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COMMITTEE ON THE PEACEFUL
USES OF OUTER SPACE
Scientific and Technical Subcommittee
Thirty-fourth session
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DRAFT REPORT OF THE SCIENTIFIC AND TECHNICAL SUBCOMMITTEE ON THE WORK OF ITS THIRTY-FOURTH SESSION

B. Technical report of the Subcommittee for 1997

1. Concerned about the influence of space debris on the space environment and on the operation of spacecraft, the Committee on the Peaceful Uses of Outer Space had included the item on space debris on its agenda in 1994. It was agreed that it was important to have a firm scientific and technical basis for future action on the complex attributes of space debris.

2. The Subcommittee agreed to focus on understanding aspects of research related to space debris, including debris measurement techniques; mathematical modelling of the debris environment; characterizing the space debris environment; and measures to mitigate the risks of space debris, including spacecraft design measures to protect against space debris. Accordingly, a multi-year work plan was adopted in 1995 for specific topics to be covered during the time-span 1996-1998. It was also agreed that that work plan should be implemented with flexibility, so that all relevant issues on space debris could be addressed.

3. The report of the Subcommittee would be structured according to the specific topics addressed by the work plan during the period 1996-1998. The report would be carried forward and updated each year, leading to an accumulation of advice and guidance, in order to establish a common understanding that could serve as the basis for further deliberations of the Committee on that important matter. The report for 1997 concentrates on the modelling of the space debris environment and risk assessment.

2. Modelling of the space debris environment and risk assessment

2.1 Modelling of the space debris environment

2.1.1 Introduction and methodology

4. Space debris models provide a mathematical description of the distribution of objects in space, the movement and flux of objects and the physical characteristics of objects (e.g. size, mass, density, reflection properties, intrinsic motion). These models can be deterministic in nature (i.e. each object is described individually by its orbital parameters and physical characteristics), statistical in type (i.e. characterization of an ensemble by a sample number of objects) or a combination (i.e. hybrid). These models can be applied to risk and damage assessments, prediction of debris detection rates for ground-based sensors, prediction of avoidance manoeuvres of operational spacecraft and long-term analysis of the effectiveness of debris mitigation measures.

5. Space debris models must consider the contribution to the population of orbiting objects of the following source mechanisms:

(a) Launches (including launch vehicle upper stages, payloads and mission-related objects);

(b) Manoeuvres (to account for solid rocket motor firings);

(c) Breakups (produced by explosions and collisions);

(d) Material separation from surfaces (ageing effects, e.g. paint flakes);

(e) Material due to leakage (e.g. nuclear power source (NPS) coolant).

6. The following sink mechanisms must also be considered:

(a) Orbital decay due to atmospheric drag or other perturbations;

(b) Retrievals from orbit;

(c) Deorbiting.

A debris environment model must contain all or some of these elements.

7. Space debris models make use of all available data sources. These include:

(a) Deterministic data on decimetre-size and larger objects within the United States Space Command Satellite Catalogue and the Russian Space Surveillance Catalogue;

(b) Statistical data on centimetre-size objects derived from dedicated radar campaigns in low-Earth orbit (LEO);

(c) Statistical data on encountered submillimetre debris populations inferred from analysis of retrieved surfaces;

(d) Ground-based simulations of hypervelocity collisions with satellite and rocket bodies;

(e) Ground-based simulations of explosive fragmentations.

8. These models are limited by the sparse amount of data available to validate the derived relationships. The models must rely upon historical records of satellite characteristics, launch activity and in-orbit breakups; in addition there is only limited data on spacecraft material response to impact and exposure to the orbital environment. Further, major assumptions must be made in applying these models to predict the future environment. In particular, future traffic scenarios and the application of mitigation measures will have a major influence on the outcome of the model predictions. Space debris models must be continually updated and validated to reflect improvements in the detail and size of observational and experimental data sets.

9. Environment models may take two forms: as discrete models, which represent the debris population in a detailed format, or as an engineering approximation, in the form of distribution functions. Furthermore, these models can be short term in nature (considering time-frames of up to 10 years) or long term (considering time-frames of over 10 years). In the preparation of all these models, the initial debris population is represented at a particular starting epoch and this is propagated forward in time in a stepwise manner taking account of source and sink mechanisms and relevant orbit perturbations.

