NASA /JSC ORBITAL DEBRIS MODELS

Nicholas Johnson and Eric Christiansen
NASA Johnson Space Center, SN3, Houston, Texas, 77058, USA

Robert Reynolds, Mark Matney, Jing-Chang Zhang, Peter Eichler and Al Jackson
Lockheed Martin Space Mission Systems and Services, 2400 NASA Road 1, Mail Code 23,, Houston, Texas, 77058, USA

ABSTRACT

NASA Johnson Space Center's orbital debris program develops and maintains an extensive assortment of computer models and simulations, along with the requisite input databases. The major models and simulations can be categorized as environment definition and risk assessment. The EVOLVE, CHAIN, and ORDEM96 (Orbital Debris Engineering Model 1996) computer programs determine the past, present, and/or future near-Earth orbital particulate environment, while the BUMPER and DAS (Debris Assessment Software) computer programs provide a means for evaluating the risks of specific space missions. The ORDEM96 engineering model has recently been completed and has been officially released to the international orbital debris community. The BUMPER model, which has been adopted by the US Space Shuttle program and the International Space Station program, has also been improved recently and now incorporates the ORDEM96 environment prediction. DAS also assists the space program manager in making debris mitigation decisions in accordance with NASA Safety Standard 1740.14. To support these principal models and to conduct specialized analyses, NASA/JSC employs a host of auxiliary models, including explosion and collision satellite breakup models, orbit propagation and decay models, space traffic models, solid rocket motor effluent models, hypervelocity impact ballistic limit models, and models to relate debris measurements to debris environment model parameters. Special emphasis is now being placed on increasing the fidelity of GEO environment models, future traffic models, highly elliptical orbit propagation models, and solid rocket motor ejecta models.

1. BACKGROUND

The first NASA attempt to calculate the probability of collision between orbital debris and a manned spacecraft occurred in 1966 in support of the Gemini 8 mission. At that time approximately 1,100 objects were known to be in Earth orbit. The following year under the Apollo program, collision probabilities in Earth orbit were again calculated using only the cataloged satellite population. Despite the knowledge of three earlier major breakups in long-lived orbits (1961-15C, 1965-20D, and 1965-82B), the number of untrackable debris was assessed as insignificant. This policy continued through the Skylab program. Although the windows of the Skylab Apollo Command Modules were found in 1974 to have been struck by small hypervelocity particles, the orbital debris origin of some of the craters was not realized until 1980.

Since the beginning of the official NASA orbital debris program in 1979, the Johnson Space Center team of scientists and engineers has consistently pressed the state-of-the-art in orbital debris measurements and modeling. Applying techniques developed in the 1960's to define the natural meteoroid environment, NASA personnel, led by Don Kessler, Drew Potter, and Burt Cour-Palais, during the past two decades have created a family of computer programs to assess the current and future hazards of orbital debris to both manned and unmanned vehicles. The models briefly described in this paper represent the latest tools available to understand and to accommodate the orbital debris environment.

The objectives of the NASA orbital debris modeling effort are five-fold:

(1) Assess the orbital debris environment,
(2) Predict the effects of future launch traffic and space operations on the near-Earth space environment,
(3) Support efforts to minimize and reduce the accumulation of orbital debris,
(4) Assist in the development of debris mitigation techniques, and
(5) Support the formulation of NASA and US orbital debris policies.

2. MAJOR ELEMENTS OF ORBITAL DEBRIS MODELING

The first and foremost requirement of orbital debris modeling is to compile the most comprehensive set of measurement data possible, using both remote and *in situ* instruments. In addition to taking advantage of the common products of the US Space Surveillance

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Network (SSN), NASA has expanded the orbital debris database by special applications or data reductions of specific space surveillance sensors, especially the Haystack, FPS-85 (Eglin), and FPQ-16 (PARCS) radars and the GEODSS (Ground-based Electro-Optical Deep Space Surveillance) facilities. Pioneering work with the Goldstone and Arecibo radiotelescopes, the Haystack Auxiliary Radar, NASA's Liquid Mirror Telescope, NASA's CCD Debris Telescope, and the examination of returned spacecraft surfaces have dramatically extended the range of orbital debris measurements from 10-cm diameter debris to particles as small as one micron. Together, these data have permitted the high quality orbital debris models in use today, not only in the US but also in other space-faring nations.

Understanding the environmental processes which govern the dynamic orbital debris population are essential for present-day as well as future assessments. Today, the major sources of orbital debris are categorized as intact objects, breakup fragments, solid rocket motor (SRM) effluents, nuclear power supply coolant, and debris produced by surface degradation under the harsh space conditions, including thermal stress and atomic oxygen erosion. Since 1980, the measurements programs have been instrumental in the recognition of previously unknown sources of orbital debris. Likewise, to model accurately the current and future orbital debris environments, a thorough understanding of sink processes is necessary. The most important removal forces are atmospheric drag, solar-lunar perturbations, solar radiation pressure, de-orbit maneuvers, and retrievals. All of these effects must be included in complete orbital debris environment models.

