N92-22375

THE ASSESSMENT OF LONG-TERM ORBITAL DEBRIS MODELS

by

F. M. Jonas, PhD
K. W. Yates

ORION International Technologies, Inc.
300 San Mateo NE, Suite 200
Albuquerque, NM 87108

Abstract

This paper presents the results of on-going research being conducted for the U. S. Air Force Phillips Laboratory by ORION International Technologies, Inc. The purpose of this research is to assess existing long-term orbital debris models as a first step in the Air Force's effort to develop an Air Force long-term orbital debris modeling capability. Existing models are assessed against Air Force requirements for a long-term orbital debris model which can; (a) operate with the necessary accuracy at the relevant altitudes and orbital parameters, (b) benefit from new Air Force and non-Air Force debris measurements, and (c) accommodate current and future Air Force space scenarios. Model assessment results are shown for the NASA engineering model. The status of the NASA EVOLVE model assessment is discussed.

INTRODUCTION

This paper presents the results of studies conducted for the U. S. Air Force Phillips Laboratory, Albuquerque, NM, on long-term orbital debris models. The research was conducted by ORION International Technologies, Inc., as a task under contract F29601-89-C-0001. The objective of the research is to assess existing long-term orbital debris predictive models against Air Force (AF) needs for such a model which can: (1) operate with the necessary accuracy at relevant altitudes and orbital parameters; (2) benefit from new debris measurements; and (3) accommodate current and future AF space scenarios. Specifically, assessment results are shown for models developed by the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC). First, summary assessment results are presented for the NASA empirical engineering model developed for spacecraft in low earth orbit (LEO). The model formulation, sensitivities and uncertainties are discussed. Although the model does meet the NASA objective of designing a model that is easy to use by the design community, it does not meet the AF needs as stated above. Next, the status of the current investigation on the NASA EVOLVE computer code is summarized. EVOLVE is a more sophisticated empirical and physics based computational model designed to operate on both mini- and micro-computer systems. The EVOLVE model formulation and typical results will be shown.

BACKGROUND

The man-made orbital debris environment is becoming of increasing concern to the international space community. The majority of the man-made debris is in LEO, with the estimated total mass of orbital debris in LEO ranging anywhere from 1.5 to 3 million kg (Ref. 1, 2). Orbital debris consists of large objects such as non-functioning payloads to small objects such as paint flakes . Most of these objects are in high inclination orbits and pass one another at average relative velocities of 10 km/s (Ref. 2). The concern to space users ranges from catastrophic collision with large particles to surface erosion, especially of sensors, due to the smaller particles. Although the threat due to impact of orbital debris on space systems is not yet substantial, it is growing, and if left unchecked the future debris environment may indeed be extremely serious (Ref. 1,2). Currently, the best information on this environment comes from the Space Surveillance Network and returned spacecraft surfaces. It is estimated that the Space Surveillance Network currently cannot track objects less than 10 cm in diameter (Ref. 2). Only 5 percent of the approximate 6500 objects currently being tracked by USSPACECOM represent functioning operational spacecraft (Ref. 1, 2). 99 percent of the estimated orbital debris mass resides in these large trackable objects. The majority of the surface impact data to date comes from the Solar Maximum Mission Satellite (Solar Max) (Ref 3). Over 3 m^2 of surface area was returned for examination, recording 300 plus impacts during four plus years exposure at nominally 500 km and 28.5 deg orbital inclination. Orbital debris particles impacting these surfaces were estimated to have diameters ranging from 10^{-4} to 10^{-2} cm. Other limited data does exist giving some information on sizes around 1 cm; however, very little is known about this environment, other than at 500 km, and for sizes greater than 10 cm in diameter.

NASA ENGINEERING MODEL

NASA has developed an engineering model of the debris environment intended for spacecraft operating in LEO (Ref. 4 , 5). This empirically based model represents curve fits to available data. An assessment of this model by ORION shows that the model only be used at altitudes below 1000 km, and for debris sizes in the range $10^{-4} \leq d \leq 10^3$ cm. Orbital debris flux using this model is predicted using the following expression:

$$F(d,h,i,t,S) = H(d)\ \Phi(h,S)\ \Psi(i)\ [F_1(d)g_1(t) + F_2(d)g_2(t)] \tag{1}$$

