# SPACE DEBRIS MODELING AT NASA

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## ABSTRACT

Since the Second European Conference on Space Debris in 1997, the Orbital Debris Program Office at the NASA Johnson Space Center has undertaken a major effort to update and improve the principal software tools employed to model the space debris environment and to evaluate mission risks. NASA's orbital debris engineering model, ORDEM, represents the current and near-term Earth orbital debris population from the largest spacecraft to the smallest debris in a manner which permits spacecraft engineers and experimenters to estimate the frequency and velocity with which a satellite may be struck by debris of different sizes. Using expanded databases and a new program design, ORDEM2000 provides a more accurate environment definition combined with a much broader array of output products in comparison with its predecessor, ORDEM96. Studies of the potential long-term space debris environment are now conducted with EVOVLE 4.0, which incorporates significant advances in debris characterization and breakup modeling. An adjunct to EVOLVE 4.0, GEO_EVOLVE has been created to examine debris issues near the geosynchronous orbital regime.

In support of NASA Safety Standard (NSS) 1740.14, which establishes debris mitigation guidelines for all NASA space programs, a set of evaluation tools called the Debris Assessment Software (DAS) is specifically designed for program offices to determine whether they are in compliance with NASA debris mitigation guidelines. DAS 1.5 has recently been completed with improved WINDOWS compatibility and graphics functions. DAS 2.0 will incorporate guideline changes in a forthcoming revision to NSS 1740.14. Whereas DAS contains a simplified model to calculate possible risks associated with satellite reentries, NASA's higher fidelity Object Reentry Survival Analysis Tool (ORSAT) has been upgraded to Version 5.0. With the growing awareness of the potential risks posed by uncontrolled satellite reentries to people and property on Earth, the application of both DAS and ORSAT has increased markedly in the past two years.

This paper describes the aforementioned as well as other space debris models currently in use by NASA.

## 1. INTRODUCTION

Space debris modeling has been an important element at NASA since the inception of the agency in 1958. Initially, only the natural meteoroid environment posed a threat to human space flight and to robotic missions in Earth orbit or beyond. However, less than 10 years after the beginning of the Space Age, NASA recognized that artificial, i.e., man-made, debris could no longer be ignored. The year 2001 marks the 35$^{th}$ anniversary of orbital debris modeling at the NASA Johnson Space Center in Houston, Texas.

Although NASA researchers are now equipped with extensive measurements databases, sophisticated statistical techniques, and ever-increasing computational power, the basic objectives of the NASA space debris effort remain unchanged:

(a) assess the space debris environment,
(b) predict the effects of future launch traffic and space operations on the near-Earth space environment,
(c) support efforts to minimize and reduce the accumulation of orbital debris,
(d) assist in the development of debris mitigation techniques, and
(e) support the formulation of NASA, US, and international orbital debris policies.

This paper highlights the advances made at NASA in space debris modeling since the program summary presented four years ago at the Second European Conference on Space Debris [1].

## 2. ORDEM2000

In 1996 NASA introduced its first computer-based orbital debris engineering model, ORDEM96 [2]. This semi-empirical model was developed to combine direct measurements of the environment with the output and theory of more complex orbital debris models. The principal purpose of the model was to provide orbital debris researchers and space system designers with an easy-to-use tool to assess the nature of the orbital debris environment, including its component parts, in specific LEO regimes.

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ORDEM96 quickly became a community standard and for several years has served as the foundation of risk assessments for the U.S. Space Shuttle, the International Space Station (ISS), the Extravehicular Activity (EVA) space suits, and a host of Earth-orbiting robotic space missions. However, faced with (1) a growing and diverse set of new environment measurements over a broad span of particle sizes (10 microns to 10 cm), (2) affordable, high capacity computational equipment, and (3) an obviously dynamic environment, NASA embarked upon an effort to replace ORDEM96 with a much more capable and user-friendly orbital debris engineering model. The product of this undertaking, ORDEM2000, has recently been completed and subjected to an international peer review.

A more complete description of ORDEM2000 is given in another paper prepared for this conference [3]. Here, it is sufficient to say that ORDEM2000 has adopted a new approach for its characterization of the near-Earth environment up to 2000 km. The particle population is no longer simplified into orbital inclination and eccentricity families. Instead, a 3-dimensional definition of the environment in cells of longitude, latitude, and altitude has been created. Each cell contains information on spatial density as well as velocity and inclination distributions, permitting a wide range of analyses (Fig. 1).