To date natural collisions with orbital debris have played a very minor role in the makeup of the Earth satellite population. However, when modeling the far-term environment, the probabilities and consequences of such interactions cannot be ignored. Therefore, the material- and velocity-dependent phenomenology of hypervelocity impacts must also be addressed. Finally, the effects of debris mitigation practices can be evaluated through modeling, leading to the implementation of effective orbital debris policies.

3. PRINCIPAL NASA/JSC ORBITAL DEBRIS MODELS

Five models currently serve as the foundation of the NASA orbital debris program: ORDEM96, BUMPER II, EVOLVE, CHAIN, and Debris Assessment Software (DAS). All of these models (Table 1) are the subject of continuing improvement, verification, and validation efforts to ensure that their results represent the highest level of accuracy possible with the existing knowledge base.

3.1 ORDEM96

The purpose of ORDEM96 is to provide a sufficiently accurate description of the low Earth orbit (LEO) debris environment to assess the risk of collisions with small debris for design and operational considerations. The model does not directly reflect the sources of debris, but it does predict fluxes on a satellite which are consistent with measurements and with other models used to tie these measurements together. Unlike earlier engineering models, ORDEM96 does not describe the flux on a satellite; instead it primarily describes the orbital elements of particles in near-Earth space and then computes the flux (Fig. 1). The environment is approximated by six inclination bands, each of which possesses a unique distribution of semi-major axes for nearly circular and highly elliptical orbits. In addition,

Table 1. Principal NASA/JSC Orbital Debris Models

Model	Type	Principal Application	Platform Requirements	Documentation
ORDEM96	Near-Term Environment	Mission Support	386 PC or Higher	User/Reference Manual
BUMPER II	Near-Term Risk Assessment	Mission Support	VAX, Workstation	User and Reference Manuals
EVOLVE	Near- and Long-Term Environment	Debris Growth and Mitigation Studies	VAX, PC	None Currently Available
CHAIN	Long-Term Environment	Debris Growth and Mitigation Studies	VAX, PC	Reference Manual
DAS	Debris Mitigation Assessment	Mission Support	386 PC or Higher	User Manual

