LIFETIME PREDICTIONS FOR THE SOLAR MAXIMUM MISSION (SMM) AND SAN MARCO SPACECRAFT*

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ABSTRACT

This paper describes lifetime prediction techniques developed by the Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD). These techniques were developed to predict the Solar Maximum Mission (SMM) spacecraft orbit, which is decaying due to atmospheric drag, with reentry predicted to occur before the end of 1989. Lifetime predictions have also been performed for the Long Duration Exposure Facility (LDEF), which was deployed on the 1984 SMM repair mission and is scheduled for retrieval on another Space Transportation System (STS) mission later this year. Concepts used in the lifetime predictions have been tested on the San Marco spacecraft, which reentered the Earth's atmosphere on December 6, 1988. Ephemerides predicting the orbit evolution of the San Marco spacecraft until reentry were generated over the final 90 days of the mission when the altitude was less than 380 kilometers. The errors in the predicted ephemerides are due to errors in the prediction of atmospheric density variations over the lifetime of the satellite. To model the time dependence of the atmospheric densities, predictions of the solar flux at the 10.7-centimeter wavelength ($F_{10.7}$) are used in conjunction with Harris-Priester (HP) atmospheric density tables.

Orbital state vectors, together with the spacecraft mass and area, are used as input to the Goddard Trajectory Determination System (GTDS). Propagations proceed in monthly segments, with the nominal atmospheric drag model scaled for each month according to the predicted monthly average value of $F_{10.7}$. Calibration propagations are performed over a period of known orbital decay to obtain the effective ballistic coefficient. Propagations using $\pm 2\sigma$ solar flux predictions are also generated to estimate the dispersion in expected reentry dates. Definitive orbits are compared with these predictions as time elapses. As updated vectors are received, these are also propagated to reentry to continually update the lifetime predictions. Noted trends can be used to infer the accuracy of initial and subsequent predictions of the reentry dates.

1. INTRODUCTION

This paper describes analysis performed by the Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD) to predict the reentry of the Solar Maximum Mission (SMM), San Marco, and Long Duration Exposure Facility (LDEF) spacecraft. An overview of the mission and orbit characteristics is given in Table 1.

Table 1. Spacecraft Mission and Orbit Characteristics

MISSION AND ORBIT CHARACTERISTICS	SPACECRAFT		
	SAN MARCO	SMM	LDEF
LAUNCH DATE	3/24/88	2/14/80	4/7/84
INITIAL ALTITUDE (KILOMETERS)	447	574	482
INCLINATION (DEGREES)	2.5	28.5	28.5
ECCENTRICITY	0.007	0.001	0.001
MASS (KILOGRAMS)	237	2315.59	6820
AREA (SQUARE METERS)	1.0	17.5	74.3
MISSION OBJECTIVE	DRAG STUDIES	SOLAR STUDIES	WEATHERING IN SPACE
REENTRY DATE	12/6/88	PREDICTED FOR LATE 1989	PLANNED FOR RETRIEVAL

SMM reentry support commenced in 1986 using the Rapid Orbit Prediction Program (ROPP) (References 1 and 2). Development of the present modeling for decay analysis using the Goddard Trajectory Determination System (GTDS) (References 3 and 4) began in 1987, and the SMM baseline reentry prediction was established in February 1988. Monthly update reporting began in August 1988. The San Marco lifetime analysis was performed from August 1988 to January 1989. Current activities include LDEF and SMM lifetime modeling.

For SMM, definitive altitude data and orbit solution initial state vectors for orbit propagation are obtained from daily orbit determination operational support provided by the FDD. For San Marco and LDEF, operational support is not provided by the FDD, and orbit solution state vectors were provided in the form of North American Aerospace Defense Command (NORAD) two-line elements. These are converted to Cartesian elements for use in ephemeris propagation, and they are also converted to Brouwer mean elements for the altitude representation. In this paper, orbital altitude is expressed as the mean altitude, which is the Brouwer mean semimajor axis minus the mean equatorial radius of the Earth (6378.14 kilometers).

For SMM, orbital lifetime estimates are important for planning science operations. For San Marco, reentry estimates were requested to coordinate San Marco measurements with sounding rocket measurements scheduled in November 1988. For LDEF, lifetime estimates are important for planning a Space Shuttle retrieval mission later this year.

Lifetime prediction techniques developed by the FDD employ a drag force calibration using historical data, followed by a GTDS lifetime prediction ephemeris propagated in monthly segments. In each segment, the Harris-Priester atmospheric density table and a drag force scaling parameter, ρ_1, are changed to accommodate variations in the drag force model due to predicted monthly average variations of the solar flux at the 10.7-centimeter wavelength ($F_{10.7}$).

Section 2 of this paper provides background information about the orbit propagators (ROPP and GTDS) and the aerodynamic drag models (Harris-Priester and Jacchia-Roberts) used in this analysis. Also discussed are the actual solar flux data and several predicted solar flux models, which drive the atmospheric density model. Section 3 presents the reentry analysis results for SMM, including the early ROPP results, the GTDS drag model calibration, and SMM lifetime predictions based on the various solar flux models. Section 4 describes the San Marco reentry analysis, and Section 5 presents the LDEF reentry analysis. Section 6 summarizes the key points of this study.

2. BACKGROUND

ROPP is designed to perform long propagations efficiently where high precision is unnecessary. It uses an eighth-order Adams-Moulton integrator with a Runge-Kutta starter, integrates in mean elements, and ignores short-period gravitational perturbations. The ROPP drag model allows for direct input of $F_{10.7}$ data and geomagnetic (K_p) data.

GTDS uses a 12th-order Cowell integrator with an iterative starter. The geopotential model is the Goddard Earth Model-9 (GEM-9) with terms up to order and degree 21. For SMM, this is truncated to maximum order and degree 16 and includes resonant harmonics above order and degree 16. For San Marco and LDEF, the GEM-9 is truncated to maximum order and degree 8 and also includes higher order resonant harmonics.

Two options for the GTDS atmospheric density model are applicable to the current analysis. The modified Harris-Priester (HP) atmospheric density model provides tables of density versus altitude corresponding to each of 10 discrete levels of $F_{10.7}$. The tabulated values are the global minimum and maximum density values (ρ_{min} and ρ_{max}) of the diurnal density variation cycle for each altitude. The density, ρ, is a function of the angle ϕ between the spacecraft and the apex of the diurnal bulge, which is at a point 30 degrees east of the subsolar point. The diurnal bulge is modeled by

$$\rho = \rho_{min} + (\rho_{max} - \rho_{min}) \cos^n \left(\frac{\phi}{2}\right) \tag{1}$$

The spatial shape of the diurnal density bulge is adjustable in GTDS by varying the power, n, of the cosine term. Both n = 6 and n = 2 have been used operationally, but n = 2 is preferred for low-inclination orbits.