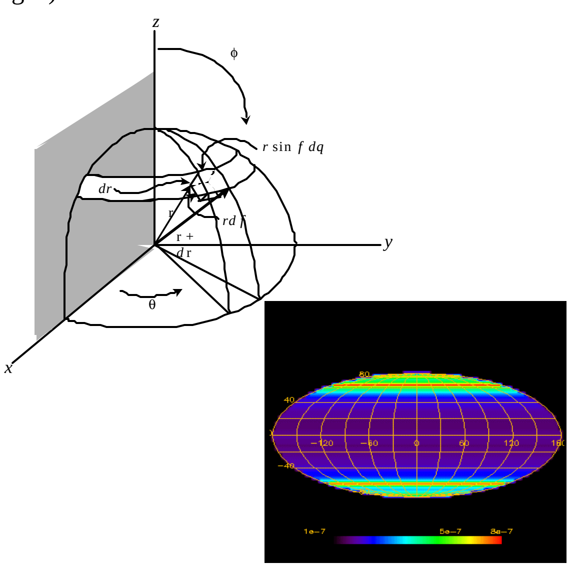


Fig 1. Three dimensional environment definition of ORDEM2000.

The new model explicitly takes into account the change in the LEO environment during the past decade. The U.S. Satellite Catalog reflects large object increases at virtually all altitudes [4]. At the other end of the spectrum, U.S. Space Shuttle debris impact experience population estimates, previously based on LDEF exposure in the 1980's. Intermediate-size particle populations have been refined with data from the Haystack, Haystack Auxiliary, and Goldstone radars [5].

Since ORDEM2000, like its predecessor, must support debris vulnerability assessments for long-lived space systems now under development, projections of environmental changes through the year 2030 are included in the model. The basis for these projections is found in NASA's new evolutionary debris environment model, EVOLVE 4.0.

## 3. EVOLVE and GEO_EVOLVE

Perhaps the most significant modeling improvements at NASA in recent years have been associated with long-term environment projections. A major update of the well-known NASA EVOLVE model was completed in 2000 [6]-[7], and a new GEO_EVOLVE model was created for the higher altitude regime [8].

Development of the EVOLVE 4.0 model required extensive upgrades to many of the supporting routines, such as the explosion and collision debris generation models. The explosion model, in particular, benefited from new small particle (0.5-10 cm) environment measurements, leading to the recognition of a greater number of smaller debris (Fig. 2). The orbit propagation, launch traffic, and solar activity models were also improved.

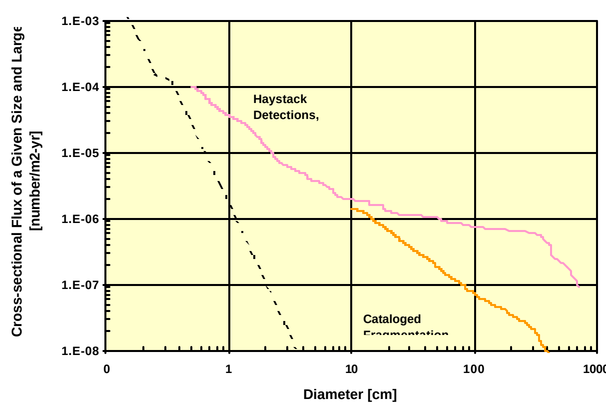


Fig. 2. Observational evidence for distribution function of explosively generated debris.

The EVOLVE 4.0 model has already been exercised to evaluate a number of environmental sensitivities. The first such study reexamined the consequences of various mitigation measures, including explosion suppression and space structure removal [9]. The results support the widely accepted recommendation to limit the orbital lifetimes of spacecraft and upper stages

(Fig. 3). Although this policy clearly illustrated a benefit to the 1-cm debris population at human space flight altitudes, the 10-cm and larger satellite population actually increased due to more spacecraft and upper stages decaying through the 400 km altitude region [10]. Other studies found the debris environment to be relatively insensitive to the collision energy threshold for catastrophic collisions but strongly sensitive to projected levels of launch traffic [11].