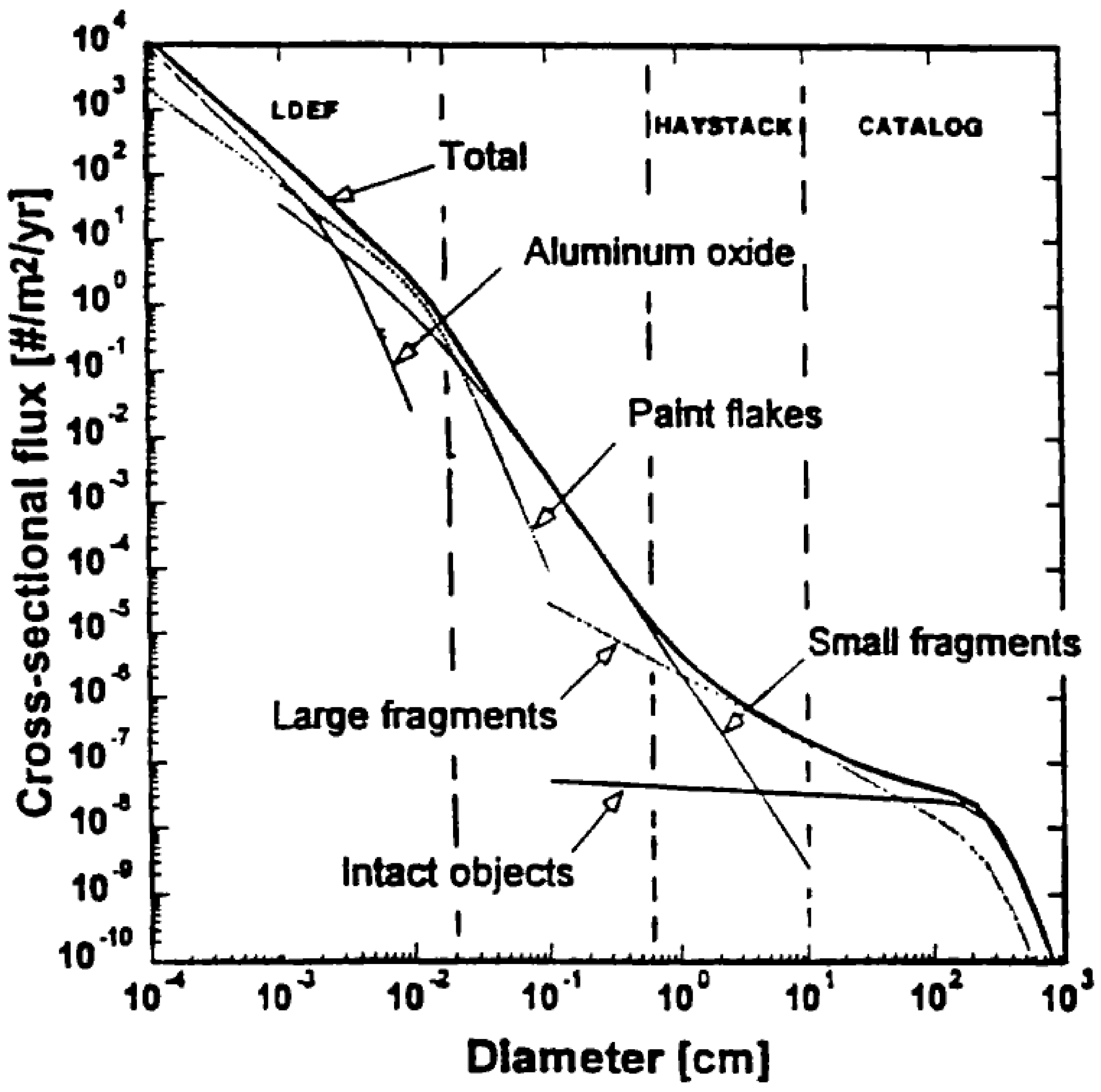

Figure 1. ORDEM96 Model Constituents.

each inclination band has a specific size distribution which depends on the assessed source of the debris.

ORDEM96 outputs the cross-sectional flux, including its angular distribution and the relationship between velocity and azimuth angle of impact. These data are sufficient for further processing to obtain the oriented surface flux, cratering flux, or penetration flux (Ref. 1). The model is valid for the vast majority of cases which are of interest for collision risk assessment, shielding design, and the planning or evaluation of observations. ORDEM96 has been verified and validated using data from the US Satellite Catalog, Haystack radar observations, LDEF returned surface analyses, and the post-flight examinations of the US Space Shuttles.

The ORDEM96 computer program is a DOS application and runs on a PC 386 or higher system. The program requires little memory, hard disk space, or running time, typically completing its computations in less than one second. ORDEM96 has been documented and released to the international orbital debris community (Ref. 2). In the near future, the model will be placed on the Internet under the NASA Johnson Space Center homepage.

3.2 BUMPER II

The BUMPER II model and associated input files are used to predict meteoroid and orbital debris damage to various spacecraft, including the US Space Shuttle and the International Space Station (ISS). For the former, BUMPER II is used to determine the probability of critical meteoroid and orbital debris impacts which endanger the crew or vehicle, the probability of radiator tube penetrations which may result in early mission termination, and the expected number of window replacements. BUMPER II predictions also assist mission mangers in designing the safest attitudes for the Orbiter for each flight. For ISS BUMPER II predicts the probability of meteoroid or orbital debris perforation of over 100 different shield types that protect critical elements such as crew modules and propellant tanks. In addition, the model is used to determine the probability of functional failures due to meteoroid or orbital debris impacts to ISS avionic, thermal control, and power subsystems. BUMPER II has also been applied to various unmanned spacecraft.

In use since 1986, BUMPER models have undergone numerous updates to reflect changes in the orbital debris environment and in the ballistic limit and penetration equations describing impact conditions which may lead to failure of different types of shields and spacecraft materials. Currently, the JSC Hypervelocity Impact Test Facility (HIT-F) employs BUMPER II, Version 1.7, which includes the NASA standard meteoroid model (NASA SSP 30425, Rev. B) and ORDEM96. Ballistic limit equations are sensitive to impactor density, velocity, impact angle, and target characteristics, such as material type, thickness, and spacings. These equations are derived from studies designed to determine the failure criteria for a particular spacecraft component, from hypervelocity impact tests, and from analytical and numerical models used to extend the limited test database to other impact conditions existing on-orbit. BUMPER II input files consist of finite element models (FEMs) of the Space Shuttle (Fig. 2), ISS, and other spacecraft which describe the geometry and spatial location of the spacecraft components and subsystems.

