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Long-Term Orbital Lifetime Predictions

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Long-Term Orbital Lifetime Predictions

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Scientific and Technical
Information Division

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BACKGROUND

Many missions require long-term orbital lifetime predictions: Hubble Space Telescope (HST) to determine when or if altitude reboosts will be necessary, Solar Max Mission (SMM) and Long Duration Exposure Facility (LDEF) to plan repair and retrieval missions.

PURPOSE

The purpose of this study was to document the long-term orbital lifetime prediction technique and to discuss the uncertainties in long-term lifetime predictions.

SCOPE

Lifetime predictions were made for SMM, LDEF, and the Pegasus Boilerplate (BP). LDEF was launched and SMM retrieved and repaired in April 1984. BP was launched by the Saturn I vehicle, SA-8, in 1965. In January 1985 these three satellites were at altitudes high enough to result in long lifetime predictions (>9 years for the best estimate case).

ANALYSIS

Once a satellite is in orbit and the altitude is known, the uncertainties in lifetime prediction result from uncertainties in the density model, the solar activity data used as input to the density model, and the ballistic coefficient.

For this report, altitude is defined as the mean semimajor axis minus the mean Earth radius. The mean semimajor axis is calculated from the two-line orbital element sets furnished by the United States Space Command (formerly known as NORAD).

In January 1985, SMM and LDEF were in nearly circular orbits; SMM at an altitude of 496 km and LDEF at an altitude of 479 km. The BP (launched in 1965) was in an elliptical orbit with perigee altitude of 427 km and apogee altitude of 518 km.

Density Model

The 1970 Jacchia density model [1] was used. The Marshall Space Flight Center (MSFC) orbital lifetime program uses tables of density as a function of altitude and exospheric temperature [2]. The uncertainty in the density model is on the order of 15 percent. Model accuracies have remained essentially constant during the past two decades [3].

Solar Activity

Solar activity consists of three different parameters that are required input for the Jacchia density model. These parameters are: the daily value of the 10.7 cm solar flux (F10.7), the 162 day midpoint average of the F10.7 (F10.7B), and the 3-hourly value of the geomagnetic activity index (Ap).

Long-range estimates are made regularly by MSFC [4] of the 13-month smooth 10.7-cm solar flux, F10.7B, and Ap. There are no long-term predictions made for daily F10.7 or 3-hourly Ap. For long-term lifetime predictions, the 13-month smooth estimates are used for F10.7B, F10.7, and Ap (F10.7 is set equal to F10.7B).

The 13-month smooth value is a midpoint average. The current monthly average is needed to determine the actual 13-month smooth value 7 months ago. This time lag means that it is 8 to 12 months after the fact before it is known that the solar cycle minimum or maximum has occurred.

Ballistic Coefficient

The ballistic coefficient is defined as: $BC = M/CDA$, where M is the vehicle mass (kg), CD is the drag coefficient, and A is the reference area (m^2).

Once a satellite is in orbit, the actual orbit decay can be observed. A ballistic coefficient can be determined by using the current solar activity prediction and varying an initial estimate of the ballistic coefficient until the predicted orbital decay is in good agreement with the actual decay. Approximately 90 days of actual decay data are sufficient to determine a ballistic coefficient. The resulting lifetime predictions will remain consistent for 6 to 18 months if the predicted solar activity is a good representation of the actual solar activity.

RESULTS

Ballistic coefficients were determined for SMM, LDEF, and BP. The initial altitude was determined from a January 1985 two-line element set. The February 1985 solar activity data were used (figs. 1–4). Over the next 18 months the actual decay closely followed the +2-sigma prediction instead of the best estimate.

Ballistic coefficients were determined from an initial altitude in July 1986 and using the July 1986 solar activity data (figs. 5–8). Over the next year the actual decay continued to closely follow the +2-sigma prediction.

In June 1987, it was known that solar cycle 22 had started. Ballistic coefficients were determined from an initial altitude in April 1987 and the June solar activity data (figs. 9–12). June 1987 was the first solar data published after the solar minimum of September 1986 which was the beginning of solar cycle 22. Solar cycle 22 began earlier than previously predicted (predictions are based on the average cycle period of 11 years) and started higher than the mean cycle. These two factors shifted predicted impact dates much earlier than previous predictions. Over the next 18 months, the actual decay fell between +2-sigma and the best estimate.

Another ballistic coefficient calibration was done in August 1987. The additional (2 months) data on cycle 22 caused some change in the solar activity prediction. The ballistic coefficients were slightly smaller than those determined in June except for SMM, which increased (figs. 13–16). There was no improvement in the accuracy of the lifetime predictions although the actual decay now closely followed the best estimate.

In October 1988, it was noted that the actual decay rates of SMM, LDEF, and BP had increased significantly, beginning in early September. Ballistic coefficients were determined from an initial altitude in early September. The October 1988 solar activity data were used (figs. 17–20). The best estimate and the +2-sigma lifetime predictions made at this time bounded the actual dates.

Over the next 7 months the actual decay closely followed the +2-sigma predictions, and another update was done. The May 1989 solar activity data were used and an initial altitude from April 1989 (figs. 21–24). Since BP was closer to predicted impact date, an initial altitude from March 1989 was used. There was no improvement in lifetime prediction accuracy.

Figures 25 through 27 show the orbital decay histories of SMM, LDEF, and BP beginning in January 1985. Figure 28 shows the actual solar activity data.

Figures 29 through 34 show the ballistic coefficients determined from the various calibrations and the resultant lifetime predictions.

The tabular results of the ballistic coefficient calibrations and the lifetime predictions are presented in tables 1 through 3.

CONCLUSIONS

The greatest uncertainty in orbital lifetime prediction occurs when the predictions are made across a solar minimum into the next solar cycle. The solar activity prediction technique assumes an 11-year cycle. Before any actual data are available for the next cycle, the best estimate is the mean cycle (which in 1985 was the mean of cycles 1–21), and the +2-sigma is the highest previous cycle (cycle 19).

To get a more realistic "worst case," the +2-sigma case should be used along with the assumption that the next cycle will start +2-sigma early (2.4 years). Table 4 shows the length of previous solar cycles. In January 1985 the "worst case" predicted impact date for SMM would have been February 28, 1990, which still exceeded the actual impact date by nearly 3 months. In July 1986, the "worst case" predicted impact would have been August 11, 1989.

The orbital decay rate should be monitored regularly. Ballistic coefficient updates should be done whenever there is a significant change in the actual decay rate or in the solar activity prediction. Otherwise, updates should be done on a regular basis (possibly once a year). Updates should be done more frequently during the 12 to 18 months prior to a reboost/retrieval mission.

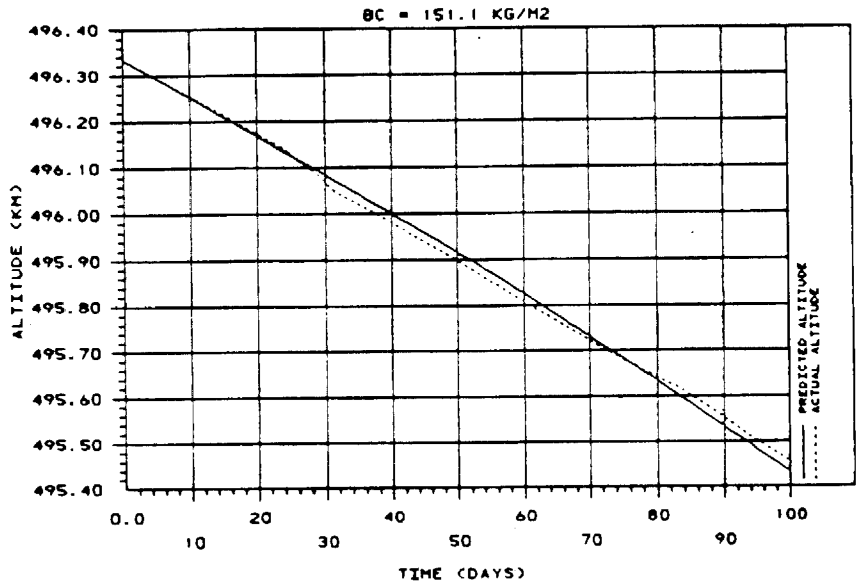

Figure 1. February 1985 ballistic coefficient calibration SMM.

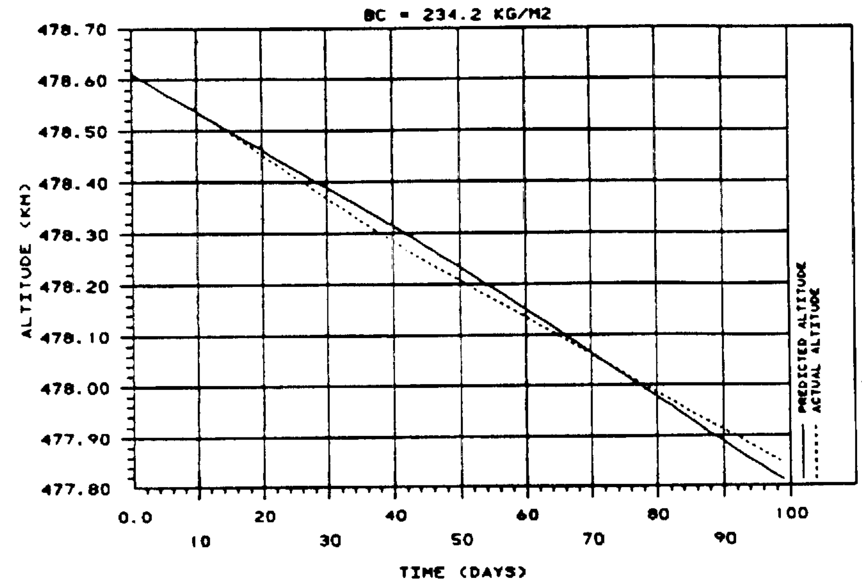

Figure 2. February 1985 ballistic coefficient calibration LDEF.