Where,

$F(d,h,i,t,S)$ = Time averaged cumulative orbital debris flux (Impacts/m^2-yr) for debris particle sizes of diameter d and greater on a single sided randomly tumbling surface
d = Debris diameter (cm)
h = Orbital altitude (km)
i = Orbital inclination (deg)
t = Year (yr)
S = 13 month smoothed solar radio flux at 10.7 cm wavelength expressed in 10^4 Jansky (Jy) for the previous year (t-1)
$H(d)$ = $\sqrt{10^{\exp\left(-(\log_{10} d - 0.78)^2/(0.637)^2\right)}}$
$\Phi(h,S)$ = $\Phi_1(h,S)/[\Phi_1(h,S) + 1\}$, Solar/Atmosphere effects
$\Phi_1(h,S)$ = $10^{(h/200\ -\ S/140 - 1.5)}$
$\Psi(i)$ = Orbital debris inclination distribution (Fig. 1)
$F_1(d)$ = $1.22\ (10^{-5})\ d^{-2.5}$, Small particle flux
$F_2(d)$ = $8.1\ (10^{10})(d + 700)^{-6}$, Large particle flux
$g_1(t)$ = $(1 + q)^{(t-1988)}$, Small particle growth where q = 0.02 (2%) until 2010 then q = 0.04 (4%)
$g_2(t)$ = $1 + p(t-1988)$, Large particle growth where p = 0.05 (5%)

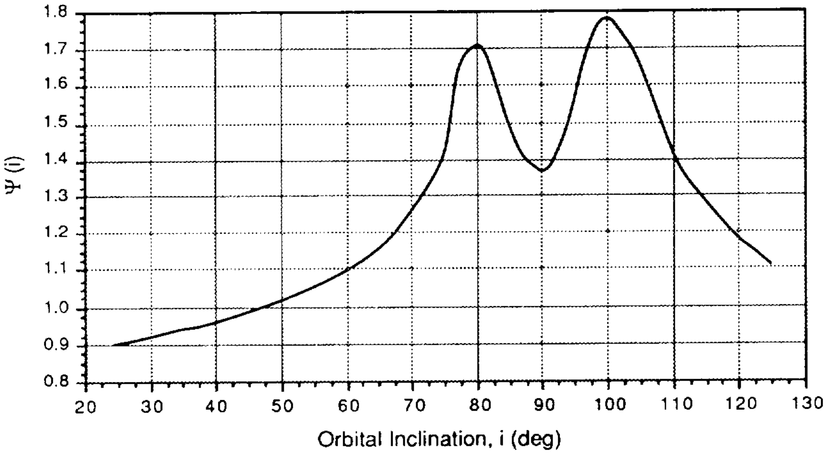

Figure 1. Orbital debris inclination distribution function, Y(i).

Predictions of the orbital debris environment using this model are shown in Figures 2 and 3 as compared to data. Note that above 1000 km the model predicts essentially constant flux (Fig. 2).

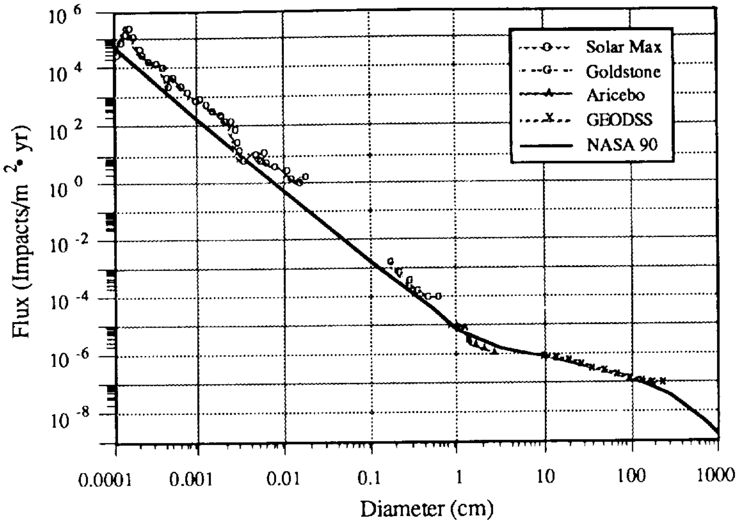

Figure 2. NASA 90 orbital-debris flux versus diameter, d (cm), compared with data from Solar Max, Goldstone, Aricebo, and GEODSS (h = 500 km, i = 28.5 deg, t = 1988, S = 140).

