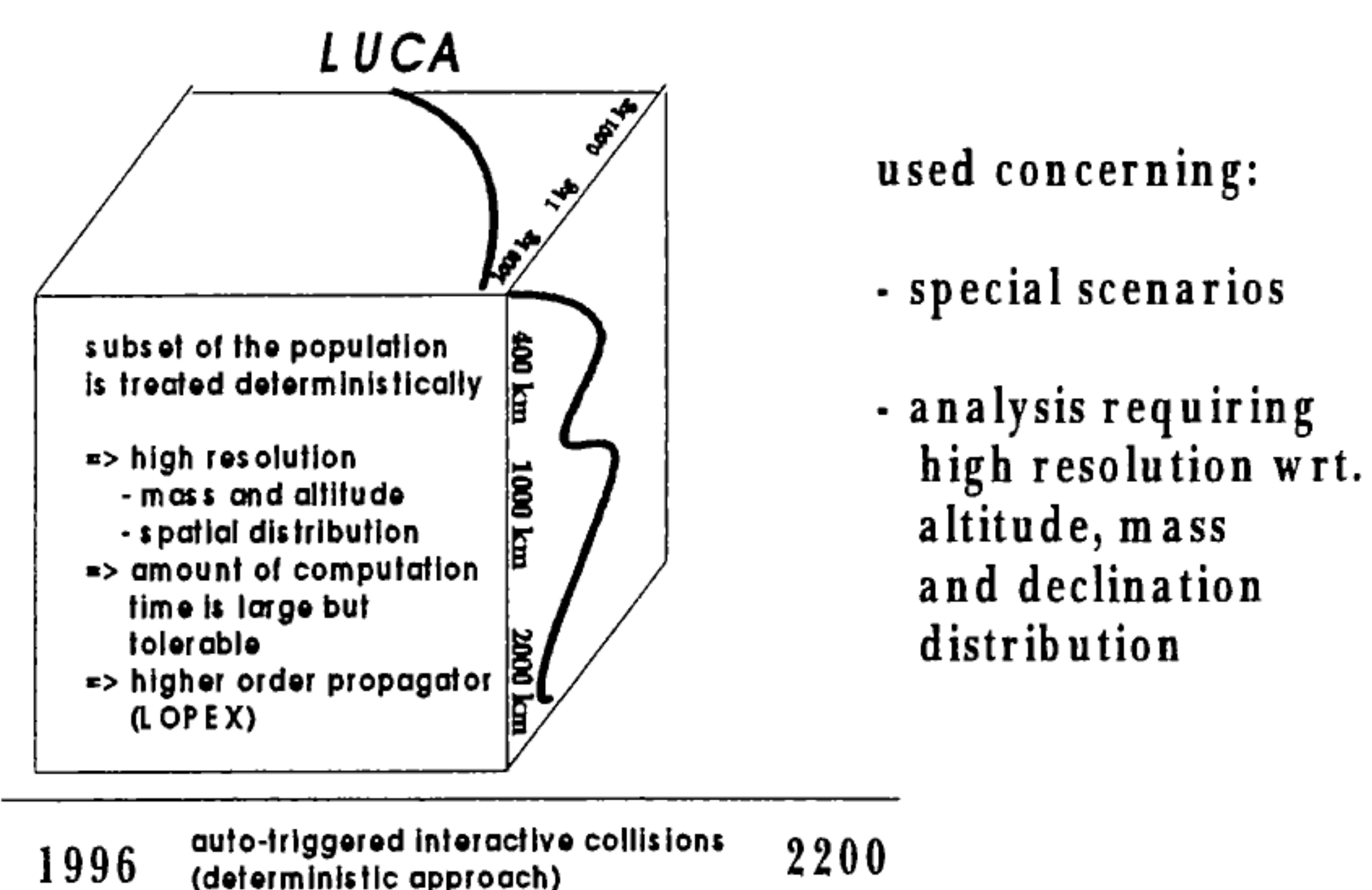


Fig. 7 Features of the long term debris model LUCA

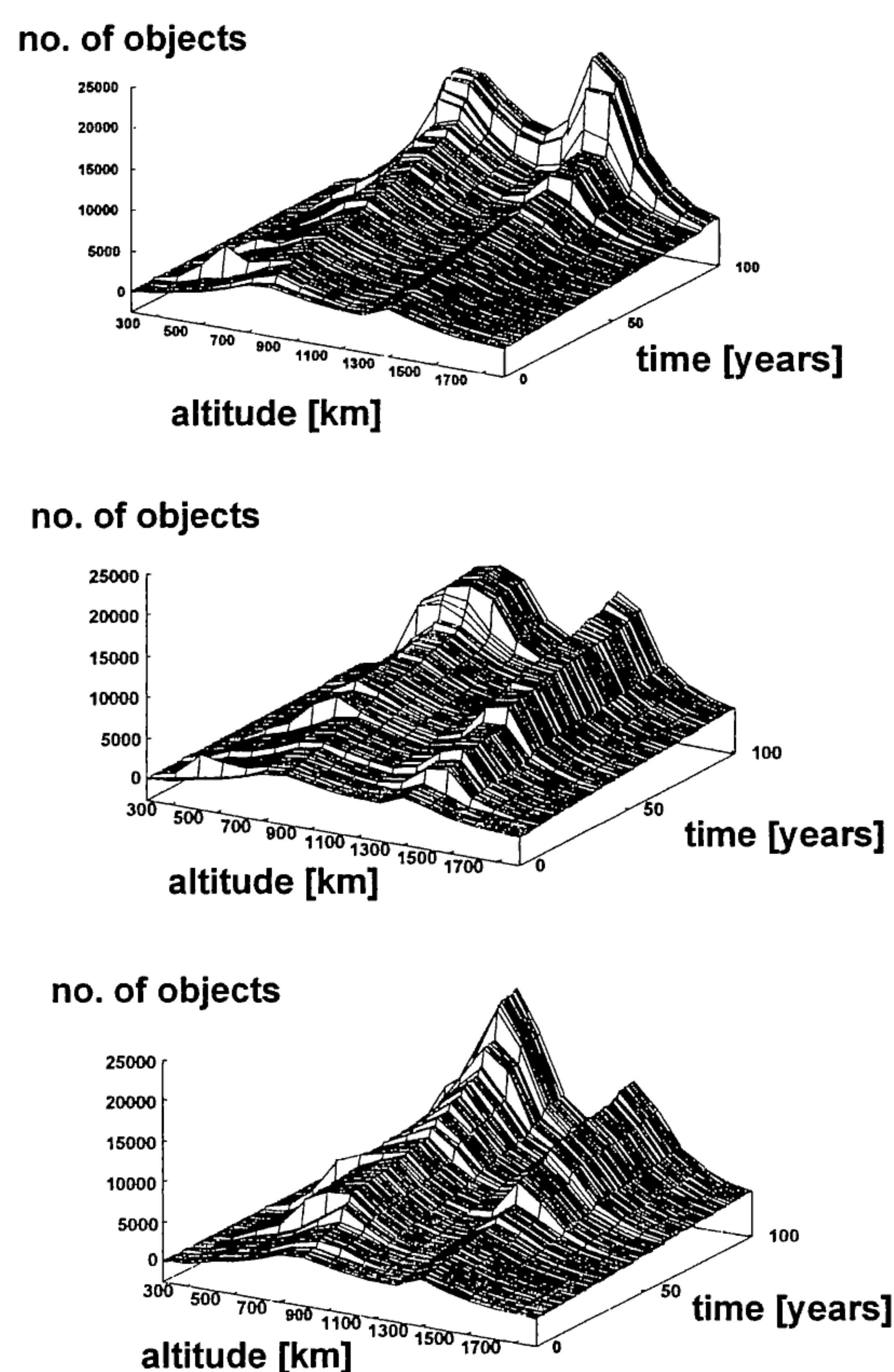


Fig. 8 The number of objects per 100 km altitude shell obtained by Monte-Carlo simulations of future debris populations > 1 cm (assuming 1.7% / year linear increase of the basic population)

One can see from Fig. 8 that one cannot determine the future population evolution including collisions exactly. In order to come to relevant result one has to average a

advantage that there is an information about the error bars. Methods which use mean value approaches are possible, but it is difficult to obtain the error bars. The mean curves obtained by averaging a number of Monte-Carlo runs have to be interpreted as trends. It is not the goal of the long term modelling to obtain results very close to reality in terms of the number of objects for a given year in the future. This is not possible due to the above mentioned stochastic and external effects. The mathematical methods used, however, are well proven methods and do not introduce major uncertainties. For the interpretation of the analysis two questions are important

- which influence have parameters on the trends ?
- do all Monte-Carlo runs react in the same way on parameters changes ?

The second question is important in view of the analysis of debris mitigation measures. If not only the mean curves, but also most of the single Monte-Carlo runs change their tendencies under a specific scenario, the effectiveness of this scenario is proven.

Fig. 9 shows, as an example, the advantage of a high resolution long term debris model. The following debris mitigation scenario was assumed :

- de-orbit/lifetime reduction (25 years) for all spent s/c up to 1500 km altitude
- the use of a disposal orbit at about 2500 km for all s/c above 1500 km that cannot be de-orbited (20 objects > 100 kg per year)

One can see from the Monte-Carlo run shown in Fig. 9 that there may be a significant increase of objects in the region of the disposal orbit due to collisions under the above assumptions. In case of de-orbit/lifetime reduction up to 2000 km and no disposal at about 2500 km no collisions may occur at about 2500 km altitude. This topic will be subject to further analysis and discussion.