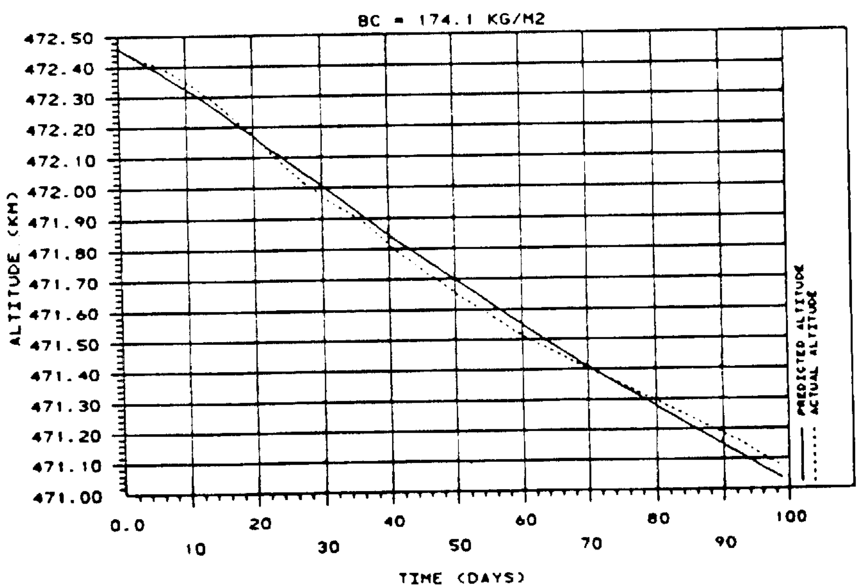

Figure 3. February 1985 ballistic coefficient calibration BP.

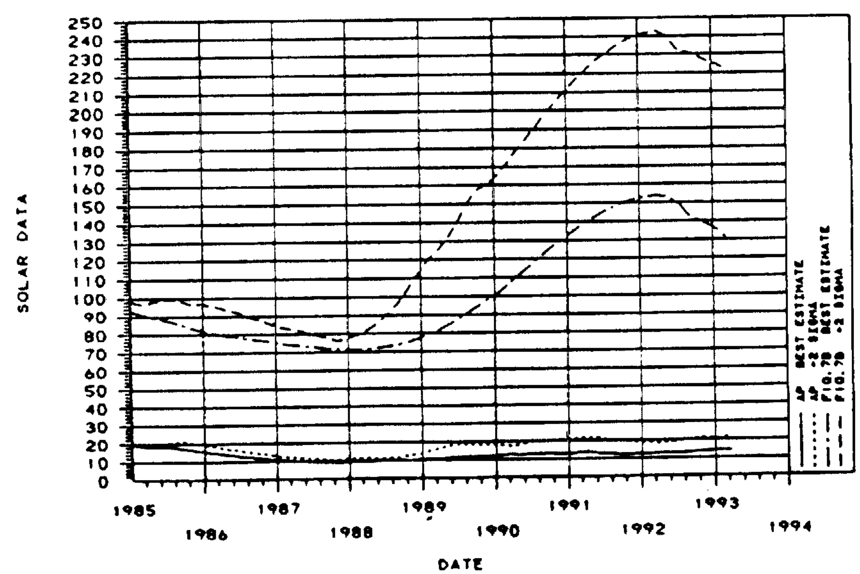

Figure 4. Solar data from February 1985 memo.

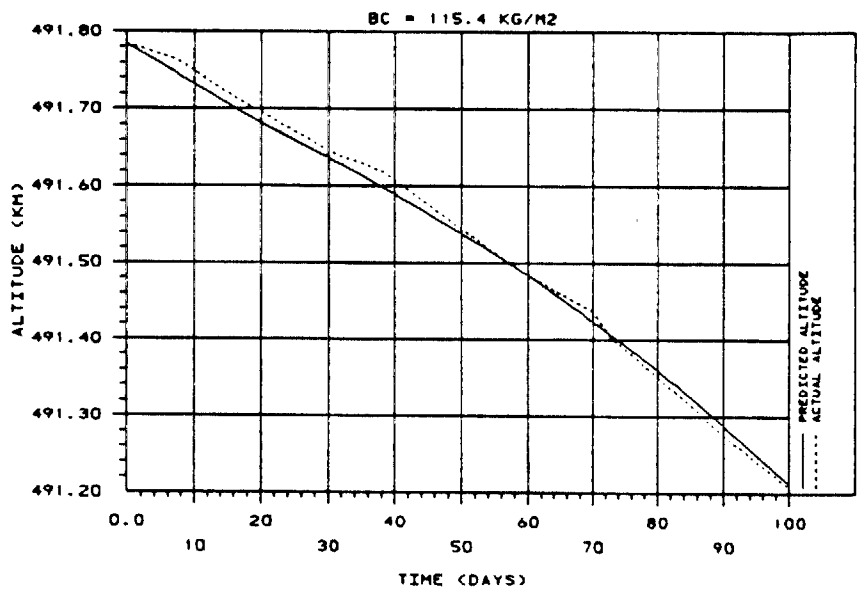

Figure 5. July 1986 ballistic coefficient calibration SMM.

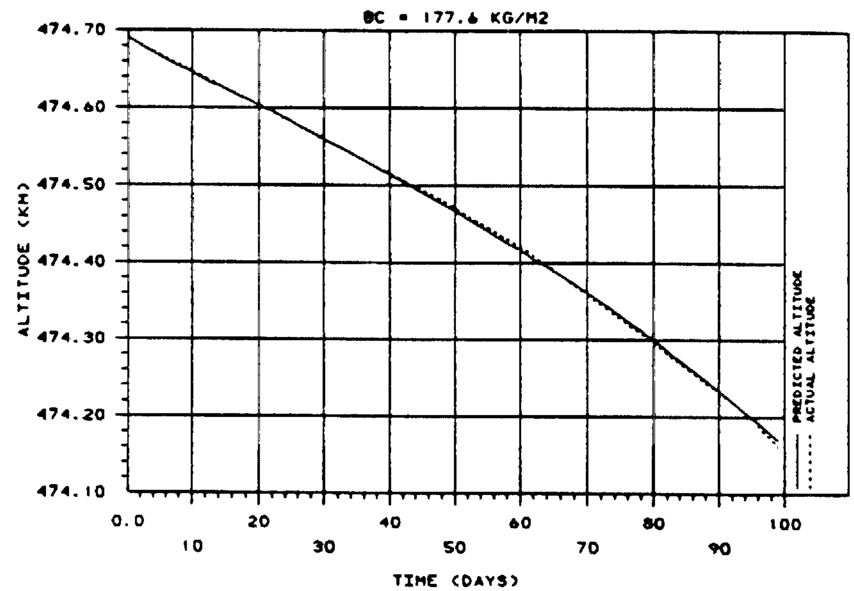

Figure 6. July 1986 ballistic coefficient calibration LDEF.

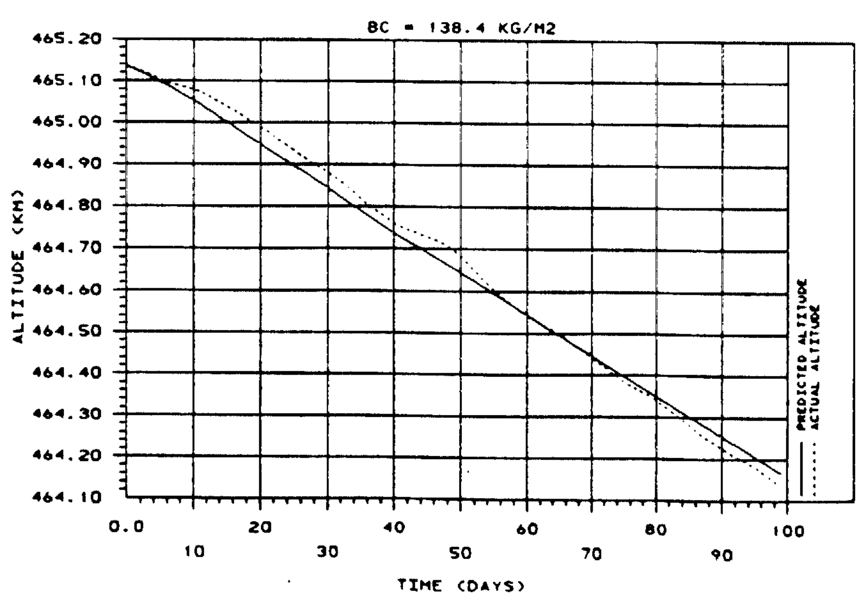

Figure 7. July 1986 ballistic coefficient calibration BP.

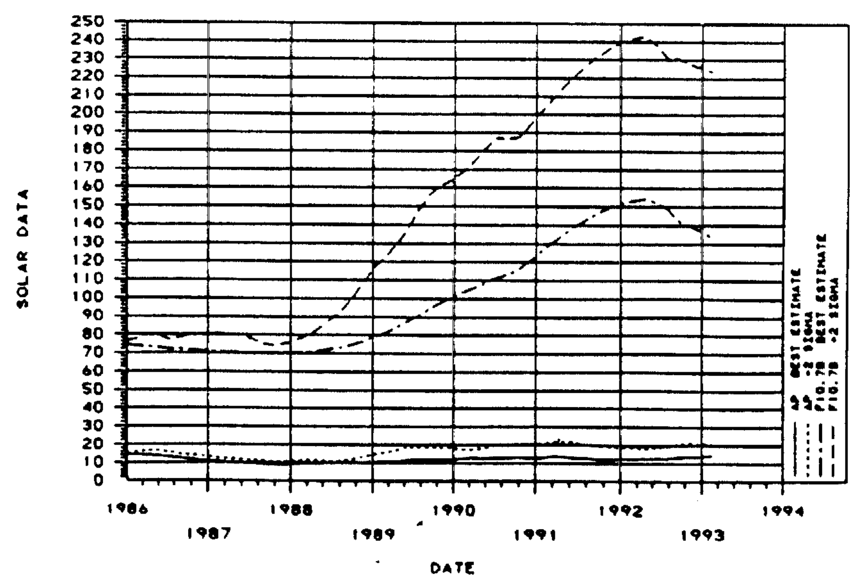

Figure 8. Solar data from July 1986 memo.