10. The pertinent characteristics of the models are compared in table ... below.

2.1.2 Short-term models

11. The following short-term models are available in the scientific and engineering community:

(a) <u>EVOLVE</u> was developed by the NASA Johnson Space Centre to provide short- and medium-term forecasts of the LEO environment with extensive source terms and detailed traffic models, based on quasi-deterministic population propagation techniques;

(b) <u>ORDEM96</u> is a semi-empirical engineering model developed by NASA Johnson Space Centre. It is based upon extensive remote and *in situ* observations and is used to support United States Space Shuttle and International Space Station design and operations;

(c) <u>MASTER</u> is an ESA semi-deterministic environment model based on 3D discretization of spatial densities and transient velocities. The model is applicable to altitudes from LEO to GEO providing environment estimates in the short term. A less detailed version of MASTER is available in an engineering format. Both models were developed by the Technical University of Braunschweig in Germany.

(d) <u>IDES</u> is a semi-deterministic model of the environment relying upon detailed traffic and satellite characteristics models to provide and short- and long-term predictions of the orbital debris environment. The model was developed by DERA Farnborough;

(e) <u>Nazarenko</u>, a model developed by CPS is a semi-analytic, stochastic model for the medium- and long-term prediction of the LEO debris environment, providing spatial density and velocity distributions. The model is based on Russian and United States catalogue data.

Model name	Source	Evolutionary period	Engineering model available	Minimum size	Orbital regime
CHAIN	NASA	Long term	No	1 cm	LEO
CHAINEE	ESA	Long term	No	1 cm	LEO
EVOLVE	NASA	Short + long term	No	0.01 mm	LEO
IDES	DERA	Short + long term	No	0.01 mm	LEO
LUCA	TUBS	Long term	No	1 mm	LEO/MEO
MASTER	ESA	Short term	Yes	0.1 mm	LEO/GEO
Nazarenko	RSA	Short term	No	0.6 mm	LEO
ORDEM96	NASA	Short term	Yes	0.01 mm	LEO
SDM/STAT	ESA	Long term	No		LEO/GEO

2.1.3 Long-term models

12. The scope of the long-term modelling of the orbital debris environment is the long-term (up to 100 years) prediction of the number of objects as a function of time, of altitude and of object size. These projections are important for assessing the necessity and the effectiveness of debris mitigation techniques.

13. In addition to the sources of space debris that are considered in the modelling of the current debris population, it is required to take into account collisions among larger objects (> 10 cm). Currently, collisions among larger objects do not play a significant role in the increase of the number of objects, since their probabilities are low. However, in the future, the interactive risk for so-called destructive collisions, i.e. collisions that generate larger fragments, may increase. This so-called interactive collision risk among all objects of the population is proportional to the square of the number of objects. Hence, if in the future the number of objects will increase as in the past (some per cent per year linearly), the interactive collision risk will increase.

14. In order to assess the consequences of collisions among larger objects it is necessary to have reliable break-up models for collisions of this type. However, it is very difficult to simulate on orbit collisions without having test data for validation purposes available. Hence, a certain degree of uncertainty is introduced into the models by the collision simulation.

15. Other than the modelling of the present debris population, the long-term modelling needs some assumptions describing the future space flight activities including the debris generation mechanisms in terms of, for example:

(a) Future number of launches and related orbits;

(b) Future number and size of payloads per launch;

(c) Future number of mission related objects (fairing, bolts etc.);

(d) Future number of explosions of spacecraft and upper stages.

16. All these parameters are subject to variations with time due to technical/scientific, financial and political aspects. Hence, some uncertainties are added to those uncertainties that are due to the mathematical model itself (break-up models etc.).

17. A number of models have been developed for the purpose of long-term modelling of the debris environment. They can be characterized briefly as follows:

(a) CHAIN, CHAINEE: CHAIN was developed by the Technical University of Braunschweig under government contract. Since 1993 this model has been maintained and improved by NASA. CHAINEE, the European extension of CHAIN, is used by ESA. The model, an analytical "particle-an-a-box" model, describes the population and the collision fragments of up to an altitude of 2,000 km using 4 altitude bins in LEO and 5 mass classes. CHAINEE is an extremely fast computer code (approximately 10 seconds for a 100-year simulation). It enables the identification of relative trends associated with specific mitigation policies. The resolution of CHAIN is limited due to the binning used;