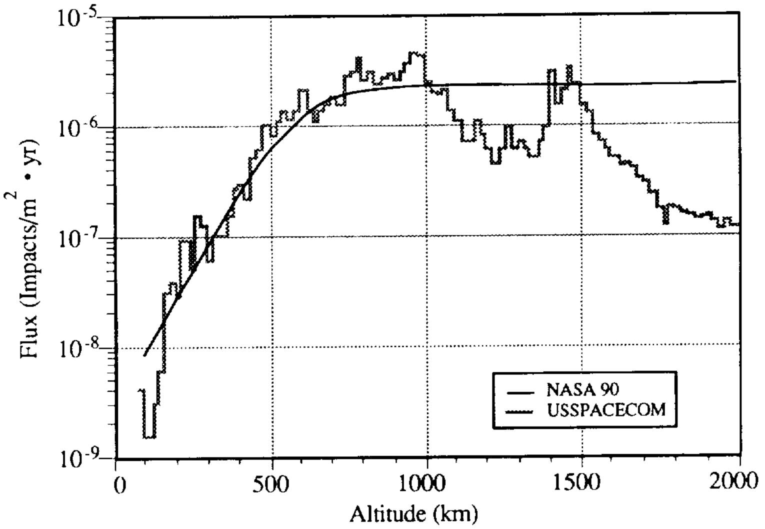

Figure 3. NASA 90 orbital-debris flux versus altitude, h (km), compared with USSPACECOM data (d ≥ 10 cm, i = 60 deg, t = 1990, S = 200).

Engineering Model Sensitivity Study

A sensitivity study of the NASA engineering model was performed to quantify the model response to variation in the parameters d, h, i, t, S, p and q. The purpose of this study was to identify the most to least sensitive parameters as well as any anomalous or singular behavior in the model. This information is useful to the designer in knowing where small relative changes in the input can cause large variations in the output or vice-versa. In addition, if there is any singular behavior the user will know to avoid these regions.

The model sensitivities were determined by examining the first-order partial derivatives of F(d, h, i, t, S) with respect to each variable (which gives the relative change in the flux prediction with respect to changes in each variable). Because the majority of functions which make up F are smooth and continuous, it is expected that the first-order derivatives also will be smooth and continuous. Ψ (i) is based upon tabular values, but results in a smooth and continuous curve over the range 25 deg $\leq i \leq$ 125 deg as shown in Figure 1. The exception is $g_1(t)$ where q changes value at the year 2010, however, $g_1(t)$ is smooth and continuous on either side of this discontinuity. Summary results of this study are shown in Figure 4 for the baseline values of h = 500 km, d $\geq$ 1 cm, i = 47 deg [Ψ(47 deg) = 1], t = 1995, S = 90, p = 5% and q = 2%. Each parameter was varied as follows:

• diameter	$\partial F/\partial d$ vs. d	for $10^{-3} \leq d \leq 10^2$ cm
• altitude	$\partial F/\partial h$ vs. h	for $100 \leq h \leq 2000$ km
• inclination	$\partial F/\partial i$ vs. i	for $25 \leq i \leq 125$ deg
• time	$\partial F/\partial t$ vs. t	for $1988 \leq t \leq 2010$
• solar activity	$\partial F/\partial S$ vs. S	for $70 \leq S \leq 250$
• small particle growth	$\partial F/\partial q$ vs. q for	$0 \leq q \leq 0.20$
• large particle growth	$\partial F/\partial p$ vs. p for	$0 \leq p \leq 0.20$.

Figure 4 plots the variation of each parameter as a function of the normalized parameter for comparison purposes.