The Jacchia-Roberts (JR) 1971 atmospheric density model includes effects correlated with the geomagnetic index, K_p, in its calculation of the exospheric temperature. It also requires 40 days of $F_{10.7}$ values beyond the day of analysis to accommodate an input for the 81-day $F_{10.7}$ average. Therefore, it is most reliable for use in past and near-current times, where $F_{10.7}$ and K_p data are known. The use of predicted $F_{10.7}$ and K_p data in the Jacchia-Roberts model is necessary for orbital lifetime predictions. The preliminary attempts described in this paper have resulted in limited success.

The definitive $F_{10.7}$ and A_p data used in this analysis are reported monthly by the National Geophysical Data Center. The solar flux data are determined each day from observations of the Sun. The K_p data are approximately logarithmic measurements made at 3-hour intervals around the world. The daily equivalent planetary amplitude, A_p, is derived by converting the K_p value to a linear index and averaging over 1 day. The $F_{10.7}$ and A_p data spanning the time period 1979 through 1988 are illustrated in Figure 1.
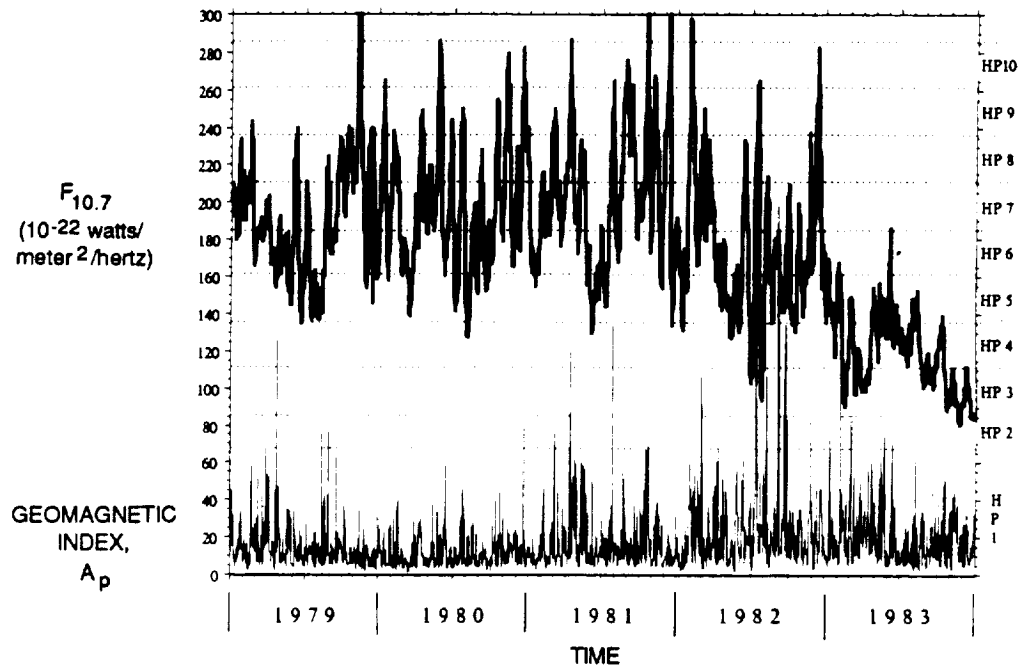
The principle source of predicted solar activity data for this analysis has been the GSFC Laboratory for Atmospheres (GSFC Code 610). Three sets of 1-year smoothed monthly $F_{10.7}$ predictions by Dr. Kenneth H. Schatten (References 5, 6, and 7) of GSFC are illustrated in Figure 2. Figure 3 illustrates the Schatten predictions in comparison with the actual solar flux activity. Each updated prediction supercedes the previous prediction.

Early analysis used predictions from the Marshall Space Flight Center (MSFC) (Reference 8). The MSFC data include a best estimate and 97.7-percent, 50-percent, and 2.3-percent probability intervals. The current work uses the Schatten predictions from February 1988, August 1988, and January 1989, hereafter referred to as SH 2/88, SH 8/88, and SH 1/89, respectively. These predictions include a nominal value, a $+2\sigma$ probability (high) value, and a -2σ probability (low) value, hereafter designated by appending a plus or minus sign, for example, (SH 2/88+) or (SH 2/88-).

The method for incorporating solar flux information into long-range GTDS ephemeris propagations using the Harris-Priester density model is described using San Marco as an example. Each monthly mean $F_{10.7}$ value is converted to a corresponding prediction of the atmospheric density represented by a Harris-Priester (HP) table number and a value of the drag scaling adjustment parameter, ϱ_1, which also depends on the spacecraft altitude. Using ϱ_1, the model of the atmospheric density is varied smoothly with the $F_{10.7}$ level between the HP tables. (In the discussion that follows, refer to Table 2.)

For an altitude of 380 kilometers, the minimum and maximum density values are retrieved from HP tables 3 through 7. The average density over one diurnal cycle is then determined by taking the arithmetic mean of the minimum and maximum values. The interpolation scheme for adjusting the HP table densities to solar fluxes between tables depends on the ratio of the average densities for the adjacent HP tables. This ratio is obtained by determining the ϱ_1 value that scales the lower table to the upper table value (see Table 2a, column 6) or scales the upper table to the lower table (see Table 2a,

a. 1979 – 1983

$F_{10.7}$
(10-22 watts/
meter ^{2}/hertz)

GEOMAGNETIC
INDEX,
A_p

1 9 7 9   1 9 8 0   1 9 8 1   1 9 8 2   1 9 8 3

TIME

b. 1984 – 1988

$F_{10.7}$
(10-22 watts/
meter ^{2}/hertz)