(b) EVOLVE: The EVOLVE model has been developed by NASA. It is a semi-deterministic model, i.e. debris objects are described individually by a set of parameters. In addition to being capable of modelling the present debris environment, it can be used to investigate future evolutionary characteristics under various mitigation practices by the use of Monte Carlo techniques. For this purpose mission model data are used. The reliability and resolution of the model in terms of orbital altitude and object size are good due to its methodology;

(c) IDES: IDES was developed at the Space Department of DERA, at Farnborough, United Kingdom. The historical data are simulated until 1996. For the analysis of future scenarios, traffic models are used and the environment is evolved forward in time to account for interactions within the satellite population;

(d) LUCA: For the detailed analysis of future scenarios, especially if a high resolution concerning the orbital altitude and the declination is required, the semi-deterministic computer code LUCA has been developed at the Technical University of Braunschweig. This code 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 reflects the increased collision risks at higher declinations (e.g. close to the polar regions);

(e) STAT/SDM: At the University of Pisa, in Italy, two programs for the purpose of long-term modelling have been developed under an ESA contract. The stochastic approach (STAT) and the semi-deterministic model (SDM) use the same initial population and the same source and sink assumptions. In SDM, orbits of a representative subset of the population are used to calculate collision rates and to map the population forward in time. Spatial densities are stored in time-dependent altitude and mass bins. By means of parametric studies, effects of launch policies and mitigation measures on the population development can be analysed. STAT is a computer time efficient "particle-in-a-box" alternative to SDM. It is based on a system of coupled, non-linear differential equations that are numerically integrated.

18. The major findings of the above-mentioned long-term debris models can be summarized as follows:

(a) The debris population may grow uncontrolled in the future if space flight is performed as in the past. This is because of the increasing number of collisions that will occur among larger objects;

(b) Currently, fragments from explosions are the main source of space debris. Beyond a certain point in time, collision fragments may dominate the population;

(c) Should the second stage of this evolution occur, the so-called collisional cascading effect will set in. This means that collisional fragments will contribute to the number of subsequent collisions. At that point in time the population will grow exponentially.

19. The results of the long-term debris models do not agree completely. However, the basic trends and tendencies obtained by the models agree.

20. The collision probabilities among the larger objects are initially low. Hence, it is essential to analyse a number of single Monte Carlo runs or to use mean value approaches in order to obtain reliable trends and tendencies. The above models take care of that effect.

2.2 Orbital debris risk assessments

2.2.1 Introduction

21. Risk assessments include the probability of an event, as well as its subsequent consequences. With the assistance of models of the orbital debris environment, the risk of collision among operational spacecraft and orbital debris can be evaluated. Spacecraft in LEO are routinely bombarded by very small particles (<100 microns) because of the large number of such debris, but the effects are normally slight due to the small masses and energies involved. Because of the smaller population of large debris objects, the likelihood of collision decreases rapidly as the size of the debris increases. However, the severity of collisions between large objects increases.

22. The principal risk factors are the spatial density and average relative collisional velocity along the orbit (altitude and inclination) of the space object of interest, the cross-sectional area of the space object and the duration of the flight. The consequences of a collision will depend upon the respective masses and compositions of the objects involved. Whereas the collision risk between an orbiting object and a meteoroid is essentially independent of altitude, the probability of collision between orbital objects is strongly related to altitude, in general being an order of magnitude higher in LEO than in GEO.

2.2.2 Collision risk assessments in LEO

2.2.2.1 Methodology

23. Risk assessments have been routinely performed on LEO spacecraft since the 1960s. The Poisson model is used in cases where there is a large number of independent events and each event has a small probability of occurring. Man-made debris and micro-meteoroids meet these criteria for independence except in cases of a recent break-up or a meteor storm.

24. To compute the probability of an impact from space debris requires a meteoroid/orbital debris (M/OD) environment model, a spacecraft configuration and a mission profile. To compute the probability of a penetration and/or a failure due to space debris requires detailed knowledge of the spacecraft configuration, including:

(a) The geometry of critical subsystems;

(b) The penetration resistance or ballistic limit equation of each subsystem;

(c) Data on the ability of each subsystem to tolerate damage.

25. Based on this information, computer codes can calculate:

(a) The probability of space debris impacts for a given size particle;

(b) The probability of impact damage to any given subsystem;

(c) The probability of damage as a function of its location;

(d) The split between damage from man-made debris and micro-meteoroids.