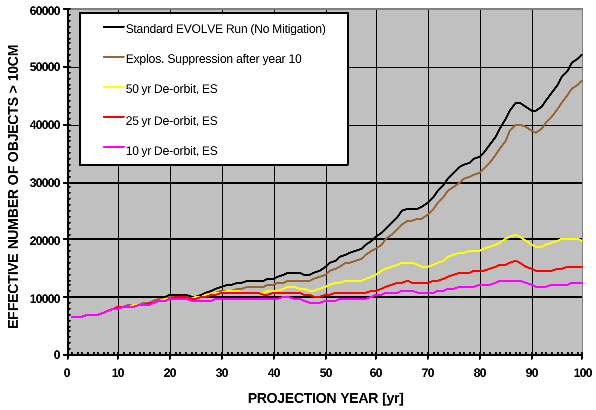


Fig. 3. Effects of different debris mitigation policies on the long-term satellite population.

NASA developed the GEO_EVOLVE 1.0 model to allow studies of the long-term nature of the near-GEO satellite population under the influences of launch traffic, explosions, collisions, and various disposal strategies (Fig. 4). The unique aspects of GEO, both in terms of orbit distributions and relative impact velocities, dictated a modeling philosophy different from that of EVOLVE 4.0. Specifically, the tendency of GEO objects to oscillate about a stable plane required a new collision computation method, and the lower collision velocities led to a different debris generation model.

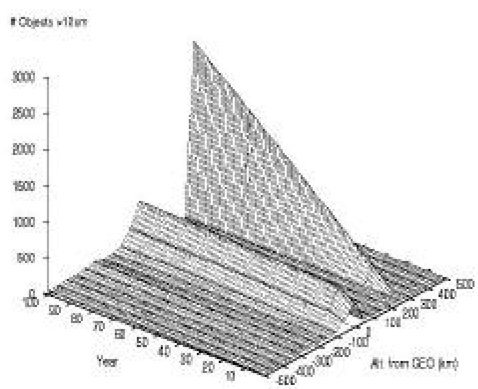


Fig. 4. Anticipated growth of the GEO disposal orbit regime.

## 4. DAS

The Debris Assessment Software (DAS) family of models is actually a collection of software models and tools tailored to assist program managers in determining their compliance with NASA Safety Standard (NSS) 1740.14, *Guidelines and Assessment Procedures for Limiting Orbital Debris*. The main subject areas are collision probabilities, orbital lifetimes, and reentry risks. However, the DAS models also include a variety of useful calculators, for example, to determine $\Delta V$ requirements for orbital maneuvers or propellant mass needed for deorbiting.

The original DAS version X.09 was upgraded in 1998 to Version 1.0 [12]. During 2000 work began on DAS Version 1.5 to install a WINDOWS-like graphical user interface and to expand upon output printing options. Some minor improvements to the technical routines were also incorporated. The DAS 1.5 model will be available for distribution in the Spring of 2001. A Version 2.0 is planned to incorporate anticipated changes in NSS 1740.14. One of these changes will be a switch from a reentry casualty area to a reentry probability of human casualty measure of merit. In addition, this calculation will be related to the specific orbital inclination in question, instead of an averaged value.

## 5. MORSAT AND ORSAT

The DAS model routine used to estimate the debris casualty area from a reentering satellite is based upon the Miniature Object Reentry Survival Analysis Tool (MORSAT), which was first released in 1994 [13]. MORSAT uses a limited input database to conduct a first order assessment of what satellite components are likely to survive the reentry process and reach the surface of the Earth.

The philosophy of MORSAT is to simplify the input requirements in a manner which leads to a conservative (potentially exaggerated) casualty area calculation. If the total calculated casualty area is less than 8 $m^2$, then the satellite can confidently be assumed to satisfy NASA guidelines. On the other hand, if the answer is in excess of 8 $m^2$, then the satellite might still be compliant with NASA guidelines, but a higher fidelity model, ORSAT, must be applied to confirm.

In 1999 the Object Reentry Survival Analysis Tool (ORSAT), Version 5.0 was released [14]. Unlike MORSAT, which was designed for ease of use, ORSAT requires a highly knowledgeable operator to prepare the input data, to execute the model, and to interpret the results. The commensurate benefits, however, are considerable [15]. The use of ORSAT to determine reentry risks, as well as impact debris locations, has grown substantially during the past few years (Fig. 5). The ORSAT model has recently been employed to address reentry issues of the Compton Gamma Ray Observatory, Iridium Satellites, the Tropical Rainfall Measuring Mission (TRMM), and the Extreme Ultraviolet Explorer (EUVE) satellite, to name a few. A summary of the EUVE satellite analysis with MORSAT and ORSAT will be presented later at this conference [16].