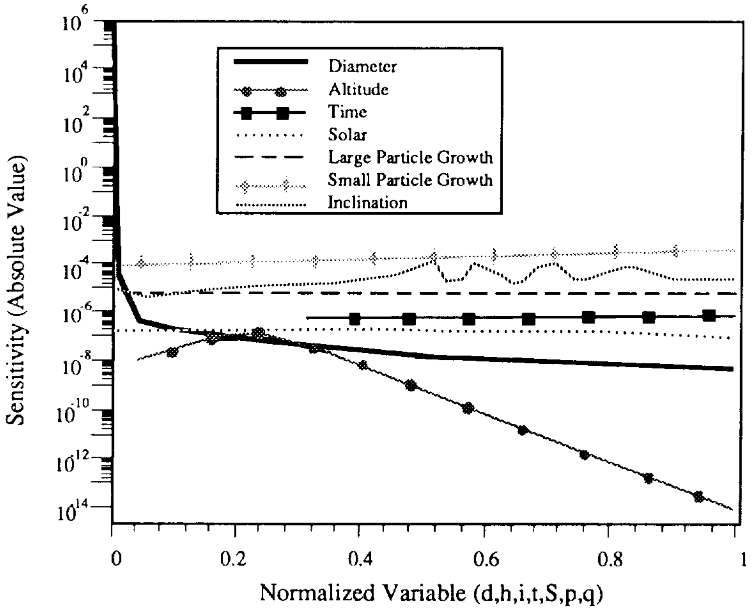

Figure 4. Flux Model Sensitivities, Summary Comparisons (Case II).
Baseline Values: h = 500 km, d = 1 cm, i = 47 deg, t = 1995, S = 90, p = 5%, q = 2%

The rank order of model sensitivities and comments pertaining thereto are as follows:

Parameter	Relative Order of Magnitude/Comments
d (diameter)	~ 10^6 at d = 0.001 cm ~ 1 at d = 0.05 cm ~ 10^{-9} at d = 100 cm

	Flux prediction becomes undefined as d → 0
q (small particle growth rate)	~ 10^{-4}, slightly increasing with increasing q
i (orbital inclination) (large particle growth rate)	~ 10^{-5} to 10^{-6}, reflects Ψ (i) variation
p (large particle growth rate)	~ 10^{-5} to 10^{-6} sensitivity is constant throughout range
t (time)	~ 10^{-7} to 10^{-8}
s (solar)	~ 10^{-7} to 10^{-8}
h (altitude)	~ 10^{-8} ($h = 500$ km) to 10^{-14} ($h = 2000$ km), predicts constant flux for $h > 1000$ km

Engineering Model Uncertainty Study

An uncertainty analysis of the NASA model was performed to quantify the accuracy of the model predictions. The study was conducted using a propagation of error analysis that examines how the root mean squared error in the data affects the results obtained from the use of the model. The uncertainty or error in the flux prediction, ε_F, was estimated using the following relationship:

$$\varepsilon_F = \pm\left\{(\varepsilon_{FM})^2 + (\varepsilon_{FH})^2 + \left(\frac{\partial F}{\partial p}\varepsilon_p\right)^2 + \left(\frac{\partial F}{\partial q}\varepsilon_q\right)^2 + \left(\frac{\partial F}{\partial S}\varepsilon_S\right)^2\right\} \quad (2)$$

where

ε_F = Uncertainty in F, e.g., F± ε_F

ε_{FM} = Uncertainty in F because of statistical and measurement uncertainties primarily as a function of debris diameter

ε_{FH} = Uncertainty in F with respect to altitude due in part to the difficulty of determining F for debris in highly elliptical orbits

ε_p = Uncertainty in large particle growth

ε_q = Uncertainty in small particle growth

ε_S = Uncertainty in the level of solar activity

Table 1. NASA Estimated orbital-debris uncertainties 90% confidence (Ref. 5).

Parameter		Estimated Uncertainty
Flux Measurements	$d \geq 10$ cm	1.5 to 0.5 x Flux
	$0.05 < d < 10$ cm	3.0 to 0.33 x Flux
	$d \leq 0.05$ cm	2.0 to 0.5 x Flux
Altitude Distribution,	$d \geq 10$ cm	2.0 to 0.5 x Flux
	$1 < d < 10$ cm	3.0 to 0.33 x Flux
		1.5 to 0.5 x Flux for $300 < h < 700$ km
	$d \leq 1$ cm	5.0 to 0.2 x Flux per every 200 km away from h = 500 km
Orbital-debris Growth, q		4% to 10%
		0% to 20%
Solar Activity, S		Use max and min values for nominal solar cycle where typically $70 \leq S \leq 210$