2.2.2.2 Results of risk assessments.

26. Risk assessments in LEO are routinely utilized to enhance the safety of space operation. In cases involving human space flight risk assessments have proved invaluable in ensuring the safety of shuttle operations. Shuttle missions are operationally reconfigured whenever a pre-flight risk assessment indicates the risks of space debris are at an unacceptable level.

27. Risk assessments are being utilized to design the location and type of space debris shielding that will protect the crew as well as the crucial subsystems on the International Space Station.

28. Risk assessments are also utilized in the design of unmanned spacecraft. They aid in the placement of shielding to protect critical subsystems, as well as in the system design of large communication satellite constellations.

Table __. Meantime between impacts on satellites with cross-section area of 100 square metres

Orbital height	Objects 0.1-1.0 cm	Objects 1 ≥ 10 cm	Objects > 10 cm
500 km	1-10 years	350-700 years	15,000 years
1,000 km	0.3-3 years	70-140 years	2,000 years
1,500 km	0.7-7 years	100-200 years	3,000 years

2.2.3 Collision risk assessments in GEO

29. Currently, the population of space objects in and near the GEO regime is known well for only spacecraft and upper stages. The limited number of these objects, their wide spatial distribution and the lower average relative velocities (500 m/sec) combine to produce a substantially lower probability of collision in GEO. Moreover, as more spacecraft and upper stages are left in orbits above or below GEO, the number of uncontrolled intact objects intersecting the GEO regime is increasing at a very slow rate. Special collision possibilities exist in GEO because of the close proximity of operational spacecraft at selected longitudes, but these collision hazards can be eliminated by spacecraft control procedures. The limited number of large objects near GEO also permits the prediction of close approaches between operational spacecraft and orbital debris in sufficient time to conduct an evasive manoeuvre.

30. The number of orbital debris of less than 1 metre in diameter near GEO is not well known. Two break-up—one a spacecraft and one an upper stage—have been identified, and some evidence suggests that additional break-ups may have occurred. Such debris, however, would be perturbed into inclined orbits, reducing the residence time in GEO but also increasing the relative collision velocity. In many cases debris fragments would be sidely dispersed in both altitude and inclination. Additional orbital debris measurements in GEO are needed before more accurate risk assessments can be performed. Also, new probability of collision techniques may need to be developed to take into account the non-random nature of close approaches in GEO.

31. There is no natural removal mechanism for satellites in GEO. Therefore operational spacecraft are at risk to be damaged by uncontrolled spacecraft. This annual collision risk for an operational satellite is currently estimated at 10^{-5}.

2.2.4 Risk assessments for re-entering orbital debris

32. The risk assessment discussed here is limited to the uncontrolled re-entry from Earth orbit.

33. There have been more than 16,000 known re-entries of catalogued space objects in almost 40 years. No significant damage or injury has been reported. In large measure this can be attributed to the large expanse of ocean surface and the sparse population density in many land regions. In the past five years, approximately once each week, an object with a cross-section of 1 square metre or more has re-entered Earth's atmosphere and some fragments have been known to survive.

34. The risk of re-entry is not only from mechanical impact, but also from chemical or radiological contamination to the environment. Mechanical damage will be caused by objects surviving aerodynamic heating. This risk will depend on the characteristics of the final orbit, the shape of the object and its material properties.

35. An assessment of re-entry risk must include the shape of the object and analysis of the altitude of the aerodynamic destruction, identification of components that can survive re-entry, the modelling of these components and the calculation of total casualty area.

36. There is no international consensus on human casualties caused by re-entry. A casualty expectation of 10^{-4} is presented in NASA safety standard 1740.14, entitled "Guidelines and assessment procedures for limiting orbital debris".

37. The Subcommittee noted that at its thirty-fifth session, it should focus on the last item of its multi-year work plan, space debris mitigation measures. It agreed that it would be desirable to invite the International Academy of Astronautics, through its Subcommittee on Space Debris, to prepare a comprehensive working paper on the mitigation practices currently in use, as well as on proposed measures of space debris mitigation.

38. The following section is to be completed at the thirty-fifth session of the Scientific and Technical Subcommittee:

3. Space debris mitigation measures

3.1 Reduction of the debris increase in time

3.1.1 Avoidance of mission-related objects

3.1.2 Improved structural integrity of space objects (explosion prevention etc.)

3.1.3 De-orbiting and reorbiting of space objects

3.2 Protection strategies

3.2.1 Shielding

3.2.2 Collision avoidance

3.3 Effectiveness of mitigation measures

4. Figures

39. Figures I-VIII, presented below, are preliminary versions and will be incorporated into the final technical report on space debris of the Subcommittee.