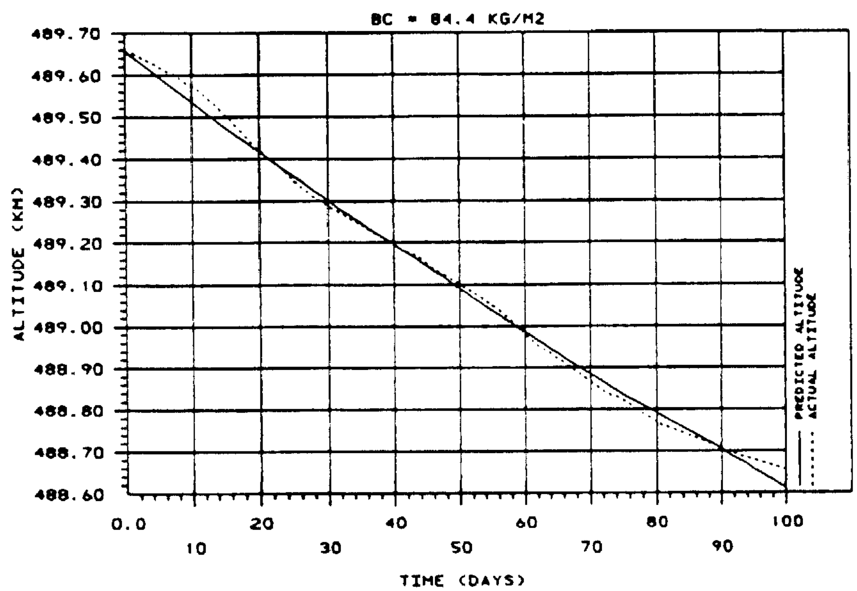

Figure 9. June 1987 ballistic coefficient calibration SMM.

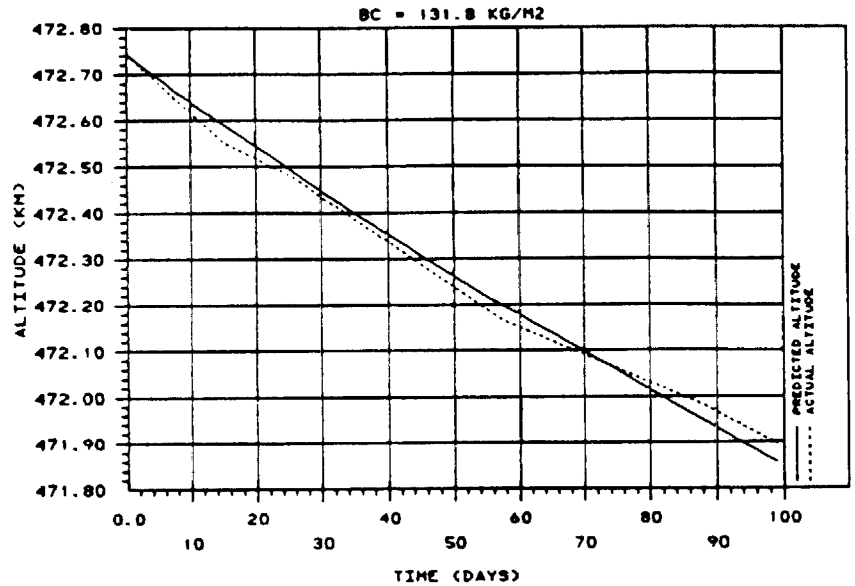

Figure 10. June 1987 ballistic coefficient calibration LDEF.

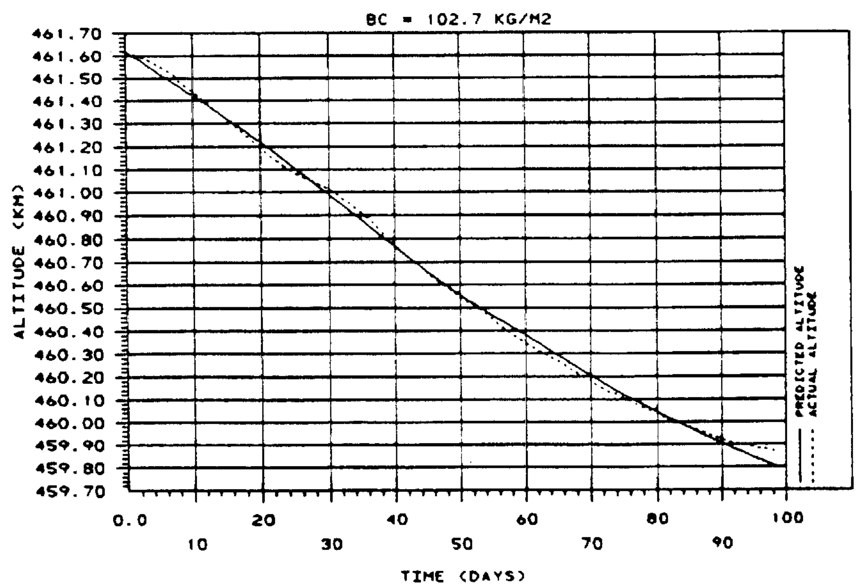

Figure 11. June 1987 ballistic coefficient calibration BP.

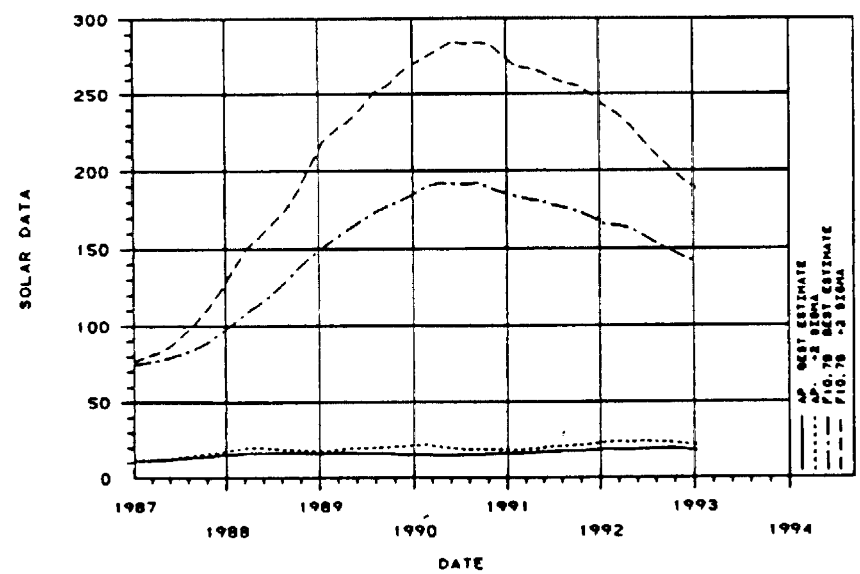

Figure 12. Solar data from June 1987 memo.

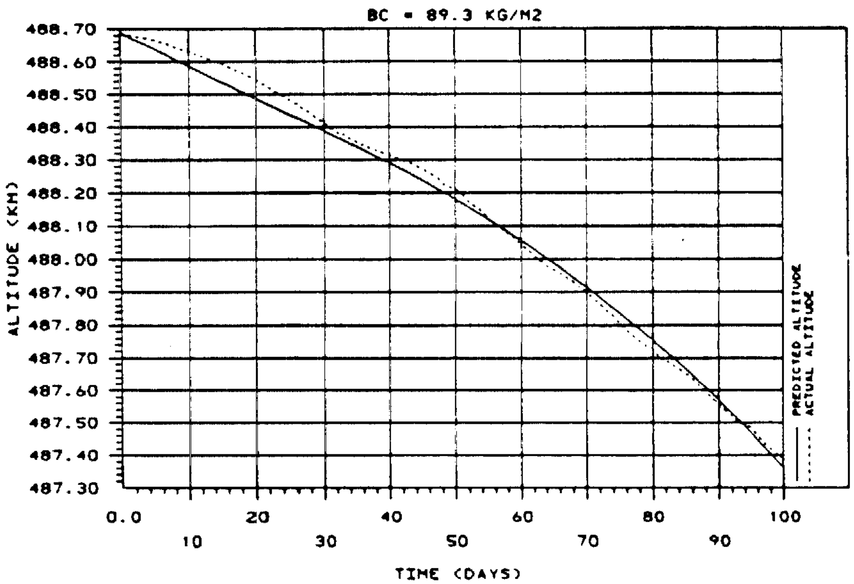

Figure 13. August 1987 ballistic coefficient calibration SMM.

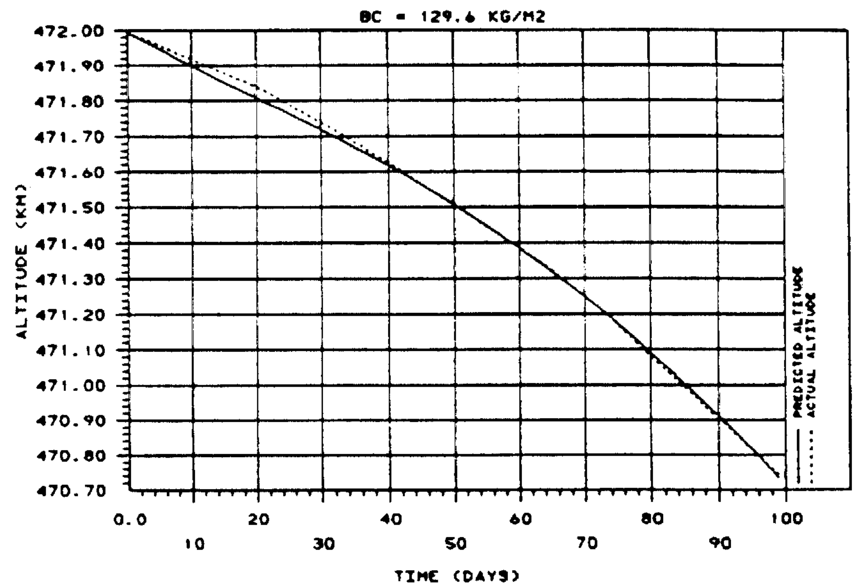

Figure 14. August 1987 ballistic coefficient calibration LDEF.