GEOMAGNETIC
INDEX,
A_p

1 9 8 4   1 9 8 5   1 9 8 6   1 9 8 7   1 9 8 8
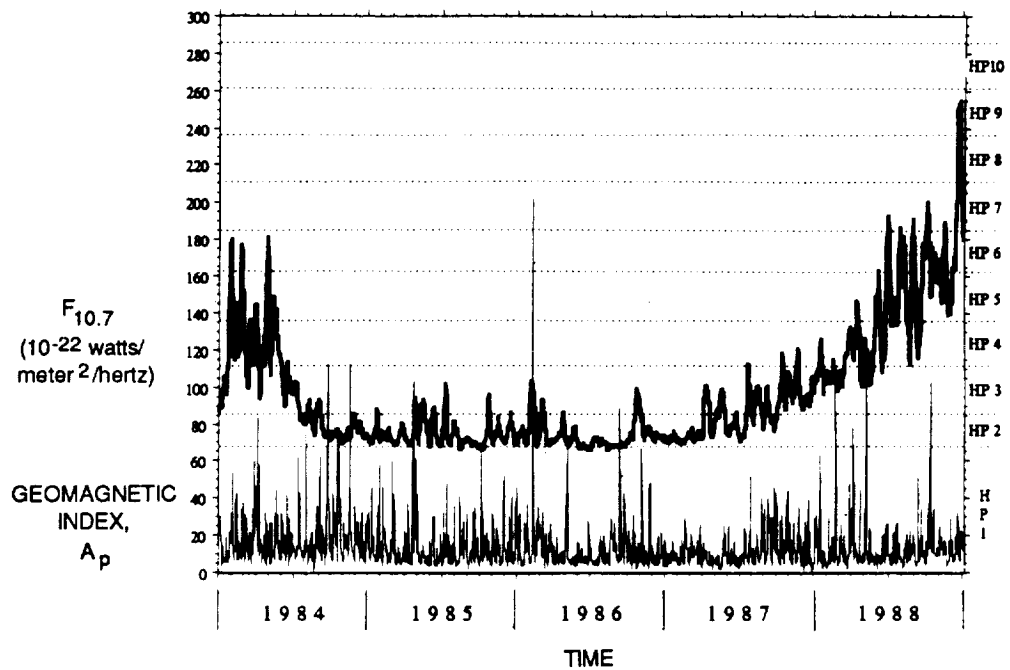
TIME

Figure 1.   Solar Flux and Geomagnetic Index Profiles for 1979 Through 1988
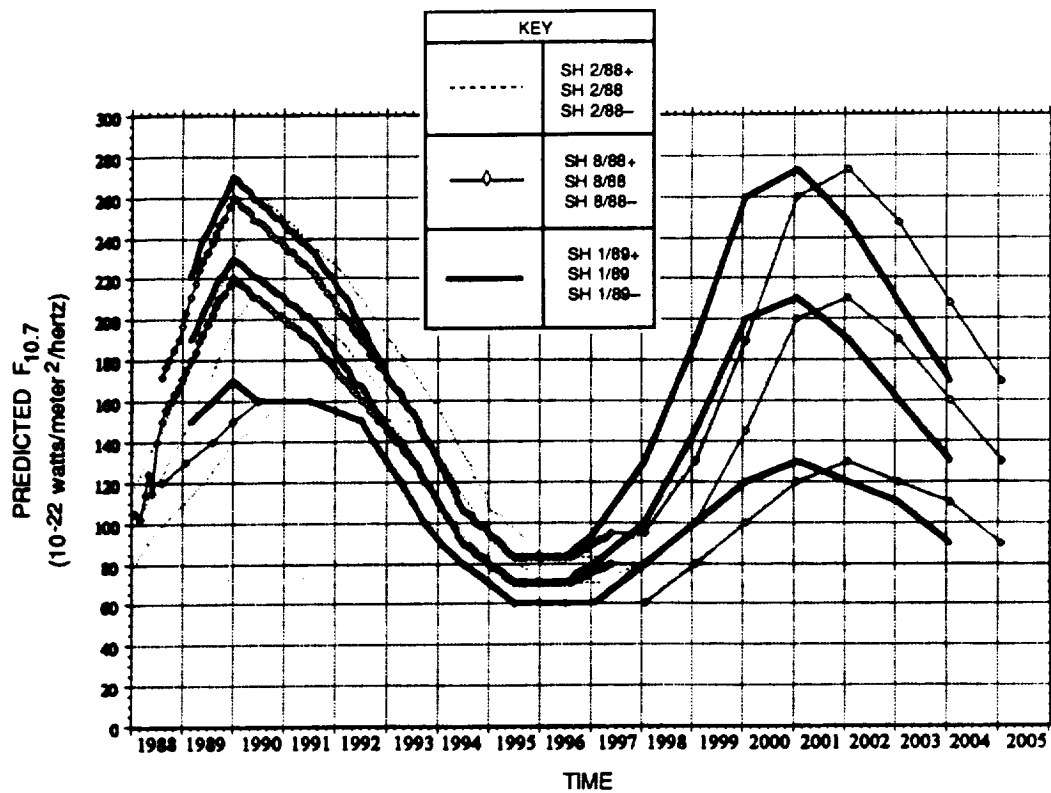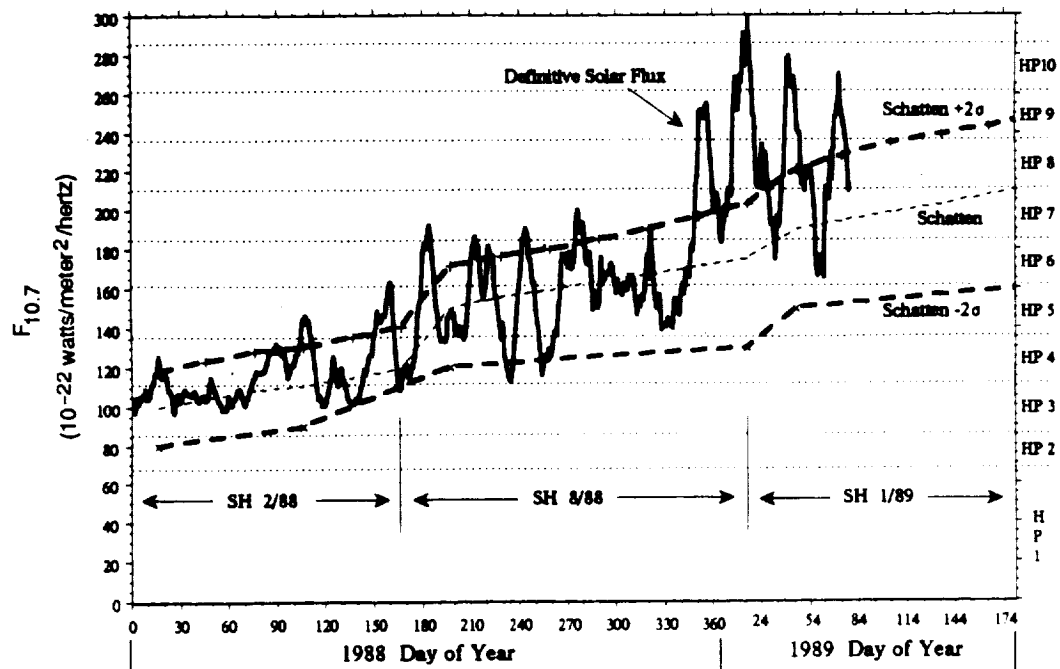
Figure 2. Schatten Solar Flux Predictions

Figure 3. Definitive Solar Flux Values Versus the Schatten
Solar Flux Predictions

column 7). For example, the ϱ_1 required to obtain the same density using HP table 3 as would be obtained for HP table 4 is 0.4223, because the average density for HP table 4 (4.688) is 42.23 percent greater than the average density for HP table 3 (3.296). In the other direction, the ϱ_1 needed to approximate HP table 3 from HP table 4 is -0.2969, because 3.296 is 29.69 percent less than 4.688.