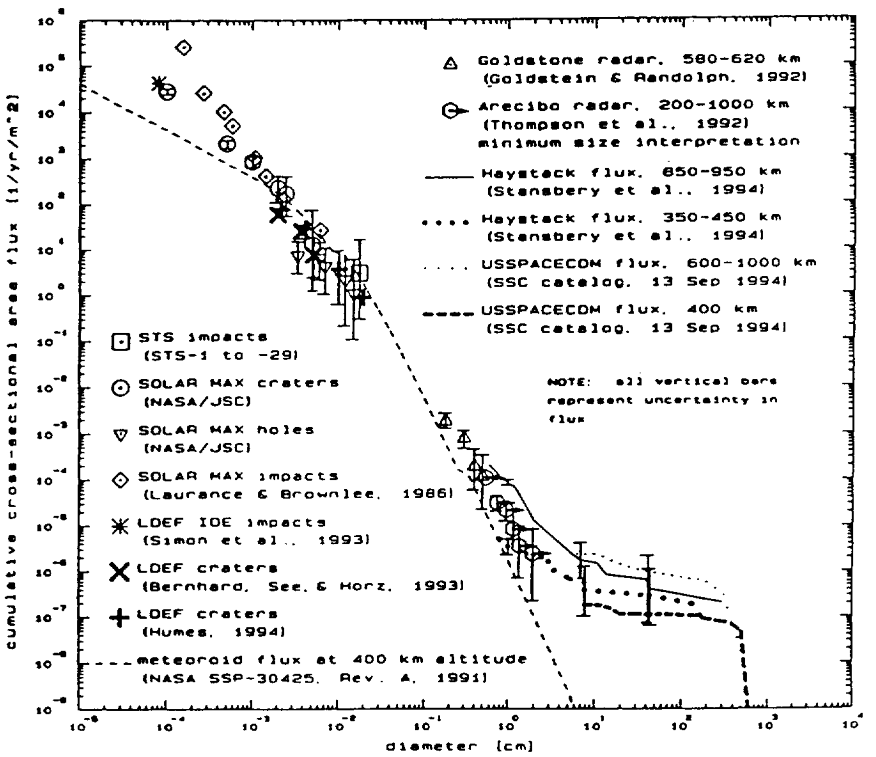

Figure I. Approximate measured debris flux in low-Earth orbit, by object size

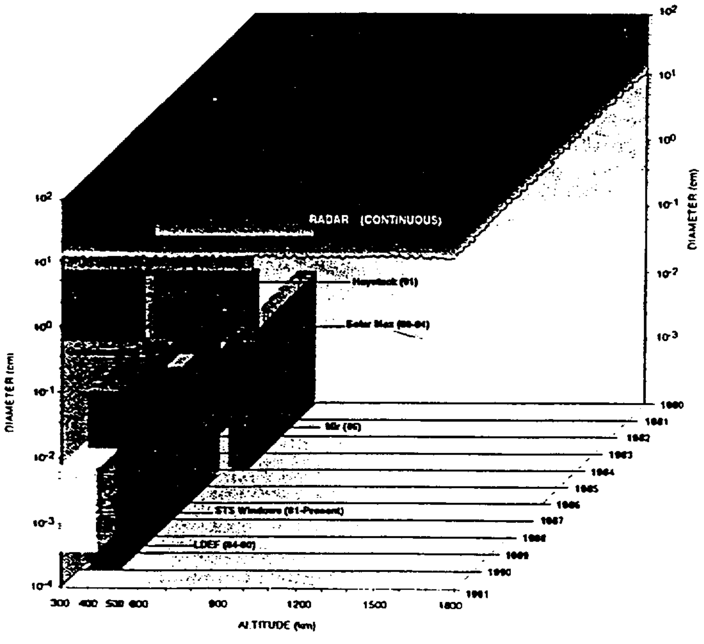

Figure II. Orbital debris characterization data: diameter versus altitude versus year