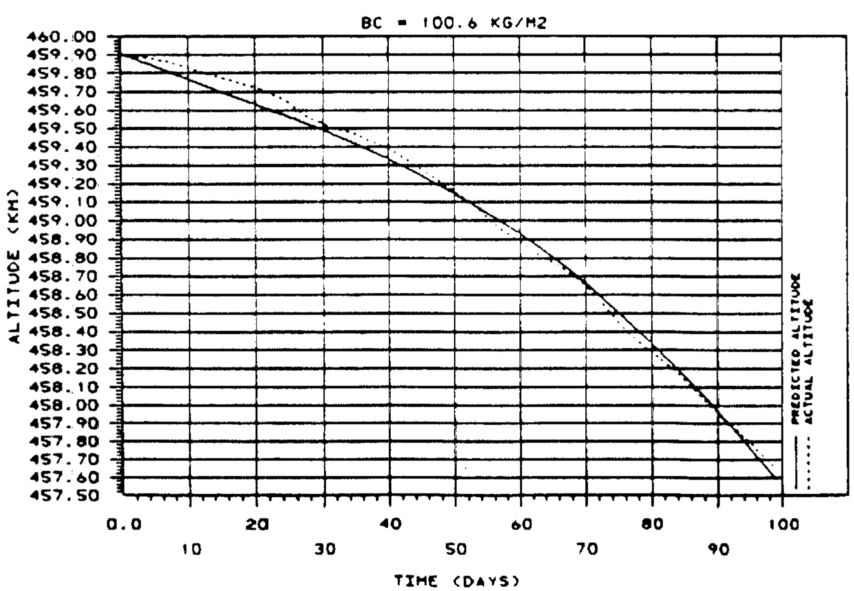

Figure 15. August 1987 ballistic coefficient calibration BP.

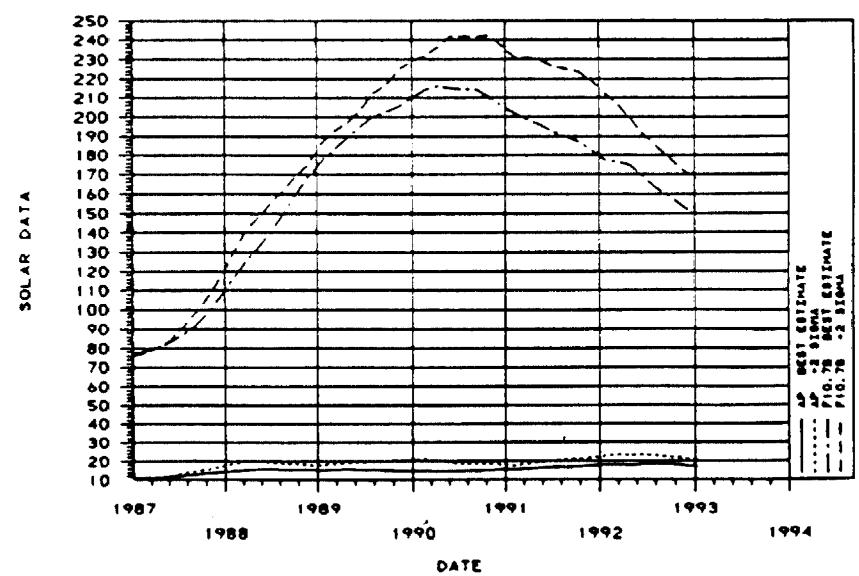

Figure 16. Solar data from August 1987 memo.

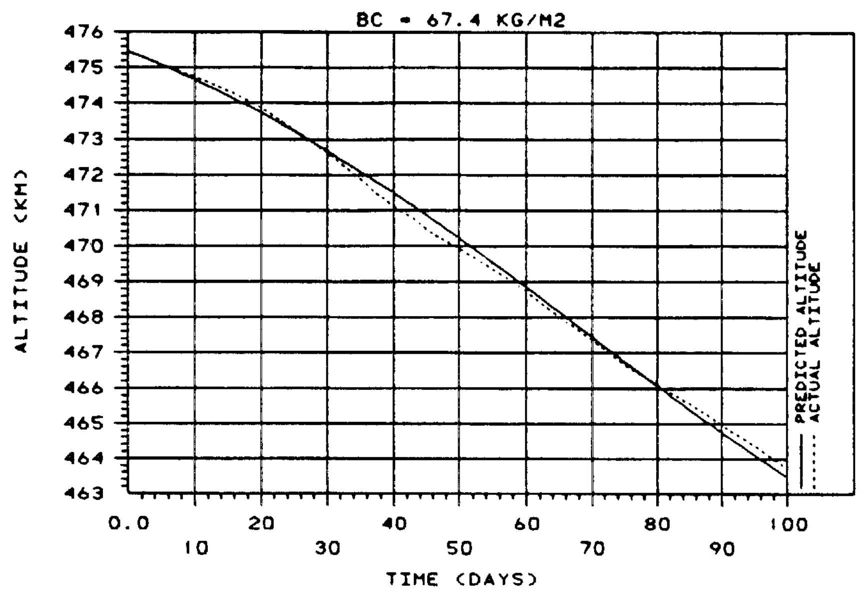

Figure 17. October 1988 ballistic coefficient calibration SMM.

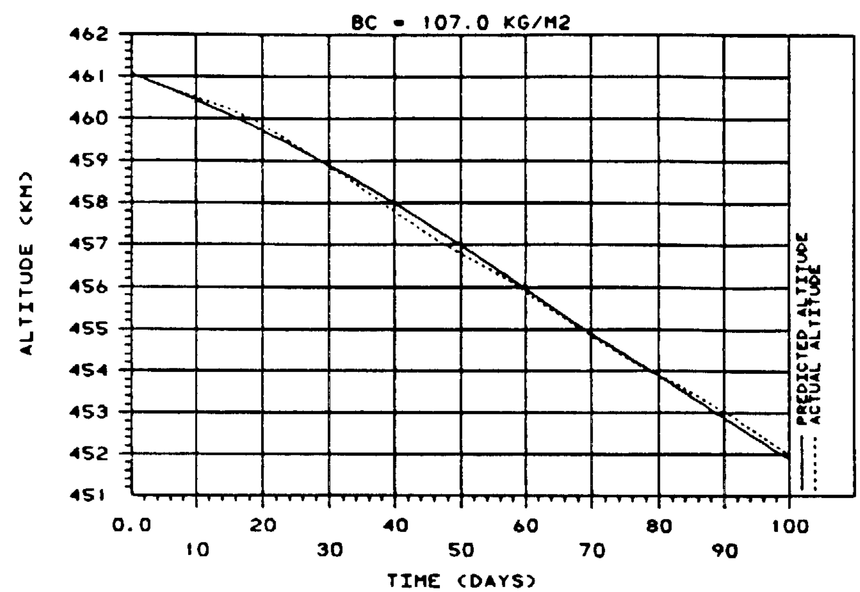

Figure 18. October 1988 ballistic coefficient calibration LDEF.

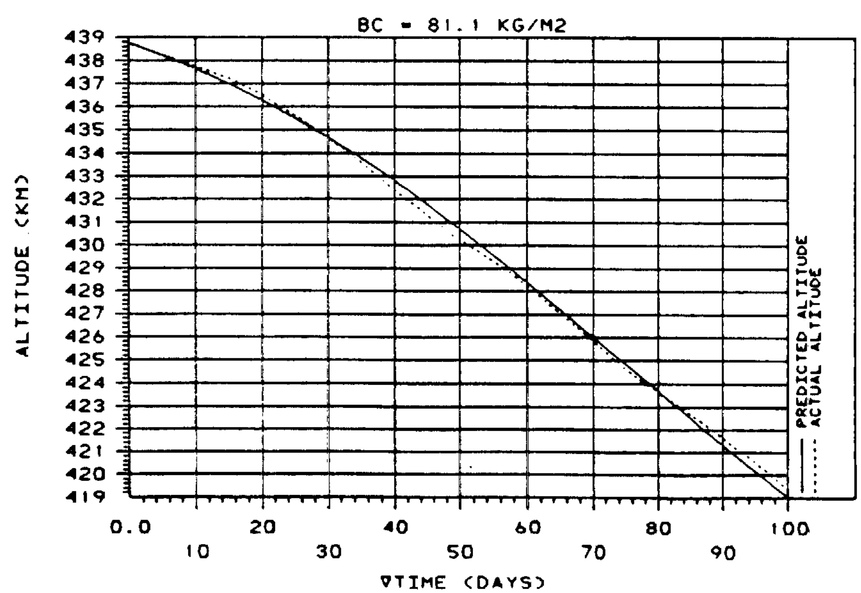

Figure 19. October 1988 ballistic coefficient calibration BP.

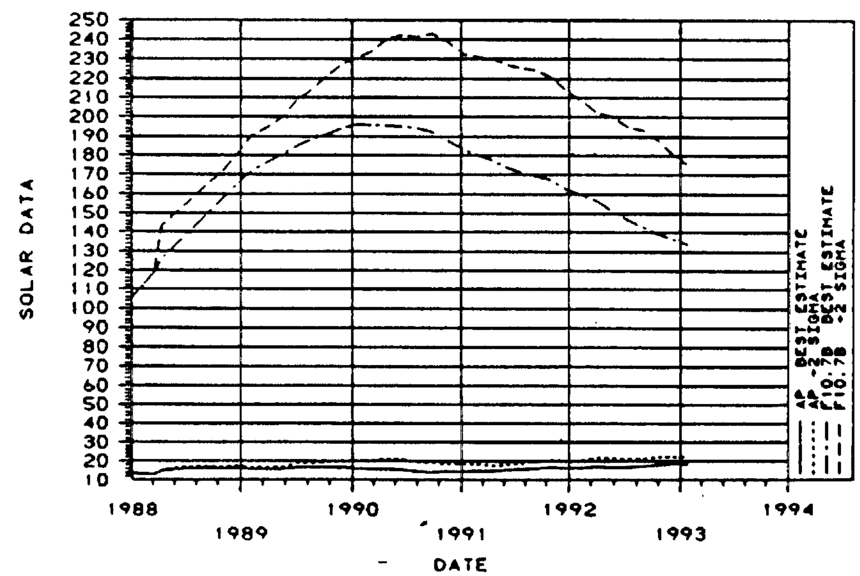

Figure 20. Solar data from October 1988 memo.