Table 2. Drag Model Parameters for Cosine-Squared Diurnal Bulge

a. ATMOSPHERIC DENSITY AND INTERPOLATING VALUES OF ϱ_1 FOR SAN MARCO AT 380 KILOMETERS ALTITUDE

HP TABLE NO.	$F_{10.7}$ $(10^{-22}$ watts/ meter^2/ hertz)	ATMOSPHERIC DENSITY (grams/kilometer^3)			ϱ_1 FOR SHIFT OF ONE HP TABLE NO.	
		ϱ_{min}	ϱ_{max}	$\varrho_{average}$	UP	DOWN
3	100	1.382	5.210	3.296	0.4223	N/A
4	125	2.094	7.282	4.688	0.4109	-0.2969
5	150	3.274	9.955	6.615	0.2641	-0.2913
6	175	4.313	12.41	8.362	0.3039	-0.2089
7	200	6.205	15.60	10.903	N/A	-0.2331

NOTE: N/A = NOT APPLICABLE

b. MONTHLY AVERAGE SCHATTEN SOLAR FLUX PREDICTIONS AND ASSOCIATED ϱ_1 VALUES USED IN THE SAN MARCO LIFETIME RUNS

SOLAR FLUX MODEL	MONTH(S)	$F_{10.7}$ $(10^{-22}$ watts/ meter^2/ hertz)	HP TABLE NO.	ϱ_1
SH 8/88	9/88	159	5	0.0951
	10/88	163	6	-0.1003
	11/88	167	6	-0.0668
	12/88	171	6	-0.0334
SH 8/88+	9/88	180	6	0.0608
	10/88	185	6	0.1216
	11/88	190	7	-0.0932
	12/88	197	7	-0.0280
SH 8/88-	9/88 - 12/88	120	4	-0.0594
	1/89 - 2/89	130	4	0.0822

Once the ϱ_1 value to shift between adjacent tables has been obtained, the predicted $F_{10.7}$ level is compared with the standard tables, and the closest HP table is selected to approximate the density. Then, the ϱ_1 value required to adjust the HP table to the intermediate

$F_{10.7}$ value is determined by linear interpolation relative to the value determined for a shift of one table. For example, the SH 8/88 solar flux model predicted a level of 159 for September 1988. The HP table 5 ($F_{10.7}$ = 150) is the closest table. A shift to HP table 6 ($F_{10.7}$ = 175) can be accounted for by a ϱ_1 value of 0.2641. The tabulated value of 0.0951 is obtained by taking 9/25 times 0.2641.

For other altitudes, the same procedure is used, but the numbers are different. Thus, the ϱ_1 values are fixed quantities that fine-tune the Harris-Priester drag model to the predicted $F_{10.7}$ level for each month of a propagation.

3. SMM REENTRY ANALYSIS

For SMM, two events are of interest: reentry and decay of the orbit to an altitude corresponding to loss of attitude control. The loss of control is modeled to occur when the spacecraft's angular momentum management system cannot compensate for the effects of atmospheric torques. The adopted altitude for this is 370 kilometers (200 nautical miles) (Reference 9).

3.1 EARLY ROPP ANALYSIS

Early analysis using ROPP to predict the SMM reentry date utilized the technique of matching the observed orbital decay up to the date of the analysis to determine the ballistic coefficient (C_D A/m), where

C_D = drag coefficient

A = spacecraft cross-sectional area

m = spacecraft mass

The ballistic coefficient determined by this approach was 0.01262 square meter per kilogram, which was somewhat lower than the value calculated from available spacecraft data, 0.01496 square meter per kilogram. Using this value, propagations to the reaction wheel saturation altitude (370 kilometers) and to reentry were performed. Starting with an orbital state vector determined for June 1, 1986, and using MSFC solar flux predictions (MSFC 4/86), the first prediction of the SMM reentry date by the FDD was for December 3, 1990.

3.2 GTDS CALIBRATION

SMM orbit solutions from launch through October 1987 were analyzed to establish that the atmospheric density variations, as measured by GTDS during orbit determination, were well correlated with observed solar flux variations (Reference 10). The drag model was then calibrated by adjusting the drag coefficient, C_D, to match the predicted and actual orbital decay over the history of the SMM mission. For the calibration runs, HP tables and ϱ_1 values were determined for each definitive monthly mean $F_{10.7}$ value in the manner previously described. Then, for each year of the mission, the value of the C_D was adjusted to obtain agreement with the actual orbital decay. Year-to-year variations

were noted and were attributed to errors in the Harris-Priester atmospheric density model associated with different $F_{10.7}$ levels. For example, during the period of solar minimum (1984 through 1987), SMM orbital decay was very moderate and C_D estimates were atypically low. For solar flux levels in the range 150 to 200 during the declining portion of solar maximum period number 21 in 1981 and 1982, a C_D of 1.38 gave the best fit. This value was adopted since solar flux levels expected for the interval before reentry were in this range. The corresponding ballistic coefficient is 0.01043 square meter per kilogram, 20 percent lower than the value obtained in the ROPP calibration analysis.

3.3 SMM PREDICTION RESULTS FROM DIFFERENT SOLAR FLUX MODELS

Orbit decay predictions were performed using the most current solar flux prediction model available at the time. When a new model or an update to an old model was obtained, the prediction modeling switched. Overall, six models were used: three versions of the Marshall Space Flight Center (MSFC) model and three versions of the Schatten model. Reentry predictions for these models are summarized in Table 3.

Table 3. Summary of FDD Reentry Predictions for SMM

SOLAR FLUX MODEL	DATES		
	EPOCH	REENTRY	LOSS OF CONTROL
MSFC 12/87 BEST ESTIMATE	12/31/87	2/14/90	11/7/89
MSFC 4/88 BEST ESTIMATE	4/1/88	4/22/90	1/9/90
MSFC 6/88 BEST ESTIMATE	7/2/88	6/3/90	2/15/90
SH 2/88	12/31/87	7/24/90	4/18/90
SH 8/88+	10/2/88	12/9/89	9/21/89
SH 1/89+	2/1/89	10/7/89	8/3/89

3.3.1 DECAY PREDICTIONS WITH MSFC SOLAR FLUX MODELS

The first set of GTDS reentry predictions for SMM was based on the MSFC 12/87 solar flux predictions. Starting from an orbital solution vector of epoch December 31, 1987, the MSFC best estimate gave a reentry date of February 14, 1990, and loss of control on November 7, 1989. MSFC predictions are updated every 2 months, though subsequent MSFC models were used only for the purpose of comparison.