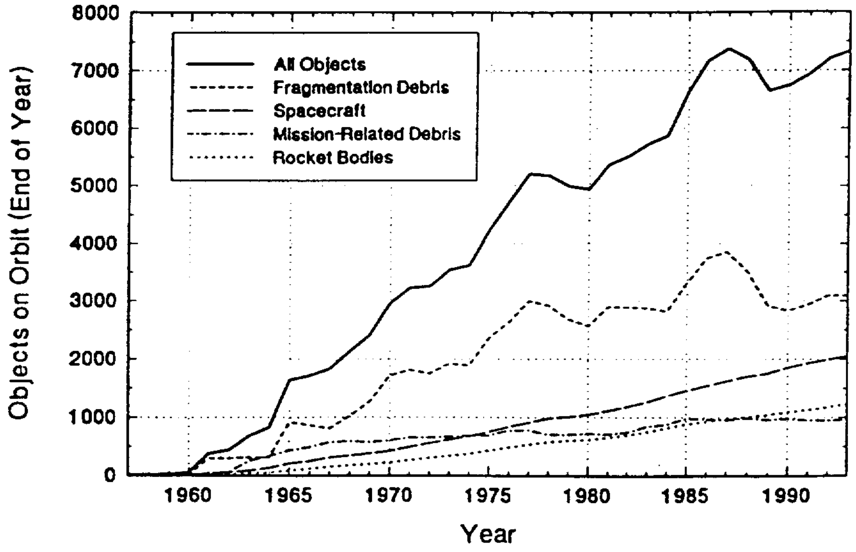

Figure III. On-orbit catalogued population, corrected for delayed cataloguing

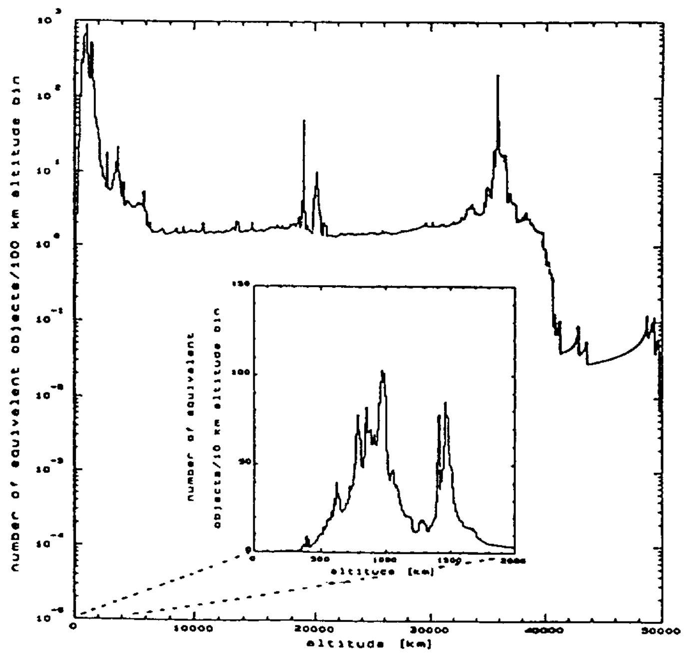

Figure IV. Distribution of satellites in Earth orbit

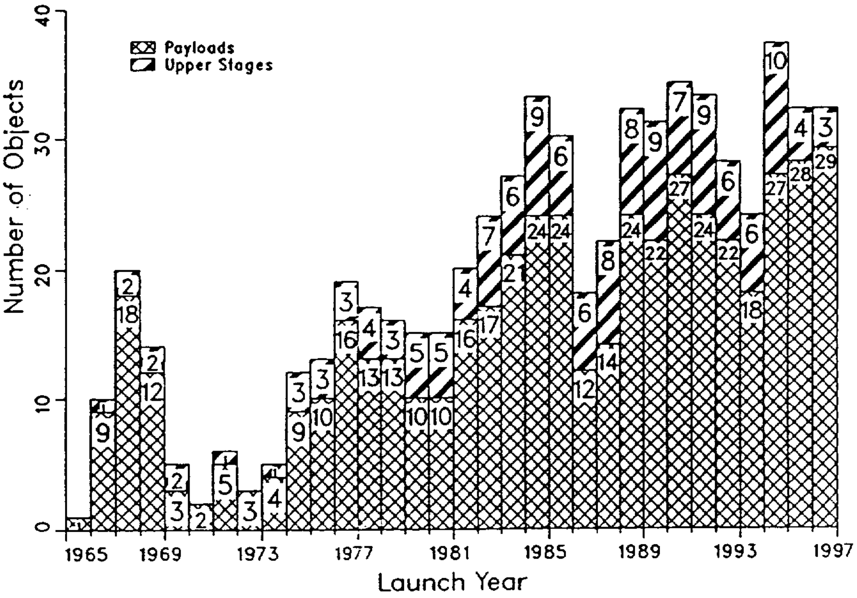

Figure V. Payloads and upper stages launched into geostationary orbit