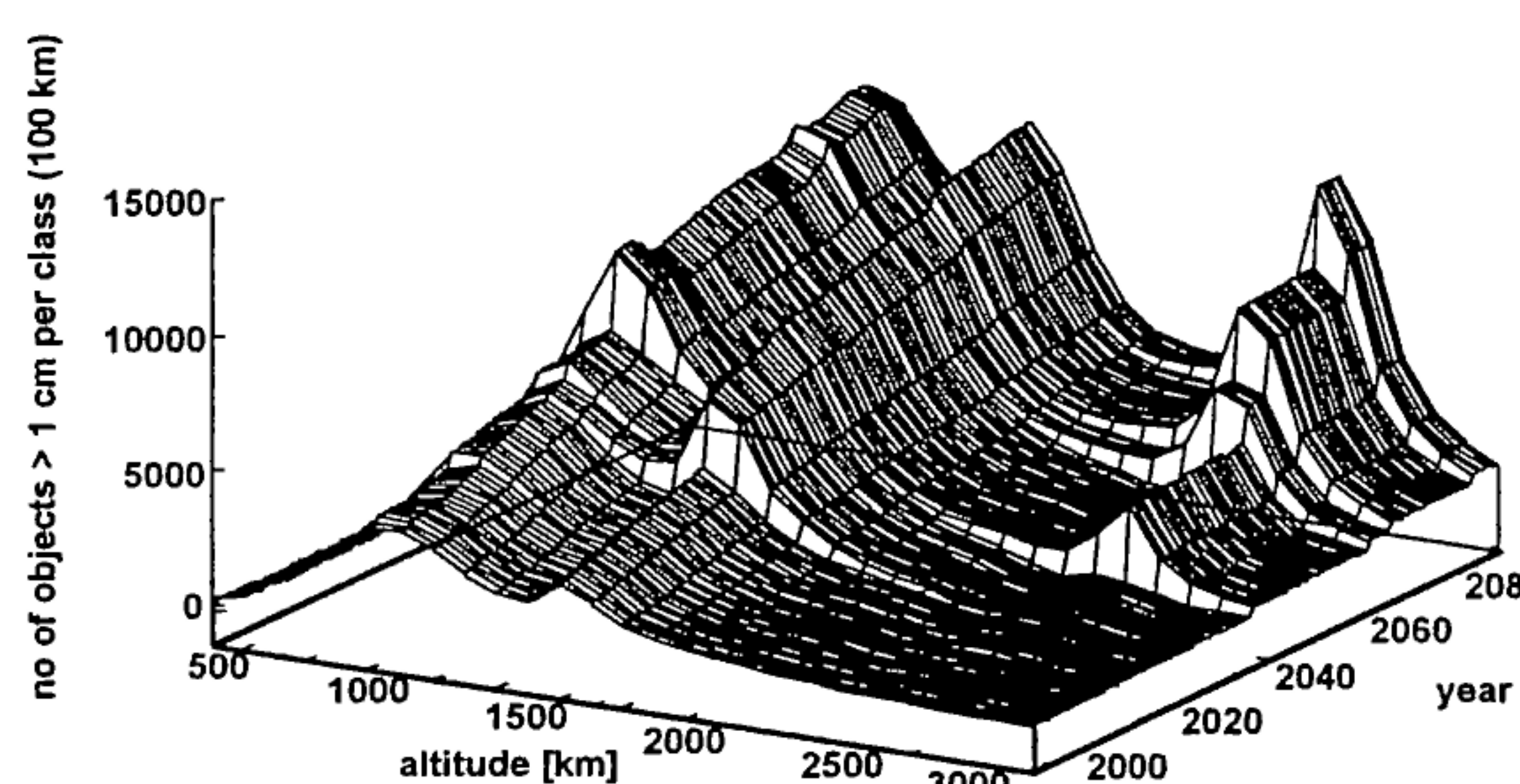


Fig. 9 Monte-Carlo simulation of a debris mitigation scenario assuming a disposal orbit at 2500 km (20 objects > 100 kg per year stored)

6. CONCLUSION

There are a number of effects due to the orbit mechanics of debris orbits that are relevant for the long term spatial density evolution. These effects, e.g.

- perigee altitude variations on high eccentric orbits due to lunisolar perturbations and their influences on data interpretation
- resonance effects, .e.g. the reduced orbital lifetime on IGSO type orbits

can be reflected by higher order propagators, which cover all relevant orbital perturbations. The aspect of computer time efficient algorithms have to be taken into account. In view of the ongoing and upcoming discussions and decisions regarding debris mitigation (Refs. 3,4), enhanced high resolution long term debris models incorporating reliable and fast orbit propagators are appropriate in order to enable state of the art scientific analysis.

7. REFERENCES

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