3.3.2 DECAY PREDICTIONS WITH THE SH 2/88 SOLAR FLUX MODEL

After completion of the work described in Section 3.3.1, the FDD adopted the Schatten solar flux predictions for all subsequent reentry predictions. The SH 2/88 solar flux

model was used for a propagation starting from an epoch of December 31, 1987. This resulted in the prediction of loss of control on April 18, 1990, and reentry on July 25, 1990. Because a period of constancy in solar flux prediction models occurred after February 1988, this propagation was established for reporting purposes as the FDD baseline reference.

The trend in these first predictions toward later reentry dates for later starting epochs is consistent with the fact that the later MSFC models and the first Schatten model predicted lower solar flux levels than the first MSFC models. Later updates to the Schatten model predicted higher solar flux levels, and the corresponding predicted reentry dates were earlier.

Following the establishment of a baseline prediction, comparisons were made between the mean altitude of the predicted and actual trajectories to monitor and report the orbit evolution and to assess trends in the actual orbit decay. Figure 4 shows the actual SMM mean altitude data from operational orbit determination in 1988 and also shows some of the predicted trajectories, including the baseline. Another trajectory is based on the definitive mean $F_{10.7}$ value for each month. These predicted trajectories are in close agreement until June 1988, when the actual $F_{10.7}$ values began to exceed the SH 2/88 model. The change in the decay rate for the actual SMM altitude data occurs 2 to 3 months later. At the end of 1988, the observed SMM orbital decay and the orbit predicted with the HP density table driven by the actual $F_{10.7}$ levels showed close agreement, in spite of discrepancies for several earlier months.

3.3.3   ANALYSIS USING THE JACCHIA-ROBERTS DENSITY MODEL

Subsequent work with the Jacchia-Roberts model resulted in a propagation that correctly predicted the shape of the orbital decay throughout 1988. Definitive $F_{10.7}$ and geomagnetic index (K_p) data were used as input up to December 1, 1988, after which predicted values from the SH 8/88 model were incorporated. A calibration performed using the interval from 1/1/88 to 12/1/88 requires a drag coefficient, C_D, of 3.35 to produce agreement. The fit to the anomalous downturn in the definitive SMM altitude data is quite good. By including the K_p data and incorporating the 81-day average $F_{10.7}$ into the density calculation, the Jacchia-Roberts model predicted the detailed time dependence of the definitive data. The Jacchia-Roberts model begins to show sizable discrepancies as soon as the definitive $F_{10.7}$ and K_p data run out and the predicted solar flux data begin. The cause of this is being investigated.

3.3.4   DECAY PREDICTIONS WITH THE SH 8/88 SOLAR FLUX MODEL

The SH 2/88 predictions were updated in August 1988 to accommodate the observed early rise to the solar maximum. The SH 8/88 predictions agreed well with the observed solar flux for several months, until the observations again increased beyond the predictions. The monthly mean $F_{10.7}$ value was 200.5 for December 1988, and 236.4 for January 1989, both above the SH 8/88 +2σ levels. The original baseline propagation for SMM shows large differences with recent definitive data because solar activity has been much higher than the SH 2/88 model on which it was based. Month-by-month
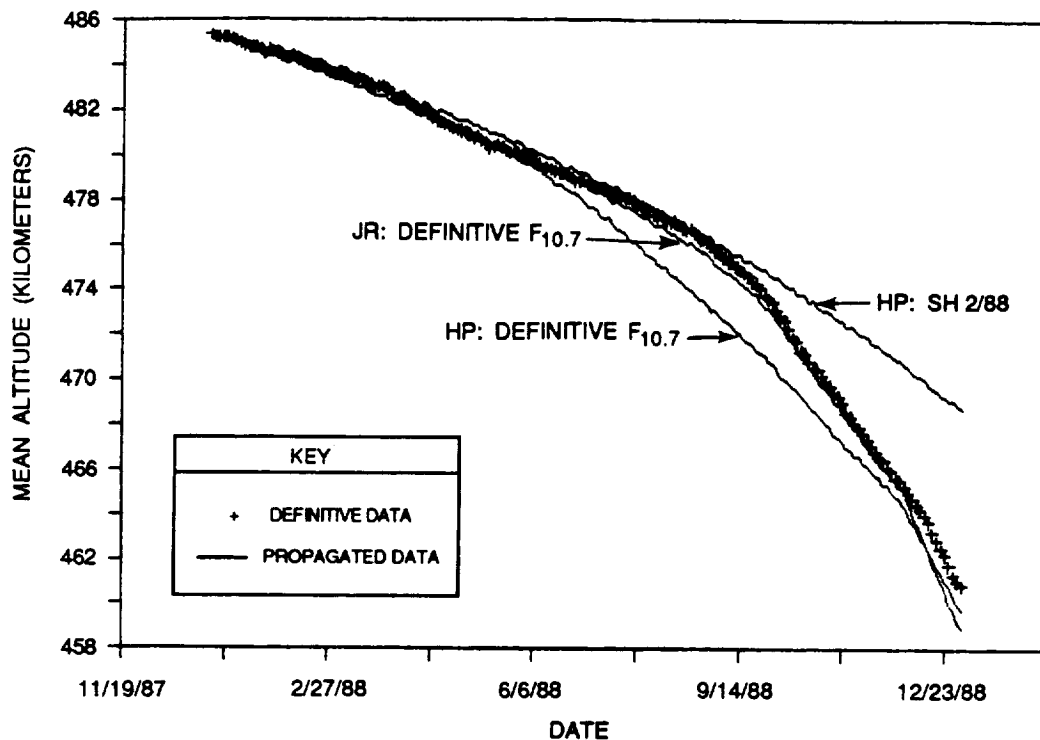
Figure 4. SMM Orbital Altitude for 1988

comparisons to the baseline reference ephemeris are given in Table 4. The angular difference between the predicted and actual spacecraft position now amounts to several orbits. The number of days that orbital decay is ahead of schedule is determined by noting when the predicted altitude will reach the .current definitive altitude.