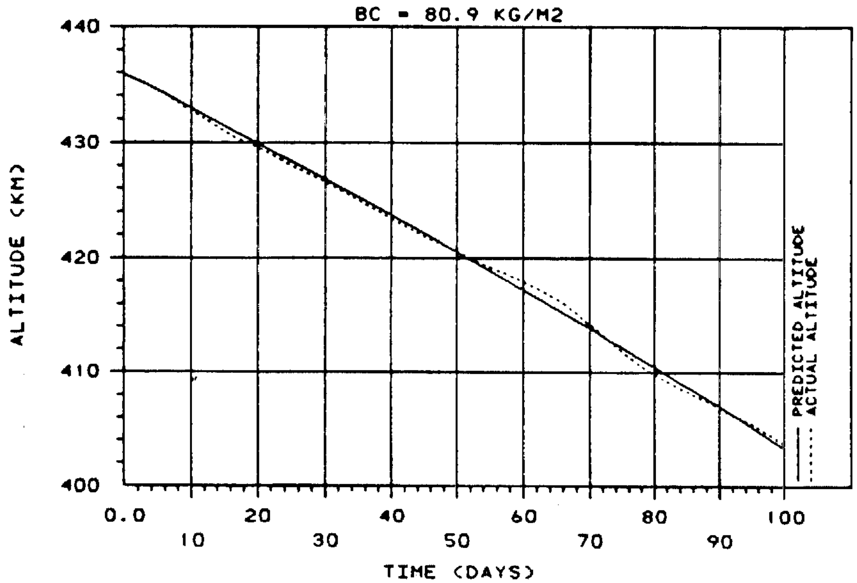

Figure 21. May 1989 ballistic coefficient calibration SMM.

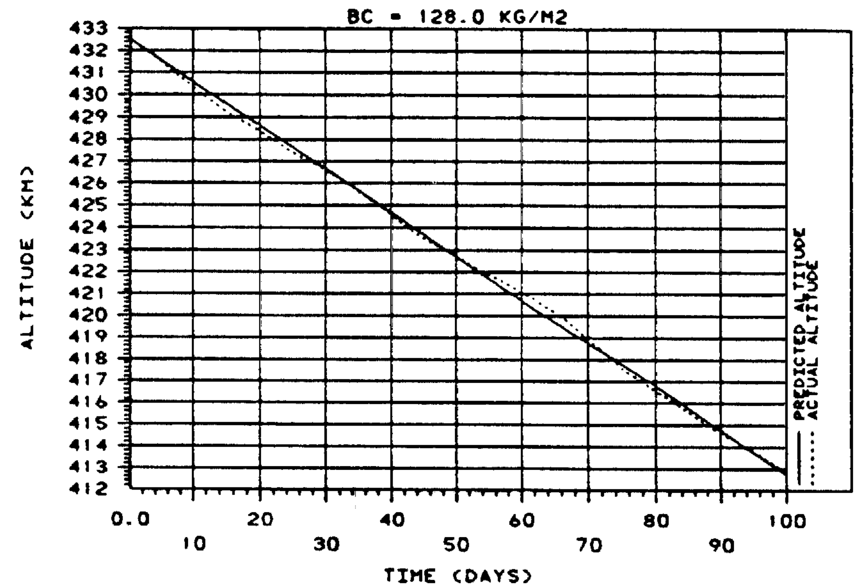

Figure 22. May 1989 ballistic coefficient calibration LDEF.

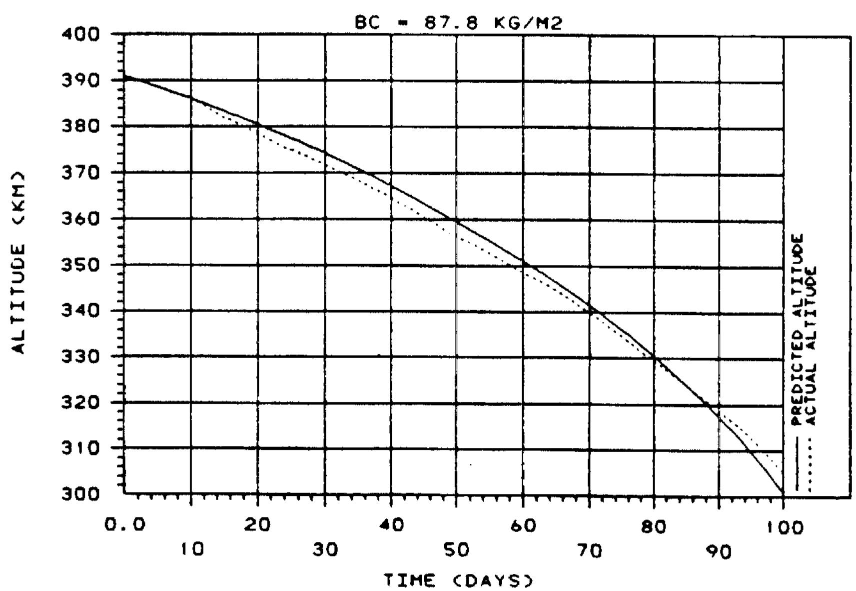

Figure 23. May 1989 ballistic coefficient calibration BP.

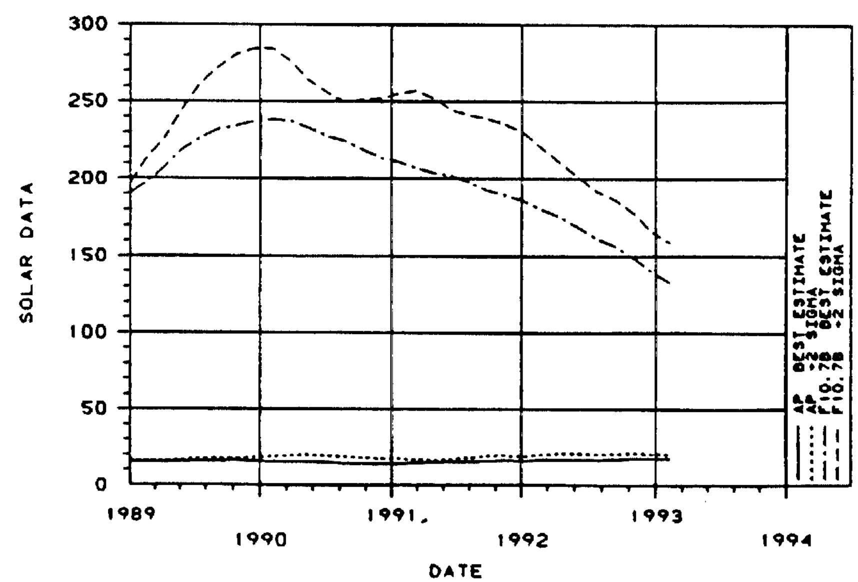

Figure 24. Solar data from May 1989 memo.

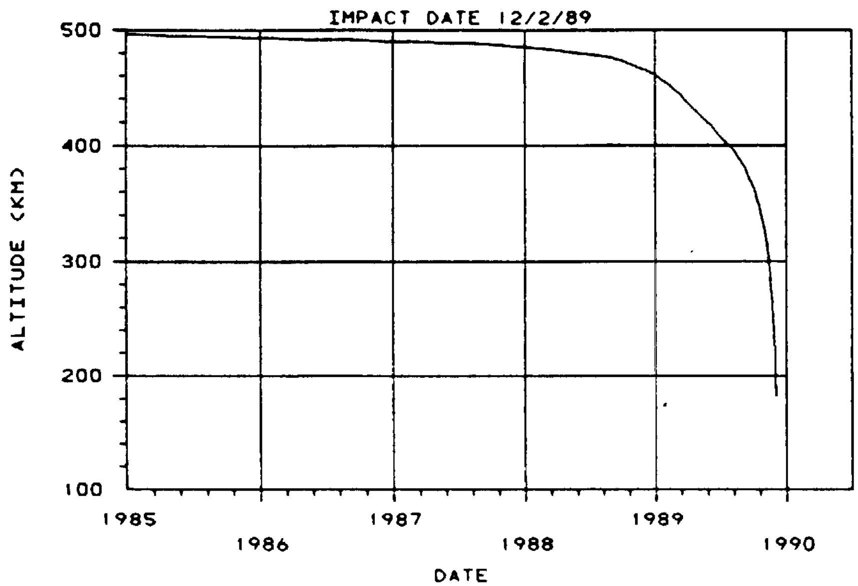

Figure 25. SMM orbital decay.

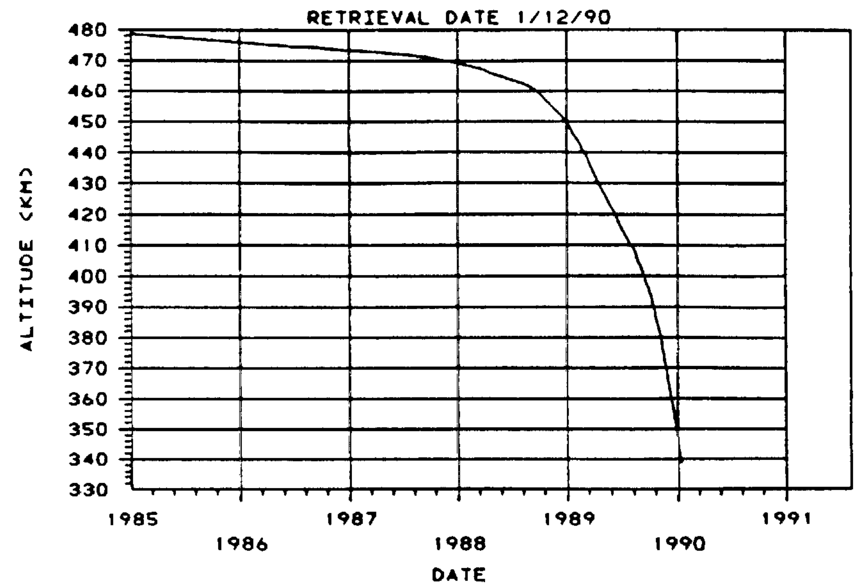

Figure 26. LDEF orbital decay.