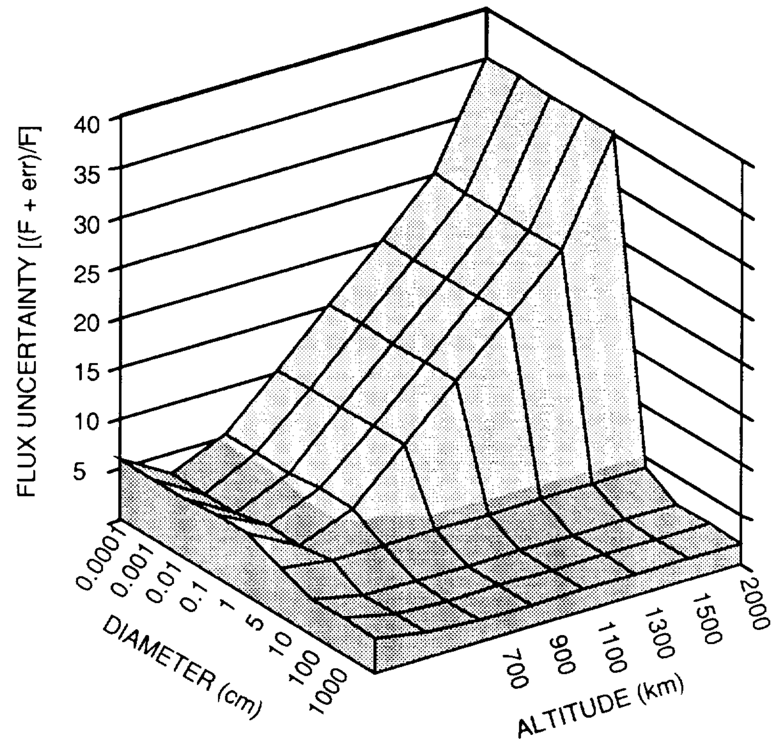

Figure 5. Flux model uncertainty vs. altitude and diameter (i = 30 deg, t = 1995, S = 90)

Figure 5 shows the summary results, $[(F + \varepsilon_F)/F]$, versus altitude and diameter at an orbital inclination of 30 deg for the year 1995. As can be seen in this figure, the best model predictions (factor of 2-4) occur at 500 km and/or for particle sizes greater than 5 cm in diameter. The uncertainty for the smaller particles and higher altitudes is seen to be at least an order of magnitude. Similar results are obtained for all orbital inclinations. As a result of the sensitivity and uncertainty analyses it is recommended that use of the model be restricted to diameters, 10^{-4} cm $\le d \le 10^{3}$ cm, and altitudes, $h \le 1000$ km, through the year 2010.

NASA EVOLVE (Evolutionary) MODEL

The NASA EVOLVE model (Ref. 6) is a NASA in-house numerical model developed to predict the man-made orbital debris environment. A schematic of the EVOLVE model is shown in Figure 6. The EVOLVE model uses USSPACECOM data (intact objects) to generate a historical data base covering the years 1957 - 1989. To project future traffic, the program uses data files containing anticipated launches determined from mission and traffic models. Any combination of mission models may be employed to project traffic for U.S. civil, DoD, Soviet, and other foreign agencies. Currently, the program uses a data base for 1990 - 2010 comprised of the U.S. Civil Needs Data Base (U.S. civilian traffic including shuttle missions) and a copy of the 1988 historical data to simulate DoD and foreign traffic. Historically documented breakups are included in the historical data base from 1957 - 1989. Explosions and/or collisions are determined stochastically and added to the deterministic flux environment. Objects are allowed to decay as a function of their interaction with the atmosphere. The program ultimately predicts the flux environment as a function of altitude and particle size for any given time. Sample results obtained by ORION using EVOLVE are shown in Figure 7.