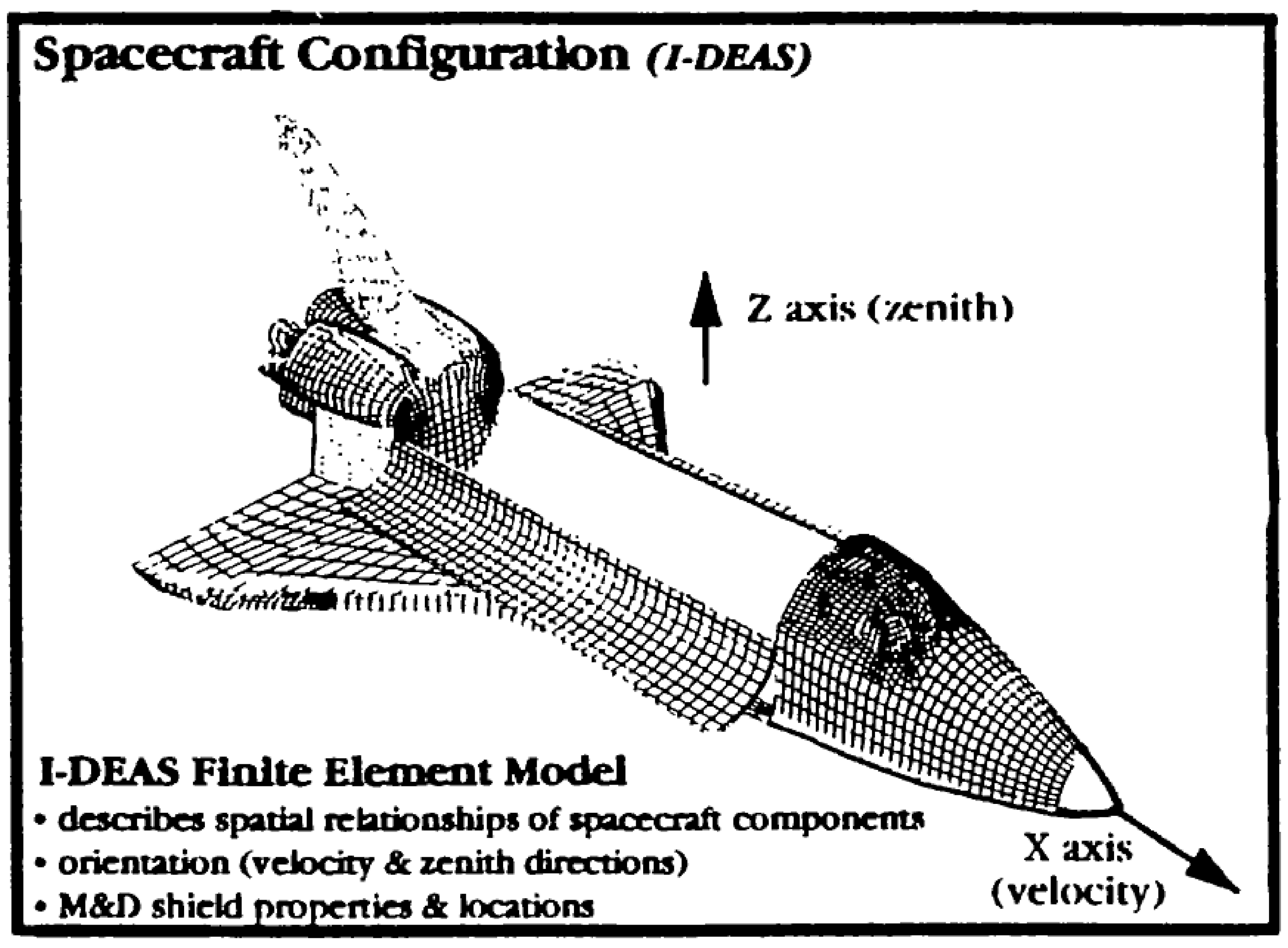

Figure 2. Sample BUMPER II Finite Element Model.

BUMPER II calculates the probability of shield penetration and component failure to determine the risk drivers or areas of a spacecraft which are most vulnerable to meteoroid and orbital debris impact.

Color contours graphically illustrate the areas of highest impact risk. BUMPER II is an excellent tool to assess the effectiveness of various methods (e.g., attitude changes, increased localized shielding or component relocation) to improve spacecraft protection. BUMPER II can assess damage modes for a broad range of different shield types (Whipple, Multi-Shock, Mesh Double-Bumper, Stuffed Whipple, etc.) and various spacecraft materials, including ceramic tiles, ceramic blankets, and reinforced carbon-carbon.

Workstation and VAX versions of the code are available. Configuration-controlled source code and parent executable are archived by JSC/SN3. A BUMPER code is publicly available through the COSMIC program library although this version is approximately three years old and does not contain the latest updates. NASA plans to provide an update to the COSMIC library after formal approvals are completed. User's manuals and reference manuals are also available (Refs. 3 and 4). Additional and higher fidelity FEMs are planned for ISS, Space Shuttle, EVA space suits, the Mir space station, advanced manned spacecraft, and unmanned satellites.

3.3 EVOLVE

The EVOLVE model combines historical space operations data with special purpose routines to simulate semi-deterministically the evolution of the orbital debris environment to the present, while Monte Carlo techniques are employed for investigations of future evolutionary characteristics under various debris mitigation practices. Launched objects, explosion and collision breakup fragments, and non-fragmentation debris are placed into specific orbits by the model, which then calculates how these orbits will change in time and such characteristics as flux as a function of time, altitude, and debris size as well as collision rates between large objects in orbit. A fast orbit propagator, which accounts for J_2 and solar-lunar perturbations and aerodynamic drag, is a part of the EVOLVE model.

EVOLVE places breakup fragments into the environment according to the mass and velocity distributions in special NASA breakup models, and debris from non-fragmentation sources are placed in orbits according to specific models for those debris deposition processes, e.g., SRM ejecta. Debris mitigation measures are modeled in EVOLVE through the scenario definition file. Scenarios can be run controlling future launch rates, accidental explosions, and post-mission orbit lifetimes for spacecraft and upper stages. Launched objects are placed in orbit in accordance with historical data or for environment projections with mission model data which specify the launch date and orbits for spacecraft and upper stages.