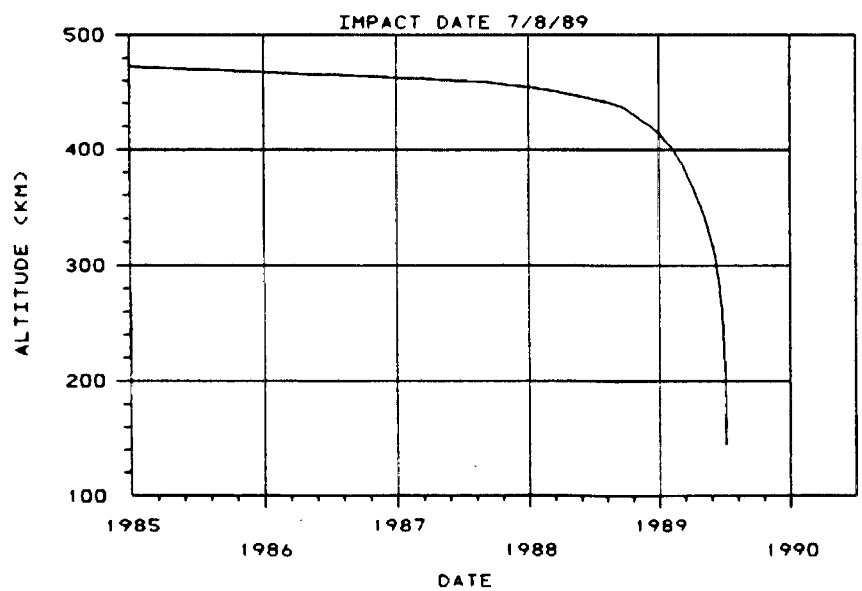

Figure 27. BP orbital decay.

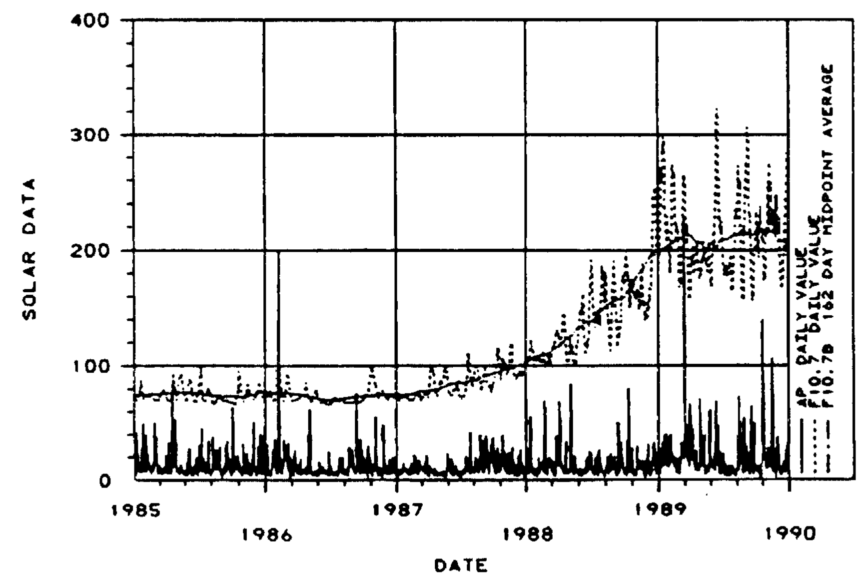

Figure 28. Actual solar data.

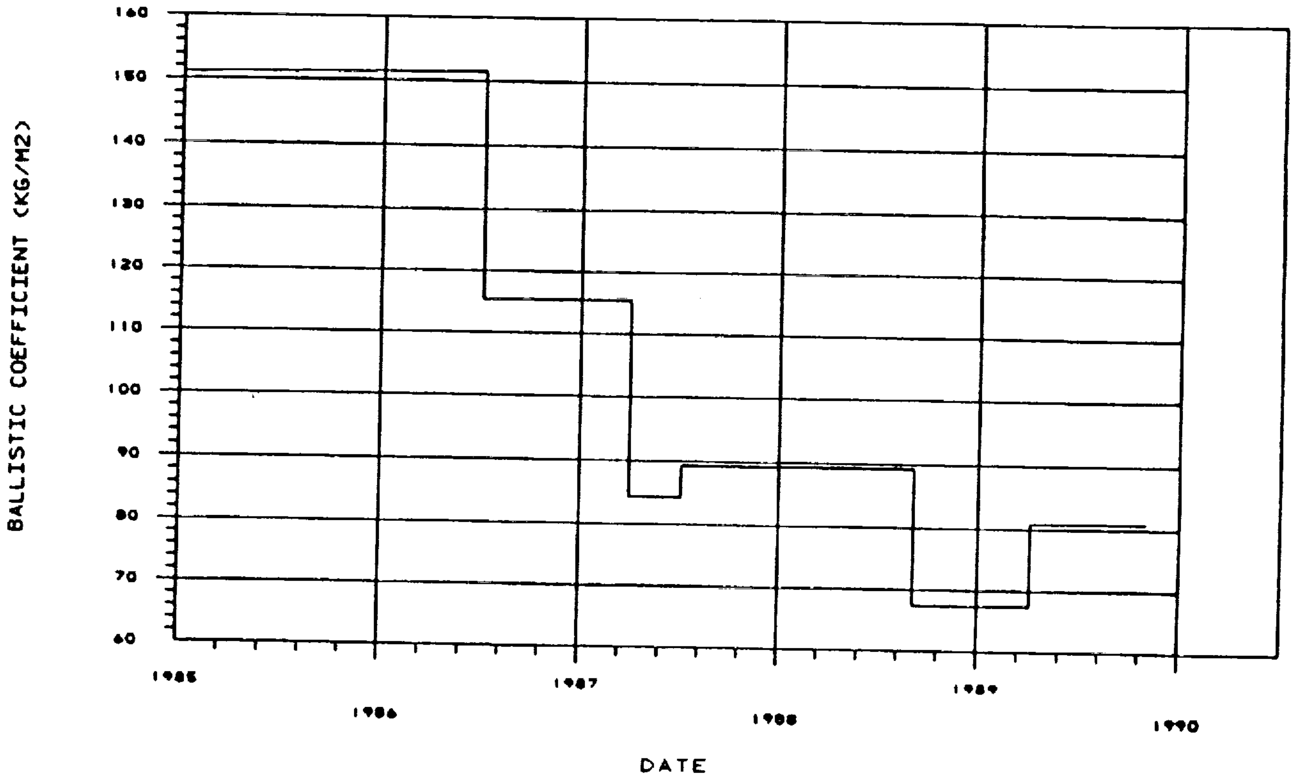

Figure 29. SMM ballistic coefficient (obtained from calibration).

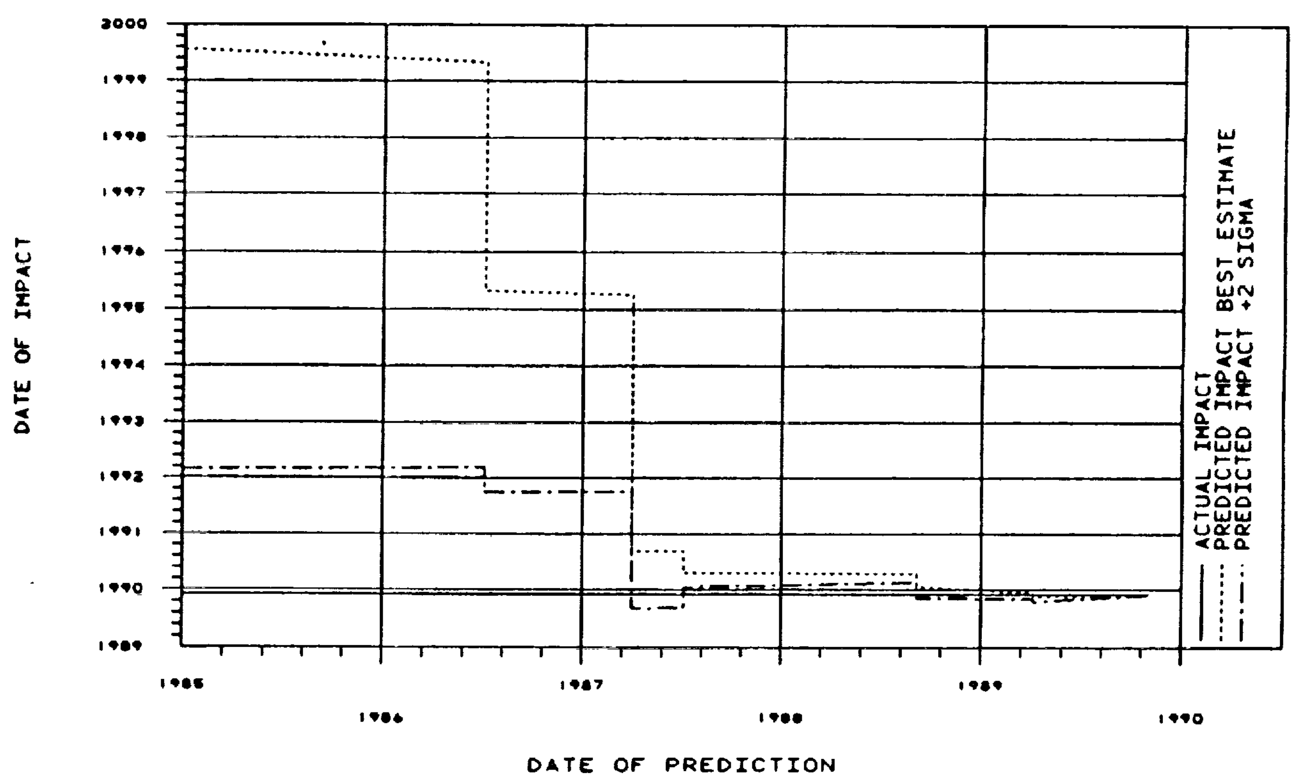

Figure 30. SMM lifetime predictions.