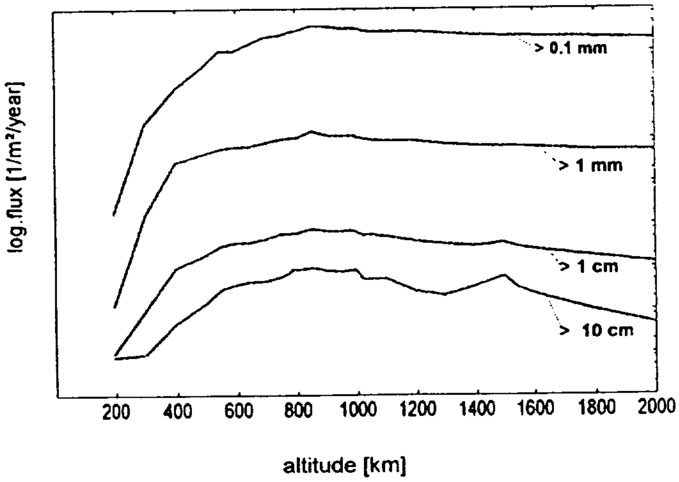

Figure VI. The object flux in low-Earth orbit

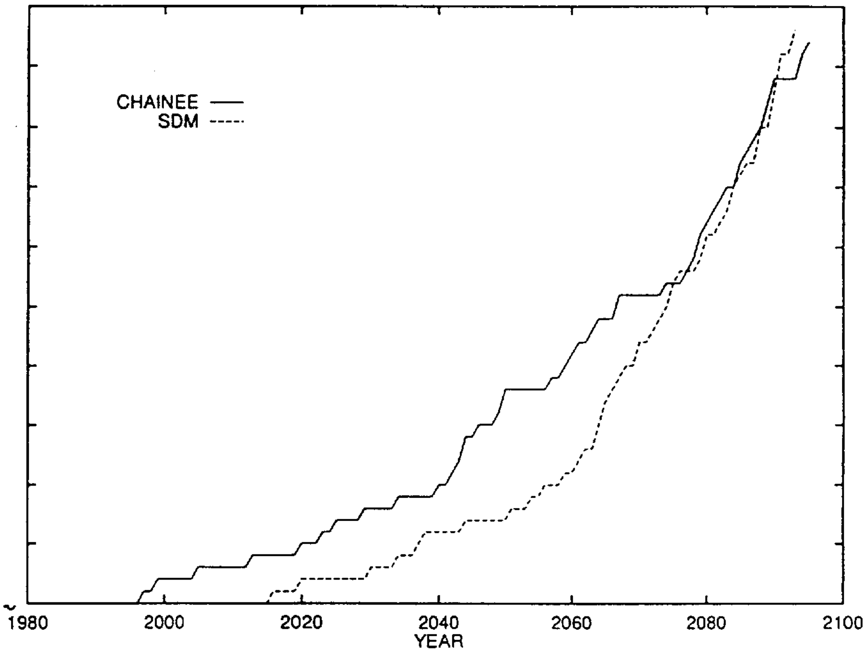

Figure VII. Cumulative number of destructive collisions

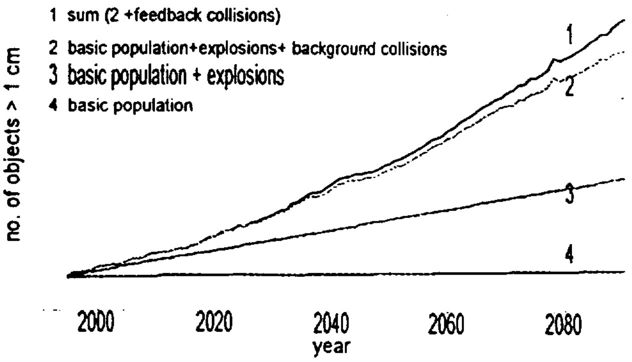

Figure VIII. Simulated population assuming business as usual