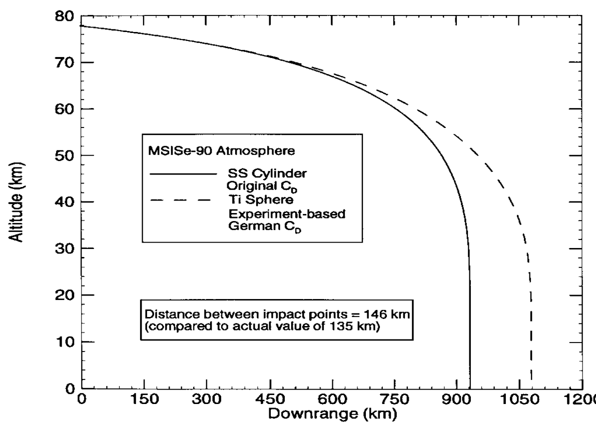


Fig. 5. Prediction of impact point separation of two major surviving components from a Delta II second stage.

## 6. BUMPER

The purpose of the BUMPER model is to quantify the space debris risks, both natural and man-made, to specific vehicles. First, a detailed finite element model (FEM) of the satellite, e.g., the U.S. Space Shuttle, is prepared denoting the different types of surface materials. The simulated vehicle is then inserted into the debris environment (ORDEM plus standard meteoroid model) at the proper altitude, inclination, and attitude to determine the probability of impact on each surface element cell. Using ballistic limit equations developed from extensive laboratory impact testing, the consequences of each impact (location, angle, velocity, impactor type), i.e., penetration or no penetration, is evaluated. Similar relationships are also used to determine the size of the impact which might have caused damage found on the U.S. Space Shuttle after a mission.

BUMPER is used before each U.S. Space Shuttle mission to assess the probability of a critical impact which might endanger the crew or vehicle, the probability of radiator tube penetrations which might result in early mission

replacements which will be required after the mission. These assessments not only guide mission managers in designing the safest attitudes for the U.S. Space Shuttle for each flight, but also have identified areas where minor vehicle changes could noticeably increase safety. For example, the U.S. Space Shuttle fleet is being modified with protective strips on the radiators above coolant lines and with additional insulation behind the leading edge of the wings, all due to BUMPER analyses.

The ISS has also been the subject of extensive BUMPER analyses. Each critical ISS element is evaluated with BUMPER to determine the element and overall ISS reliability (Fig. 6). Similar assessments have been made of the EVA space suits, and the inflatable Trans Hab module. BUMPER can assess damage modes for a broad range of different shield types (Whipple, Multi-shock, etc.) and various spacecraft materials, including ceramic tiles and blankets and reinforced carbon-carbon.

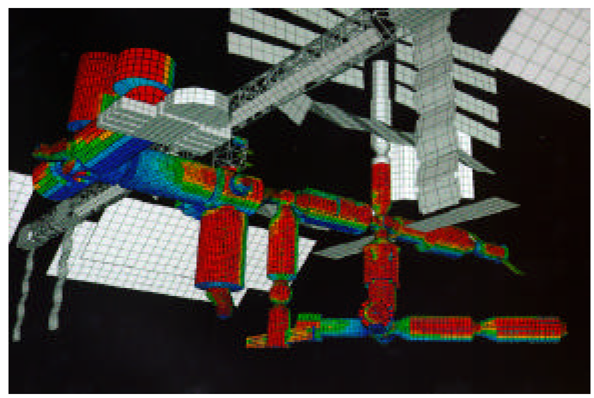

Fig 6. BUMPER debris impact probability assessment for the International Space Station.

## 7. SBRAM

On average during the 1990's, 5-6 satellite breakups were detected each year by the U.S. Space Surveillance Network (SSN). Since a single satellite breakup might generate thousands of debris greater than 1 cm in diameter, a means of determining collision risks for other spacecraft was sought by NASA. In 1998 the Satellite Breakup Risk Assessment Model (SBRAM) was developed at JSC as an operational tool for NASA human space flight missions [17].

Upon notification by the SSN of a satellite breakup, NASA personnel use SBRAM to estimate any risks to the U.S. Space Shuttle or ISS. With a knowledge of the nature and orbital parameters of the satellite involved in the breakup and using a Monte Carlo method to create test clouds of particles and propagate them, SBRAM directly calculates the probabilities of collision with collision as well as the probable direction of the impactor can be predicted for several days or weeks, until the spatial density of the debris declines to approximately background levels.