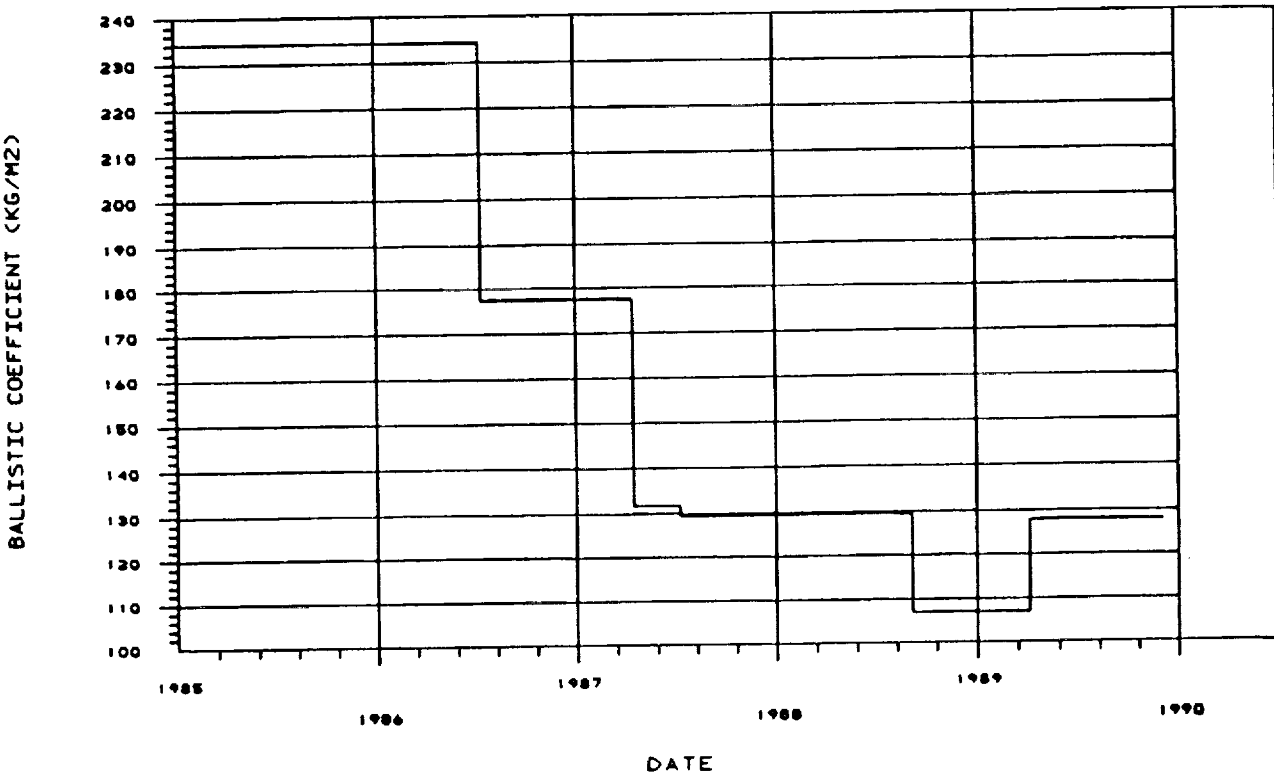

Figure 31. LDEF ballistic coefficient (obtained from calibration).

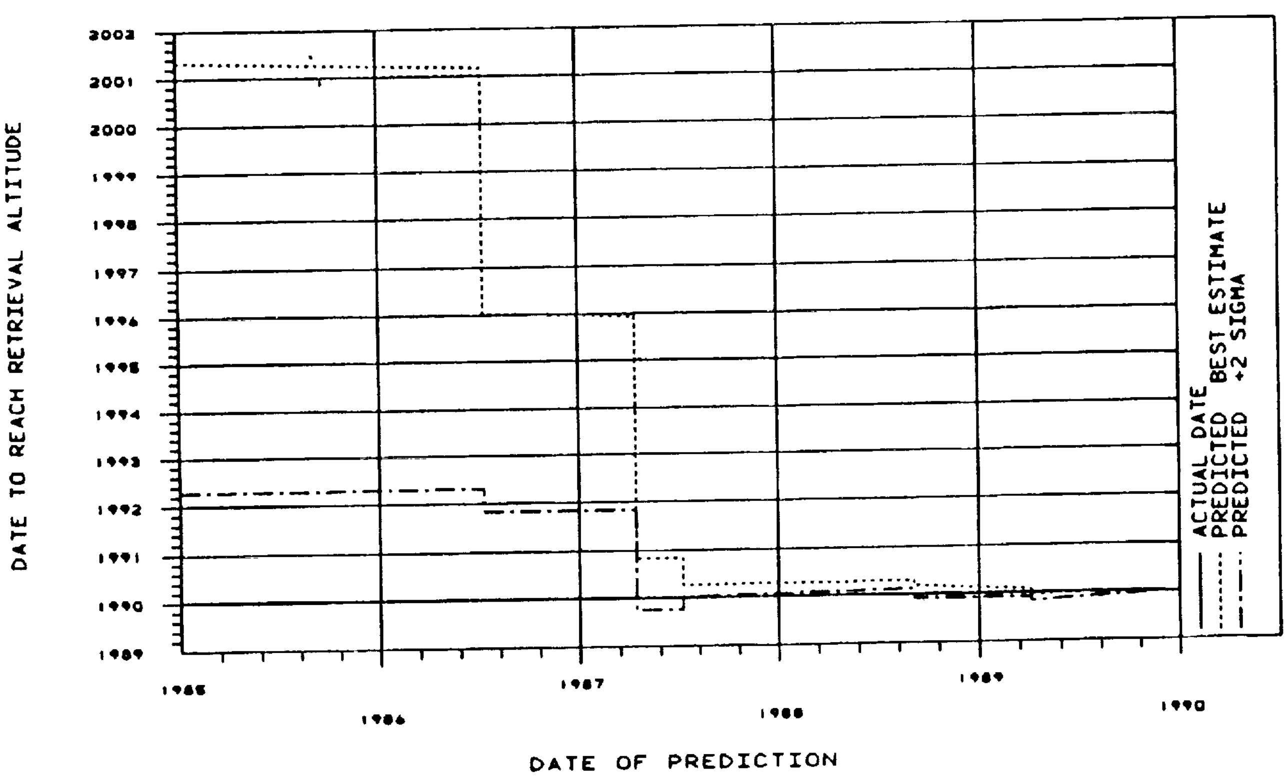

Figure 32. Predictions of date to reach retrieval altitude.

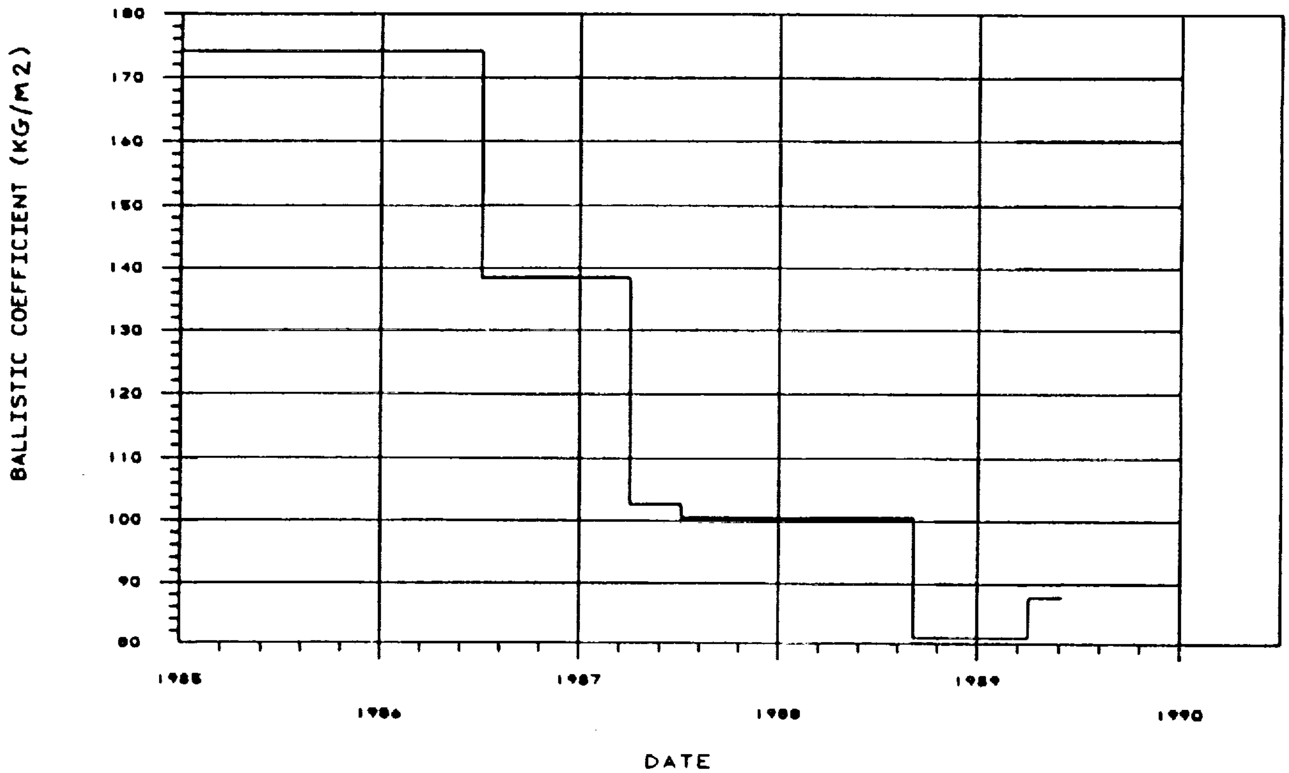

Figure 33. BP ballistic coefficient (obtained from calibration).