The typical EVOLVE environment projection is started by calculating the current environment based upon the historical record of launches and breakup events (Fig. 3). This current environment is then used as the

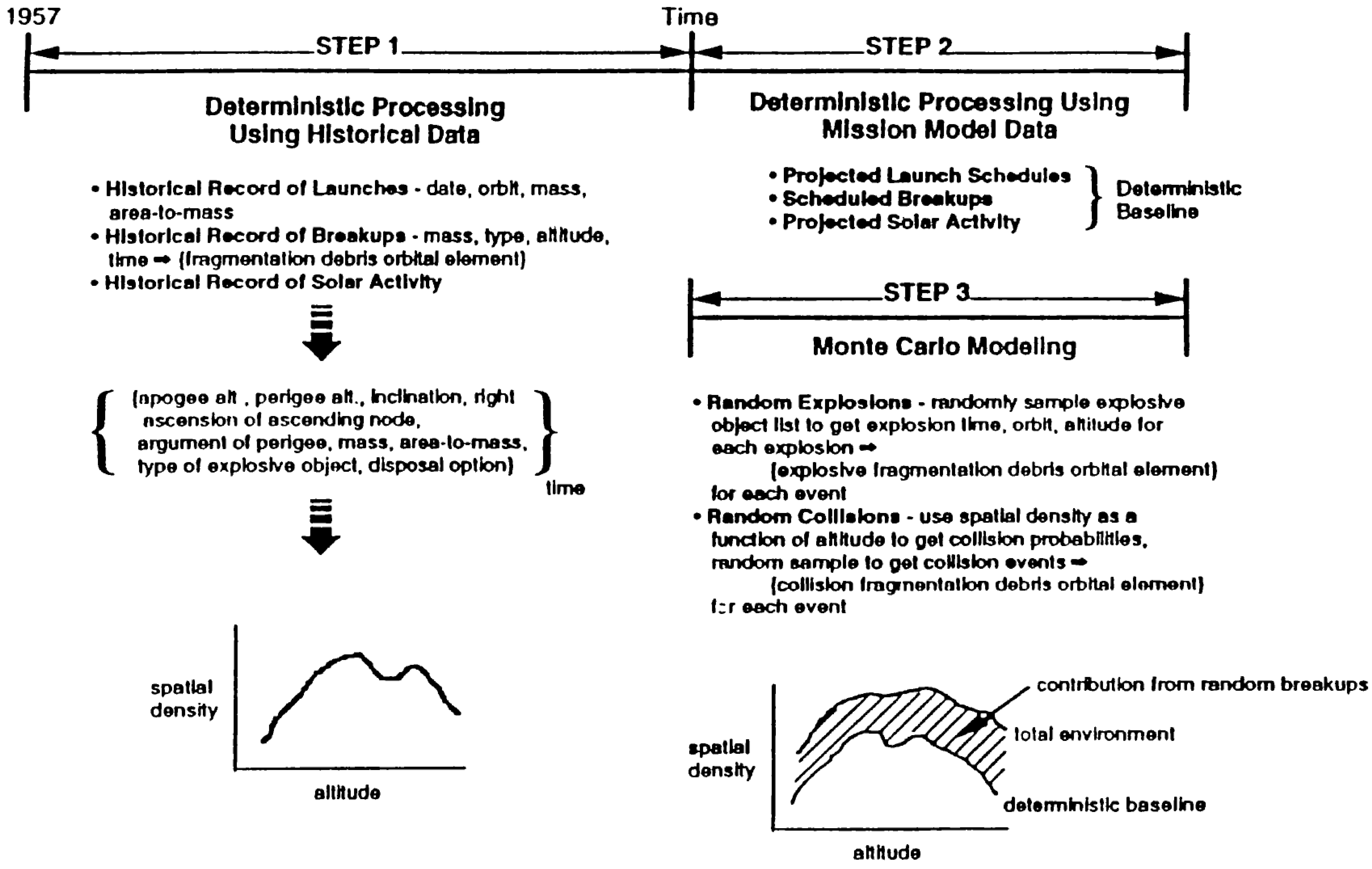

Figure 3. Program EVOLVE.

initial condition for debris projections. Since EVOLVE calculates the current environment, comparisons between this environment and measures of the current satellite population (including small particle measurements by the Haystack radar) can be used to provide confidence that historical sources of orbital debris are being handled properly.

Due to its complexity, EVOLVE currently remains a NASA in-house analytical tool run normally on a VAX system using virtual memory to accommodate the necessary large arrays, although PC versions have been tested. The present version of EVOLVE is documented through the code, but no comprehensive, up-to-date user's manual or reference manual is available. Plans exist to prepare such program documentation after modifications to the model, including revised breakup models and non-fragmentation source models, are completed in 1997. An extension of EVOLVE to GEO is also planned as is the incorporation of solar radiation effects in the orbit propagator.