SBRAM was upgraded in 2000 with a new graphical user interface and with the EVOLVE 4.0 breakup models (Fig 7).

For routine collision avoidance against resident space objects, NASA JSC personnel, in conjunction with SSN orbital analysts, have developed for the ISS program a new technique based upon modeling contours of constant collision probability. The goal of the effort was to provide high-confidence estimates of collision probability to reduce the number of collision avoidance maneuvers performed annually. The prediction uncertainties inherent with the earlier U.S. Space Shuttle procedures would have resulted in an unnecessarily high number of annual maneuvers. With the new ISS collision avoidance model, a risk reduction of 80-85% has been achieved with about two maneuvers per year.

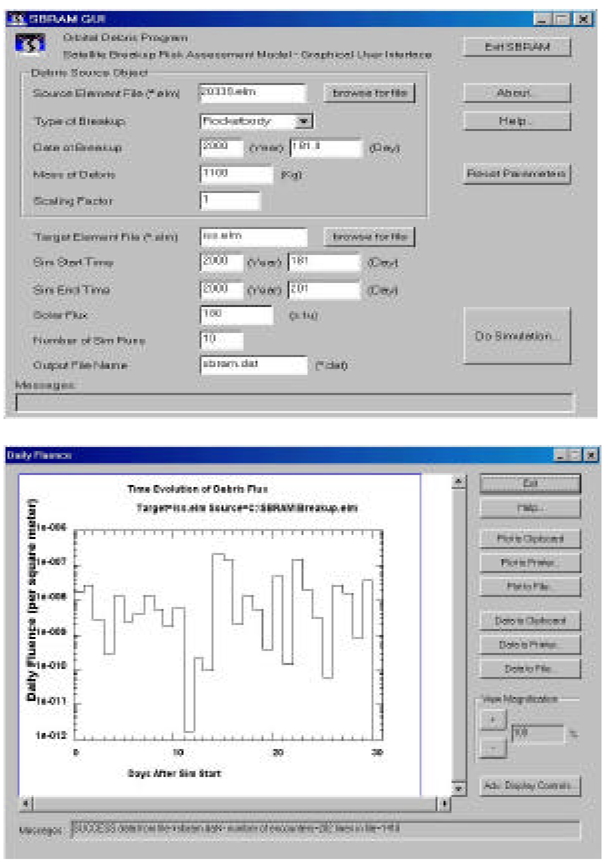


Figure 7. SBRAM graphical user interface.

## 9. OTHER MODELS

In addition to the aforementioned models, NASA has developed and employs a wide variety of special purpose software and models to support its space debris research activities. Although space limitations do not permit complete descriptions of these models, the following represent the diversity of topics addressed:

(a) Size Estimation Model (SEM): frequency-dependent method to convert the radar cross-section (RCS) estimate of a debris particle to a characteristic length, particularly for use in ORDEM and EVOLVE;

(b) Orbital Propagation Models: both analytic and numerical integration techniques to propagate satellite orbits in LEO and at higher altitudes, including the effects of atmospheric drag, solar-lunar perturbations, radiation pressure, and the Earth's gravity field;

(c) Solid Rocket Motor (SRM) Effluents Model: generator of small and large particles ejected during and after the burn of SRMs;

(d) Solar Activity Model: short- and long-term projections of solar activity (F10.7), especially for EVOLVE;

(e) Launch Traffic Models: collection of scenarios of varying levels of launch traffic to LEO, MEO, and HEO;

(f) Automatic Streak Detector: software used to detect fast moving, low altitude meteoroids and debris in Liquid Mirror Telescope videos;

(g) Automatic Star Correlator and Calibrator: software used to identify star fields and estimate the size of debris near GEO; and

(h) Meteoroid Engineering Model (METEM): integrated near-Earth, planetary, and deep space model of the meteoroid environment.

## 10. SUMMARY

Space debris modeling to meet both scientific and operational requirements remains a high priority at NASA. In recent years older models, like ORDEM and EVOLVE, have been upgraded, taking advantage of new measurement data, theoretical advances, and more capable computational equipment. Additionally, new models, such as SBRAM, have been developed to provide real-time mission support, while existing models, like DAS, ORSAT, and BUMPER, are being used with greater frequency to aid spacecraft design and mission planning. This suite of models is essential to improving our understanding of and survival in the space debris environment and to formulating policies to curtail its growth.

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