In January 1989, estimates of the SMM orbital decay trajectory were made using the SH 8/88 solar flux predictions. The epoch was set at October 2, 1988, since this was after the noticeable change in the decay rate. The definitive altitude data indicated that SMM closely followed the trajectory based on the $+2\sigma$ solar flux values and not the trajectory based on the nominal values. This is consistent, as the actual $F_{10.7}$ values were closer to the $+2\sigma$ predictions than to the nominal predictions. Based on the SH 8/88+ model, reentry was predicted to occur on December 9, 1989, and loss of control was predicted to occur on September 21, 1989.

3.3.5 DECAY PREDICTIONS WITH THE SH 1/89 SOLAR FLUX MODEL

A second update to the Schatten predictions, dated January 1989, differs from the SH 8/88 model by a shift of the $F_{10.7}$ levels upward by 10 units. The first entry is for February 1989; therefore, analysis with the SH 1/89 model is in the preliminary stages at this writing. There is evidence for another increase in the decay rate of the definitive

Table 4. Summary of the Predicted and Actual SMM Orbital Decay in Reference to the FDD Baseline Prediction

EPOCH DATE	MEAN ALTITUDE (kilometers)	OBSERVED ORBITAL DECAY (kilometers)	PREDICTED ORBITAL DECAY (kilometers)	OBSERVED MINUS PREDICTED (kilometers)	OBSERVED MINUS PREDICTED (percent)	OBSERVED MINUS PREDICTED POSITION (degrees)	OBSERVED ALTITUDE DECAY IS AHEAD BY (days)
12/31/87	485.383	- -	- -	- -	- -	- -	- -
8/1/88	477.597	7.786	7.583	.203	2.7	53.0	3
8/31/88	475.990	9.393	9.074	.319	3.5	59.5	5
9/30/88	473.458	11.925	10.732	1.193	11.1	84.9	21
11/1/88	469.299	16.084	12.671	3.413	26.9	180.8	52
12/1/88	465.574	19.809	14.425	5.384	37.3	345.7	71
12/31/88	460.832	24.551	16.677	7.874	47.2	582.2	91
2/1/89	454.067	31.316	19.099	12.217	64.0	N/A	122
3/1/89	446.830	38.553	21.587	16.966	78.6	N/A	150

SMM altitude data near January 10, 1989. The observed orbital decay exceeds the predicted decay using the SH 1/89+ model with C_D = 1.38. For February 1989, the monthly mean $F_{10.7}$ was 222.8, very close to the SH 1/89 +2σ predicted value of 221. Matching the actual February orbital decay to predictions using the SH 1/89+ model requires C_D = 1.64. The corresponding ballistic coefficient is 0.01240 square meter per kilogram, which is close to the value obtained in the early ROPP calibration analysis. Using this C_D with the SH 1/89+ model and starting with a solution vector on February 1, 1989, reentry occurs on October 7, 1989 and loss of control is on August 4, 1989.

4. SAN MARCO REENTRY PREDICTIONS

In August 1988, the FDD was requested to predict the future orbital evolution of San Marco. Preliminary work had been done periodically during the mission using a drag model based on solar flux levels fixed at the value current at the prediction epoch. Predicted reentry dates changed uniformly with the later starting epochs, since the solar flux was steadily increasing during 1988. The consistency of the results was improved when the monthly solar flux variations were included in the propagations.

The results of the calibration runs for San Marco for the Jacchia-Roberts atmospheric model and two versions of the Harris-Priester atmospheric model are listed in Table 5. The interval for this propagation spanned from March 26, 1988, to September 1, 1988. Harris-Priester runs used the SH 2/88 solar flux model, since the actual solar flux levels closely matched this model over the calibration interval. Agreement between the predicted and actual orbital decay was quite good for n = 6; therefore, this bulge model was used

Table 5. Drag Model Calibration Runs for San Marco

DENSITY MODEL, BULGE MODEL, AND DRAG COEFFICIENT	MEAN ALTITUDE (kilometers)			ORBITAL DECAY (kilometers)		PREDICTION ERROR (percent)
	BEGINNING OF CALIBRATION INTERVAL	END OF CALIBRATION INTERNAL		PROPAGATED	DEFINITIVE	
		PROPAGATED	DEFINITIVE			
HARRIS–PRIESTER n = 6 $C_D = 2.17$	447.206	384.855	384.148	62.351	63.058	– 1.12
HARRIS–PRIESTER n = 2 $C_D = 2.17$	447.206	369.504	384.148	77.702	63.058	+23.2
JACCHIA–ROBERTS $C_D = 1.67$	447.206	384.494	384.148	62.712	63.058	–0.55

with the drag coefficient ($C_D = 2.17$) that was supplied with the spacecraft modeling parameters.

Reentry predictions for San Marco using the Harris-Priester models SH 2/88 and SH 8/88 nominal, $+2\sigma$, and -2σ solar flux levels are given in Table 6. Predictions using both n = 6 and n = 2 diurnal bulge models were performed for the starting epoch of September 1, 1988.

Table 6. San Marco Reentry Predictions

STARTING EPOCH	DIURNAL BULGE MODEL	SOLAR FLUX MODEL	REENTRY DATE
AUGUST 15, 1988	n = 6	SH 2/88	JANUARY 9, 1989
		SH 2/88+	DECEMBER 14, 1988
		SH 2/88–	FEBRUARY 21, 1989
SEPTEMBER 1, 1988	n = 6	SH 8/88	DECEMBER 12, 1989
		SH 8/88+	NOVEMBER 27, 1988
		SH 8/88–	JANUARY 23, 1989
	n = 2	SH 8/88	DECEMBER 2, 1989
		SH 8/88+	NOVEMBER 19, 1988
		SH 8/88–	JANUARY 7, 1989

The actual reentry was earlier than the predictions from the August 15 epoch because the actual solar flux was higher than the SH 2/88 model predictions. The September 1 predictions using SH 8/88+ and SH 8/88- models and a diurnal bulge model with n = 6 show a reentry envelope that brackets the actual reentry date. The actual $F_{10.7}$ levels in this timeframe closely matched the SH 8/88 model.