3.4 CHAIN

CHAIN is a fast analytical tool employing the particle-in-a-box (PIB) theory to perform long-term environment projections. A PIB model reduces the debris environment to a number of random elements in a set of mass and altitude bins. Breakup models, orbit propagation, and population growth as a function of the space traffic scenario are modeled off-line by the pre-processing software and are used as rate coefficients and fit functions in CHAIN (Fig. 4). As a result, using the analytical CHAIN code for environment projections is faster by a factor of 10^3 to 10^4 compared to EVOLVE, although at the sacrifice of some fidelity. CHAIN is calibrated to the output of EVOLVE runs over a 100-year period and then may be used (1) to perform parametric analyses by examining a large number of projections under varying model parameters and (2) to extend EVOLVE runs further into the future.

The model was originally developed by Eichler at the Technical University of Braunschweig, Germany, under contract from the German Federal Ministry of Research and Technology during 1988-1991. Since 1993 Eichler has continued the development of CHAIN at NASA/JSC. A modification of CHAIN called CHAINEE (CHAIN European Extension) has been employed by ESA since 1995.

The principal outputs of CHAIN, in 1-year time-steps, are the number and mass of objects in LEO in four altitude and six mass bins and the annual and cumulative collision rates. Non-catastrophic collisions are neglected. Verification and validation of the CHAIN code is done primarily through comparisons with NASA breakup models and the EVOLVE model which, as noted above, is used also to calibrate CHAIN. Like EVOLVE, CHAIN is primarily used as an engineering tool within NASA/JSC and has been ported to both VAX and PC platforms. A detailed description of the model is contained in Eichler's doctoral thesis (Ref. 5). Upgrades to CHAIN will follow the revision of the EVOLVE model, e.g., extending the population database to include GEO objects.

3.5 Debris Assessment Software (DAS)

DAS was developed to assist NASA program managers in conducting debris assessments, as required in NASA Management Instruction 1700.8. The collection of routines provides a complete set of models needed to perform the debris assessments for (1) debris released during normal operations, (2) debris generated by explosions and intentional breakups, (3) debris generated by on-orbit collisions, (4) post-mission disposal of space structures, and (5) survival of reentering space system components after disposal. The architecture of DAS is linked to the format of NASA Safety Standard 1740.14 for ease of report preparation, and a separate DAS user's guide serves as a companion to NSS 1740.14.

The menu-driven, interactive DAS runs on a PC 386 and higher platform in either a DOS or Windows environment. The software presents its results in numerical, graphical, or tabular form, depending upon the application. Several options are available for calculating the lifetimes of orbits and the probability of collisions with both small and large space objects. Useful routines are also provided in a separate support module to calculate related parameters, e.g., the change in velocity required to perform a specified maneuver. Software and a user's manual (Ref. 6) are available from NASA/JSC. In early 1997 DAS was updated with the ORDEM96 environment module. A further update to the model is envisioned later in 1997 to support Revision A of NSS 1740.14.

4. SPECIAL PURPOSE MODELS AND DATABASES

To support the above models, either directly or indirectly, a number of special purpose models and databases are necessary. NASA/JSC currently employs three primary fragmentation models to simulate the initial debris clouds of low and high intensity explosions and collisions. These models, based upon terrestrial tests, on-orbit observations, and analytic treatments, calculate the number of debris of a limiting size generated by the event as well as the related velocity and ballistic coefficient distributions. In the case of EVOLVE, for example, these velocity distributions are applied to the orbital characteristics of the parent object to determine the subsequent debris orbits. The NASA fragmentation models are currently under review with an objective of improving their fidelity and accuracy by the end of 1997.

Ballistic limit equations have been developed for various shields and spacecraft materials based on hypervelocity impact tests and analyses. Both generalized and specific equations are available: generalized equations cover a variety of target types with lower fidelity, while material-specific equations can provide greater accuracy results. HIT-F test data are normally limited to aluminum and plastic spherical projectiles at velocities from 2 to 8 km/s, although some higher density and velocity data are available. Analysis and hydrocodes are used to cover density and velocity ranges outside of the testing regime. Efforts are underway to develop and to verify ballistic limit equations for a wider range of possible threat particles with emphasis on density and shape variations and to provide ballistic limit equations for more target materials and shielding configurations.

Orbit propagators used to support NASA/JSC orbital debris modeling belong to one of three categories: high speed analytic, moderate speed analytic, and low speed numerical integration. The high and moderate speed analytic routines are both orbit averaged methods of trajectory propagation. The high speed propagator uses classical orbital elements with averaged eccentric anomaly and accounts for J_2 and J_3 harmonics, atmospheric drag, and first-order solar-lunar perturbations. The moderate speed propagator averages true anomaly while using Delaunay orbital elements. In addition to the forces noted above for the high speed propagator, the moderate speed propagator also considers solar radiation pressure effects. The high precision numerical integrator is an implicit Runge-Kutta method with Gauss-Radau spacings developed by Everheart. The gravity field of the Earth may be modeled up to 8x8 in the harmonics. Jacchia/Linberry density models, which include the effects of diurnal bulge, the solar cycle, and geomagnetic activity, support both the moderate and slow speed propagators. While the high speed propagator is adequate for working with most objects in LEO, the moderate or slow speed propagators are usually required for highly elliptical and geosynchronous orbit propagations.