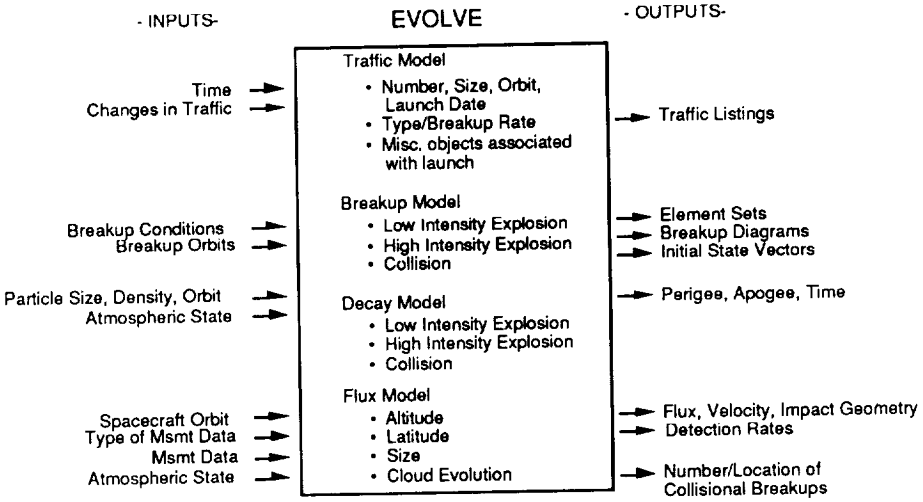

Figure 6. EVOLVE Schematic

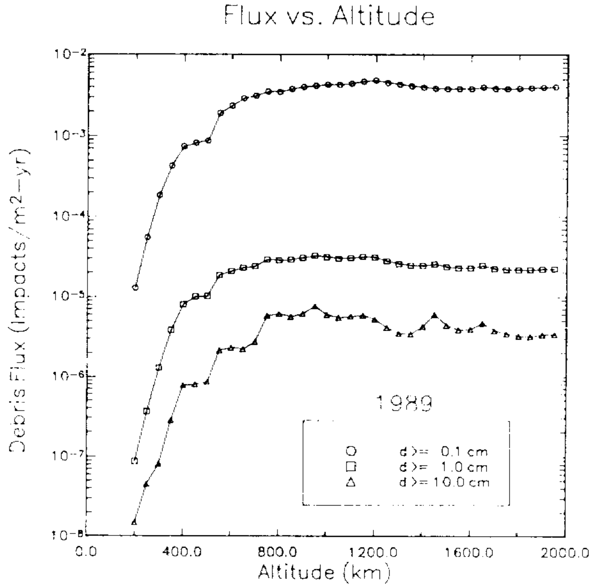

Figure 7. Debris Flux vs. Altitude (EVOLVE), 1989.

EVOLVE Assessment

The assessment of the NASA EVOLVE model is just beginning. It is planned to first dissect the EVOLVE code into its constituent parts and examine the methodologies used to calculate the various effects, and identify the critical parameters and assumptions. Next, a sensitivity study will be performed. In this analysis the code will be examined at different levels. At the upper most level the flux sensitivity to altitude, diameter and time will be examined. The sensitivity of the results to the output of various subroutines will be studied next, and finally the sensitivity of the flux prediction to critical parameters within those subroutines. The final part of the assessment will quantify the model uncertainties as compared to data of this environment. The model means and variances will be established. The assessment is to be conducted through December of this year with the results published in a Phillips Laboratory technical report early in 1992.

CONCLUSION

Existing long-term orbital debris models are being assessed against Air Force needs for a model that can (a) operate with high accuracy at the relevant altitudes and orbital parameters, (b) benefit from new Air Force and non-Air Force debris measurements, and (c) accommodate current and future Air Force Space scenarios. The models being assessed are the NASA engineering model and the NASA EVOLVE model. The assessment of the NASA engineering model has been completed. It has been concluded that this model does not meet the Air Force requirements. It should be noted however that the NASA engineering model does meet the NASA goal to design a model that is easy to use by engineers. It also has helped to establish threat levels for the first time and is pointing the way on where and how knowledge of the orbital debris environment needs to be improved. The assessment of the NASA EVOLVE model is just beginning. The results of this latter assessment will be available this fall (1991) with the final report available in 1992.

REFERENCES

1. Space Debris, A Report from the ESA Space Debris Working Group, European Space Agency, 1988.
2. Report on Orbital Debris, by Interagency Group (Space), for the National Security Council, Washington D.C., February 1989.
3. Laurance, M.R., and Brownlee, D.E., "The Flux of Meteoroids and Orbital Space Debris Striking Satellites in Low Earth Orbit." Nature, Vol. 323, 11 September 1986.
4. Kessler, Donald J., Reynolds, Robert C., and Anz-Meador, Phillip D., Orbital Debris Environment for Spacecraft Designed to Operate in Low Earth Orbit, NASA TM 100471, April 1989.
5. Proposed Revision to Section 8, "Meteoroids and Orbital Debris," Space Station Program, Natural Environment Definition for Design, NASA SSP 30425, September 1990.
6. Reynolds, Robert C., Documentation of Program EVOLVE: A Numerical Model to Compute Projections of the Man-made Orbital Debris Environment, System Planning Corp., SPC Report No. 0D91-002-U-CSP, February 1991.