As propagations using the n = 6 diurnal bulge were repeated for subsequent NORAD vectors, there was a trend toward earlier reentry dates. The n = 2 diurnal bulge model resulted in increased consistency and eliminated the trend toward earlier reentry dates. Since these runs used C_D = 2.17, the calibration runs are called into question. In effect, this approach amounted to a recalibration by trial and error. The comparison of the definitive altitude data and the September 1 (SH 8/88; n = 2) predicted reentry trajectories is given in Figure 5.
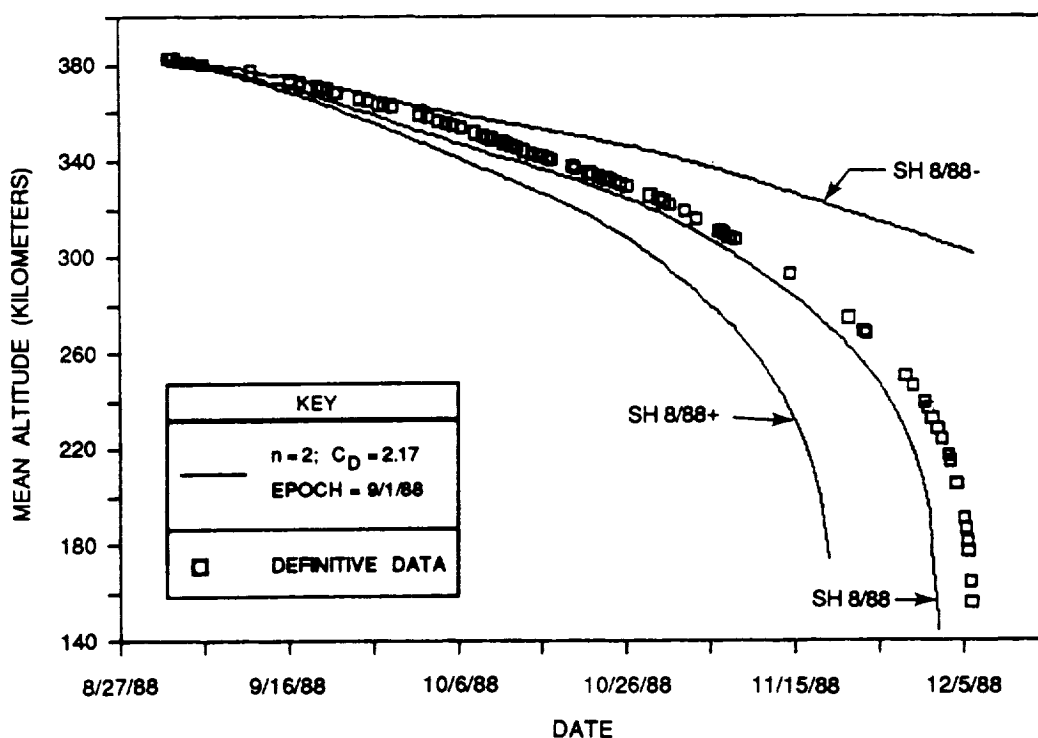
Figure 5. San Marco Orbital Altitude History

Another procedure was tried for San Marco. The drag model was calibrated by using a series of 5 to 10 NORAD vectors, spanning an interval of roughly 1 week, as input to a GTDS differential correction. The estimated solution state included the drag scaling parameter, ϱ_1. Propagations to reentry were performed with the same HP table and the solved-for value of ϱ_1. These results (listed in Table 7) were less consistent than those

Table 7. Differential Correction Reentry Predictions

EPOCH	DATA ARC	NO. OF NORAD VECTORS	HP TABLE NO.	ϱ_1	$F_{10.7}$ (10^{-22} watts/ meter^2 / hertz)	REENTRY DATE
9/1/88	9/1 – 9/6	5	5	−0.0416	146.6	12/25/88
9/16/88	9/16 – 9/22	8	5	+0.0645	155.8	12/19/88
10/1/88	10/1 – 10/7	5	6	+0.0274	177.0	12/7/88
10/8/88	10/8 – 10/13	8	6	+0.2029	190.1	11/28/88
10/17/88	10/13 – 10/18	7	6	+0.0795	180.9	12/3/88

described above. This is as expected, since this procedure ignores $F_{10.7}$ variations due to the 27-day rotation of the Sun and the gradual rise towards the solar maximum.

Reentry occurred on December 6, 1988, near 0130 coordinated universal time (UTC), with no visual confirmation. The last telemetry was received as San Marco passed over Kenya just prior to this time. Predictions made within 6 weeks of reentry were accurate to within 24 hours. Predictions made the day of the reentry were accurate to approximately one orbit. Five days before reentry, on December 1, the 2σ extremes of the atmospheric density model predicted reentry times within 24 hours. Figure 6 shows a plot of predicted reentry dates versus the prediction epoch.

When the calibration and reentry prediction were repeated using the Jacchia-Roberts model with definitive $F_{10.7}$ and K_p values, a markedly lower value of $C_D = 1.67$ was needed to match the observed decay for the calibration interval. The Harris-Priester model with n = 2 required $C_D = 1.76$ for agreement over this calibration interval. The predicted reentry date (December 16) using the calibrated Jacchia-Roberts model was late and was near the date for the Harris-Priester model with n = 2 and $C_D = 1.76$. During the calibration time interval, solar flux levels were in the range of 100 to 125; during the time interval until reentry, solar flux levels were in the range of 175 to 200. Similar inconsistencies in the Harris-Priester model dependence of the density on $F_{10.7}$ for widely different values of the solar flux were also noted in the SMM analysis.

5. LDEF LIFETIME ANALYSIS

Calibration runs for LDEF were performed using NORAD two-line elements spanning October 18, 1988, to January 24, 1989. The calibration was done twice, once with actual monthly mean values of $F_{10.7}$ and once with the SH 8/88+ solar flux model. For both solar flux models, agreement was obtained with $C_D = 0.66$, corresponding to a ballistic coefficient of 0.00719 square meter per kilogram.
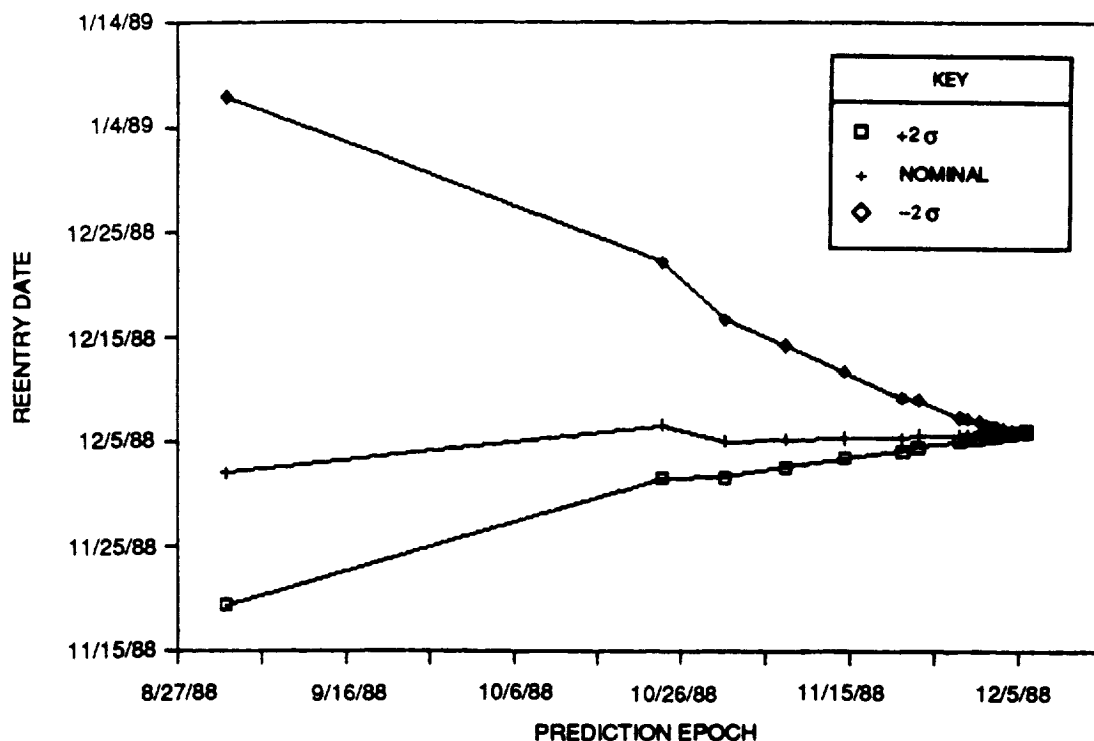
Figure 6. San Marco Reentry Dates Versus the Prediction Epoch