NASA uses two size estimation models (SEMs) that compute an average size for a given radar cross-section (RCS) value. One relies on the unweighted average RCS value from ground tests, and the other uses a simple size distribution fit approximation to compute the weighted averages. Both conversion methods give similar results and work well in simulations, but they do not preserve the amount of uncertainty introduced by this conversion. NASA is undertaking a special study to carefully quantify the magnitude of uncertainties introduced by the conversion of an RCS distribution to a size distribution, as well as the statistical uncertainties from finite sampling errors. NASA/JSC also maintains a composite RCS catalog with multiple RCS estimates for individual space objects as reported regularly by US Space Command.

An historic space traffic model is maintained for all known launches with essential characteristics such as object type, orbital parameters, date of launch, main body dimensions, dry mass, country of origin, and mission profiles. Such models are also valuable in determining the trends of satellite population growth, e.g., the annual increase of mass in LEO (Fig. 5). With this database and one of the above propagators, snapshots of the cataloged space object population can be simulated and compared with official observations. Future space traffic scenarios can be examined to determine the sensitivity of the debris environment to certain space operations. Special databases have been compiled for SRM firings, satellites with radioactive materials on-board, and geosynchronous missions. For example, the SRM database includes the type of SRM, pre- and post-maneuver orbital characteristics, and mass of propellant burned, whereas the geosynchronous mission database contains information concerning end-of-mission reorbiting maneuvers.

5. SUMMARY

The NASA orbital debris modeling effort provides environment assessments for US and international space programs. The orbital debris environment models, which provide risk assessments for both manned and unmanned space operations, are vital for extrapolating across debris regimes with limited observational data. Models of the current and projected environment are frequently updated to take advantage of the latest observational data and research efforts. NASA orbital debris models also support the development of mitigation techniques to limit the growth and effects of orbital debris.

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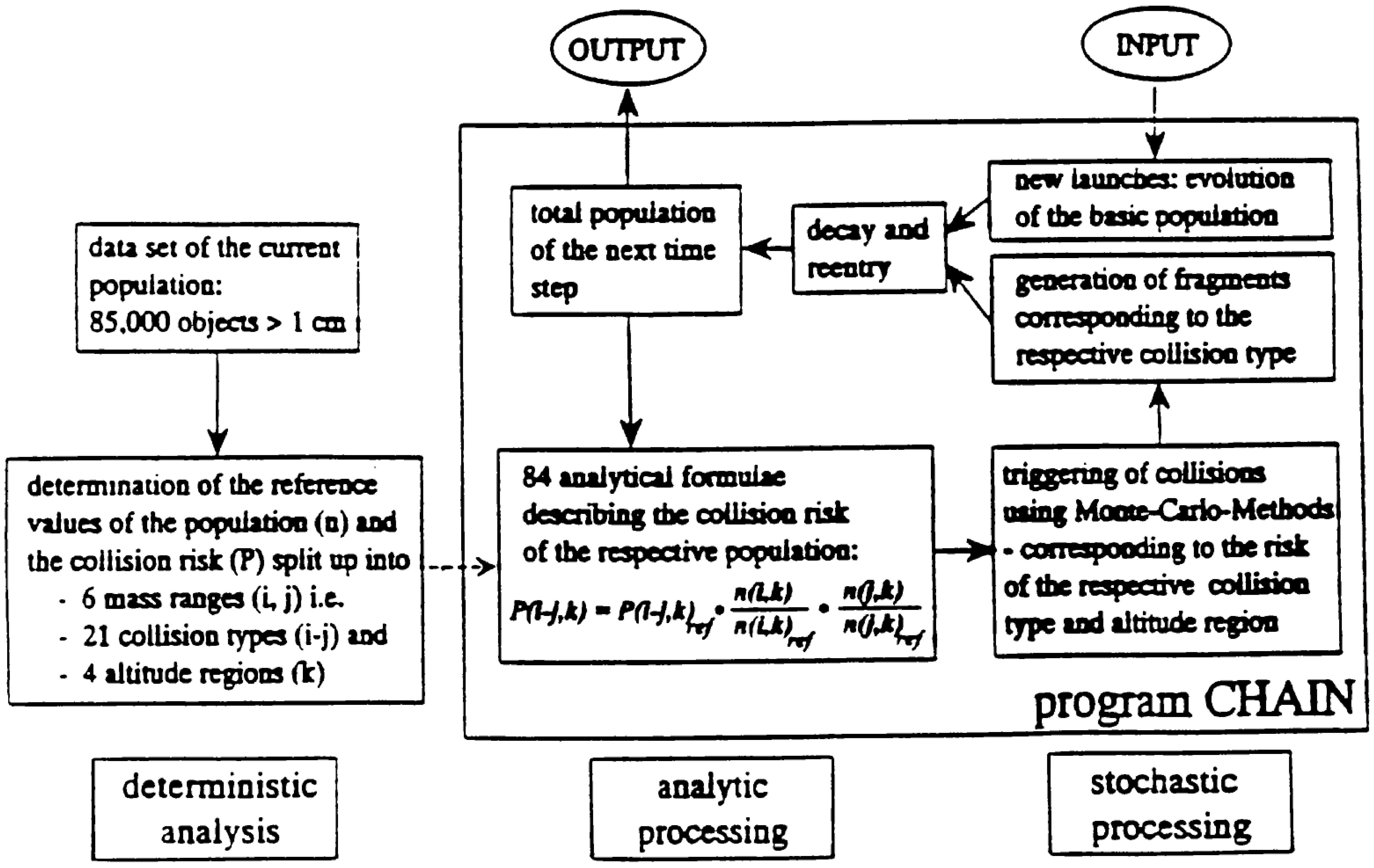

Figure 4. Program CHAIN.

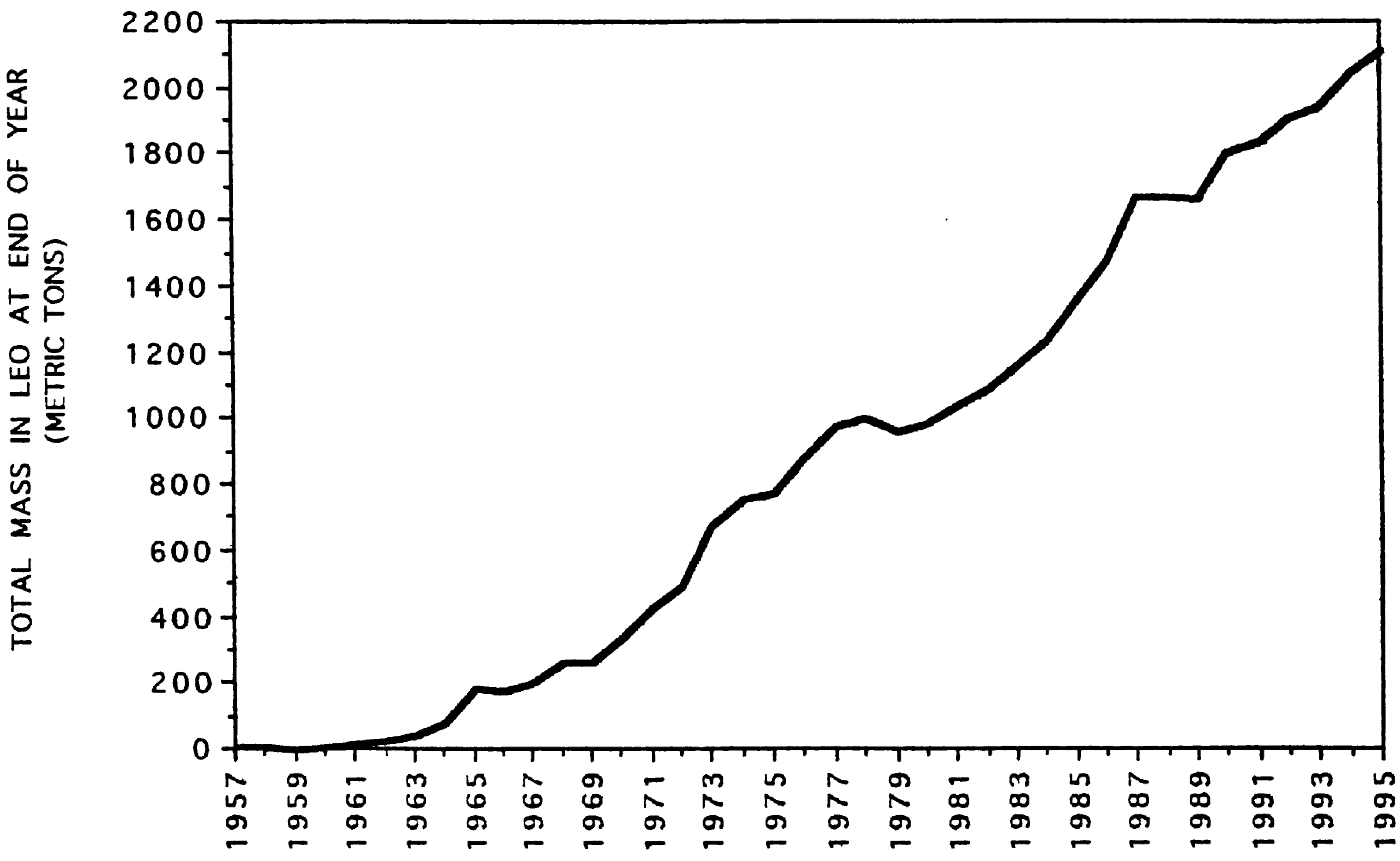

Figure 5. Growth of Satellite Mass in LEO.

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