This effective ballistic coefficient was then used to predict the LDEF orbital evolution and the reentry date. Using an orbital state vector for February 1, 1989, and the SH 8/88+ solar flux model, the LDEF reentry is predicted to occur on February 16, 1990. SMM, though currently in a higher orbit than LDEF, is decaying more rapidly and will move lower than LDEF in June 1989 as it proceeds toward reentry. At the time of the planned retrieval in November 1989, the altitude of LDEF is predicted to be in the range of 370 to 350 kilometers.

Repeating the analysis with the SH 1/89+ solar flux model yields different results. A calibration over the month of February produced agreement with $C_D = 0.74$. When this propagation is extended forward in monthly segments based on the SH 1/89+ solar flux model, LDEF reentry is predicted for December 25, 1989. The margin for error is small if LDEF is to be successfully retrieved. A moderate increase in the solar flux beyond currently predicted values could easily threaten the planned November retrieval.

6. SUMMARY

Methods and results for spacecraft orbital lifetime prediction implemented in the GSFC FDD have been described. The procedure relies on a calibration of the ballistic coefficient over an interval of known orbital decay and solar activity. The calibration is followed by propagations to reentry, based upon a time-dependent atmospheric density driven by pre-dicted $F_{10.7}$ models and starting with the most current orbital state.

As expected, the accuracy of the reentry prediction is strongly dependent upon the accuracy of the predicted solar flux model. The following additional observations can be made.

For long-term predictions, the use of the GTDS Harris-Priester atmospheric density model offers simplicity in the operational procedures and provides sufficient consistency and accuracy. This may occur because the calibration over the orbital decay intervals compensates for the limiting aspects of the Harris-Priester atmospheric density model. In particular, this model does not internally accommodate effects from the 81-day averaged $F_{10.7}$ value representing the solar disk radiance and the short-term geomagnetic index variations. Calibrations performed over intervals of the solar cycle similar to those expected in the propagation period may account for these limitations in the average sense.

Furthermore, the San Marco analysis and results provided an opportunity to practice for SMM and LDEF. When reentry is several months away, the present procedures are adequate. A baseline reference trajectory is established and used until comparisons with actual altitude data indicate that a modification is necessary. For the last few months of orbital decay, improved results can be obtained by repeating the propagations frequently and adjusting the drag model to obtain consistent reentry dates. For longer propagations, this is less practical, due not only to the longer computation time but also to the fact that errors in the predicted solar flux models dominate the uncertainties in reentry time.

Preliminary efforts to apply the Jacchia-Roberts atmospheric density model to orbital decay prediction led to mixed results, indicating that more work is necessary in this area. Good results were obtained in the calibration propagation for SMM in the 1-year interval of 1988. Less success was obtained in predicting the San Marco reentry and in predicting the SMM reentry in 1989. A successful implementation of an atmospheric density model based on the Jacchia-Roberts model should and did yield an intrinsically more accurate orbit prediction in comparison with the historical evolution where the solar flux data are well known. However, procedures are yet to be developed that are operationally simple and that can be used with predicted solar flux models.

Finally, based upon the analysis as of this writing and upon the current tendency for solar activity to often exceed the +2σ levels of the $F_{10.7}$ predictions, SMM will reenter before December 1989 and LDEF could reenter as early as late December 1989.

REFERENCES

1. TRW Corporation, 08554-6001-R000, *Rapid Orbit Prediction Program (ROPP)*, D. M. Wexler, December 1967

2. Computer Sciences Corporation, CSC/TM-79/6214, *Rapid Orbit Prediction Program (ROPP) User's Guide*, W. M. Owen, Jr., September 1979

3. Goddard Space Flight Center, X-582-76-77, *Mathematical Theory of the Goddard Trajectory Determination System*, A. J. Fuchs, C. E. Velez, and J. O. Cappellari (editors), April 1976

4. Computer Sciences Corporation, CSC/SD-85/6738, *Goddard Trajectory Determination System (GTDS) User's Guide, Revision 2*, D. Squier and K. Byers, December 1987

5. Schatten, K. H., "Solar and Geomagnetic Prediction Data," memorandum from K. H. Schatten, GSFC Code 610.2, to GSFC Code 550, February 17, 1988

6. Schatten, K. H., "Update of Solar Flux and Geomagnetic Index Predictions," memorandum from K. H. Schatten, GSFC Code 610.2, to GSFC Code 550, August 24, 1988

7. Schatten, K. H., "January 1989 Solar and Geomagnetic Prediction Data," memorandum from K. H. Schatten, GSFC Code 610.2, to GSFC Code 554, January 31, 1989

8. Marshall Space Flight Center, "Solar Activity Inputs for Upper Atmospheric Models Used in Programs to Estimate Spacecraft Orbital Lifetime", MSFC memorandums, December 1987, April 1988, and June 1988

9. Computer Sciences Corporation, CSC/TM-80/6319, *Evaluation of SMM Attitude Stability at Low Spacecraft Altitudes*, S. D. Oh and J. M. Buckley, November 1980

10. Smith, E. A., "Correlations between Solar Activity and Operationally Determined Satellite Drag Variation Parameters," Paper No. 27, presented at the GSFC Flight Mechanics/Estimation Theory Symposium, Greenbelt, Maryland, May 1988