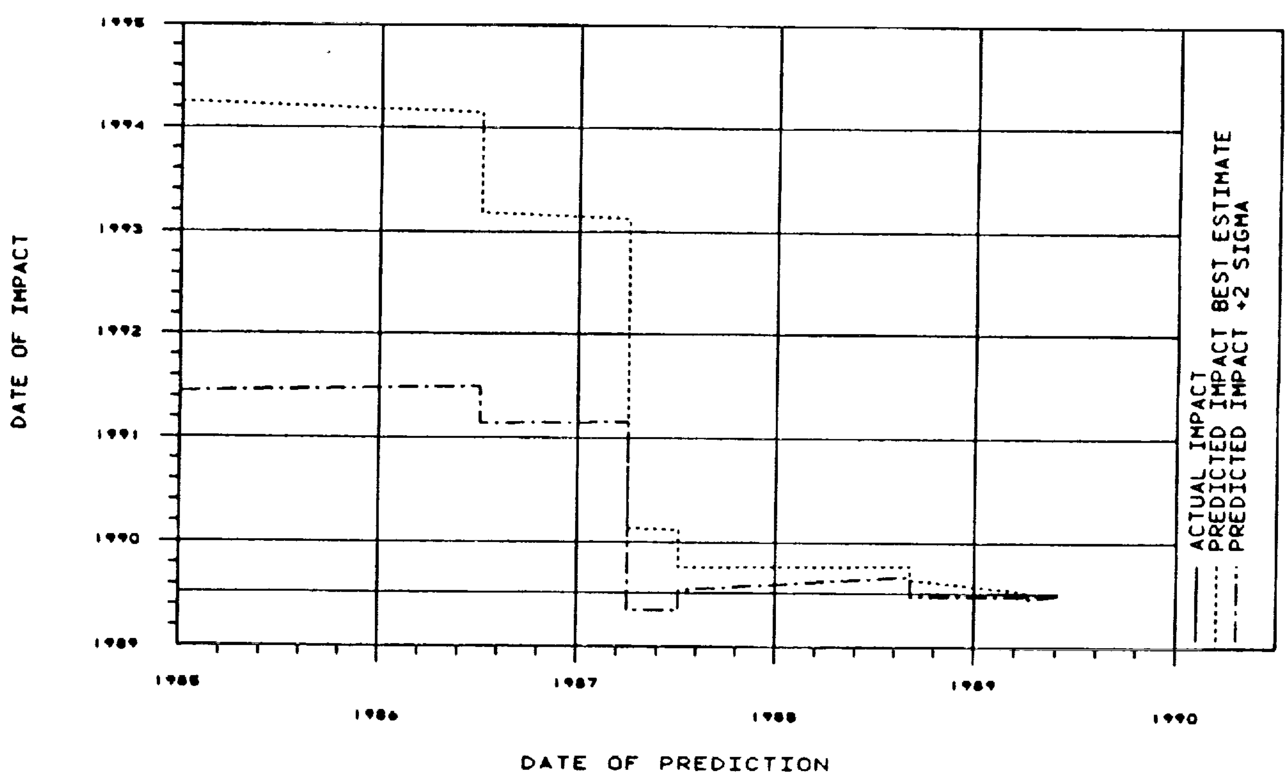

Figure 34. BP lifetime predictions.

Table 1. SMM orbital lifetime predictions.

SOLAR ACTIVITY MEMO	BC (KG/M2)	VECTOR DATE	PREDICTED IMPACT DATE BEST ESTIMATE	SHIFT IN IMPACT (DAYS)	PREDICTED IMPACT DATE +2-SIGMA	SHIFT IN IMPACT (DAYS)
FEB 1985	151.1	1/01/85	7/26/1999	----	2/24/1992	----
		6/30/85	8/16/1999	+21	3/01/1992	+ 6
		1/03/86	7/23/1999	- 3	3/09/1992	+14
		7/05/86	5/03/1999	-84	3/11/1992	+16
JUL 1986	115.4	7/05/86	4/25/1995	----	9/27/1991	----
		1/09/87	4/11/1995	-14	9/30/1991	+ 3
		4/01/87	3/31/1995	-26	9/30/1991	+ 3
		7/04/87	3/04/1995	-53	9/27/1991	0
JUNE 1987	84.4	4/01/87	9/09/1990	----	9/09/1989	----
		7/04/87	9/09/1990	0	9/10/1989	+ 1
		10/02/87	9/05/1990	- 4	9/13/1989	+ 4
		4/02/88	8/27/1990	-13	10/02/1989	+23
		10/01/88	7/27/1990	-44	10/24/1989	+45
AUG 1987	89.3	7/04/87	4/17/1990	----	1/16/1990	----
		1/01/88	4/17/1990	0	1/23/1990	+ 7
		7/01/88	4/19/1990	+ 2	2/12/1990	+27
		9/05/88	4/16/1990	- 1	2/15/1990	+30
OCT 1988	67.4	9/05/88	1/23/1990	----	11/06/1989	----
		1/01/89	1/18/1990	- 5	11/16/1989	+10
		4/04/89	12/12/1989	-44	11/03/1989	- 3
		9/05/89	11/30/1989	-55	11/15/1989	+ 9
		10/01/89	11/30/1989	-55	11/19/1989	+13
		11/01/89	11/30/1989	-55	11/26/1989	+20
MAY 1989	80.9	4/04/89	11/19/1989	----	10/16/1989	----
		9/05/89	11/24/1989	+ 5	11/10/1989	+24
		10/01/89	11/27/1989	+ 8	11/17/1989	+31
		11/01/89	11/30/1989	+11	11/26/1989	+40

Table 2. LDEF orbital lifetime predictions.

SOLAR ACTIVITY MEMO	BC (KG/M2)	VECTOR DATE	PREDICTED DATE TO REACH RETRIEVAL ALT. BEST ESTIMATE	SHIFT IN DATE (DAYS)	PREDICTED DATE TO REACH RETRIEVAL ALT. +2-SIGMA	SHIFT IN DATE (DAYS)
FEB 1985	234.2	1/11/85	4/27/2001	----	4/11/1992	----
		6/26/85	5/04/2001	+ 7	4/17/1992	+ 6
		1/01/86	4/20/2001	- 7	4/23/1992	+12
		7/10/86	3/02/2001	-56	4/27/1992	+16
JUL 1986	178.6	7/10/86	1/11/1996	----	10/30/1991	----
		1/18/87	12/16/1995	-26	10/31/1991	+ 1
		4/13/87	12/12/1995	-30	11/01/1991	+ 2
		7/08/87	11/16/1995	-56	10/31/1991	+ 1
JUNE 1987	131.8	4/13/87	10/28/1990	----	10/09/1989	----
		7/08/87	10/29/1990	+ 1	10/09/1989	0
		10/24/87	10/27/1990	- 1	10/13/1989	+ 4
		4/12/88	10/19/1990	- 9	10/29/1989	+20
		10/01/88	9/29/1990	-29	11/16/1989	+38
AUG 1987	129.6	7/08/87	4/15/1990	----	1/14/1990	----
		1/03/88	4/18/1990	+ 3	1/25/1990	+11
		7/01/88	4/23/1990	+ 8	2/16/1990	+33
		9/05/88	4/22/1990	+ 7	2/21/1990	+38
OCT 1988	107.0	9/05/88	3/14/1990	----	12/06/1989	----
		1/01/89	3/09/1990	- 5	12/17/1989	+11
		4/04/89	2/03/1990	-39	12/05/1989	- 1
		9/06/89	1/17/1990	-56	12/16/1989	+10
		11/01/89	1/18/1990	-57	12/29/1989	+23
		12/03/89	1/13/1989	-52	1/03/1990	+28
MAY 1989	128.0	4/04/89	12/25/1989	----	11/08/1989	----
		9/06/89	12/30/1989	+ 5	12/02/1989	+24
		11/01/89	1/09/1990	+15	12/22/1989	+44
		12/03/89	1/09/1990	+15	1/01/1990	+54

Table 3. BP orbital lifetime predictions.

SOLAR ACTIVITY MEMO	BC (KG/M2)	VECTOR DATE	PREDICTED IMPACT DATE BEST ESTIMATE	SHIFT IN IMPACT (DAYS)	PREDICTED IMPACT DATE +2-SIGMA	SHIFT IN IMPACT (DAYS)
FEB 1985	174.1	1/03/85	4/01/1994	----	6/12/1991	----
		6/30/85	3/20/1994	-12	6/17/1991	+ 5
		1/02/86	3/25/1994	- 7	6/30/1991	+18
		7/04/86	2/25/1994	-35	7/04/1991	+22
JUL 1986	138.4	7/04/86	3/06/1993	----	2/22/1991	----
		1/02/87	2/23/1993	-11	2/23/1991	+ 1
		4/02/87	2/16/1993	-18	2/26/1991	+ 4
JUNE 1987	102.7	4/02/87	2/16/1990	----	5/08/1989	----
		7/04/87	2/13/1990	- 3	5/09/1989	+ 1
		10/01/87	2/13/1990	- 3	5/13/1989	+ 5
		4/02/88	2/01/1990	-15	6/03/1989	+26
		10/01/88	1/02/1990	-45	6/30/1989	+53
AUG 1987	100.6	7/04/87	10/05/1989	----	7/19/1989	----
		1/01/88	10/07/1989	+ 2	8/01/1989	+13
		7/01/88	10/11/1989	+ 6	8/31/1989	+43
		9/05/88	10/10/1989	+ 5	9/05/1989	+49
OCT 1988	81.1	9/05/88	8/23/1989	----	6/27/1989	----
		1/01/89	8/19/1989	- 4	7/13/1989	+16
		4/02/89	7/13/1989	-41	6/28/1989	+ 1
		5/02/89	7/09/1989	-45	6/30/1989	+ 3
		6/02/89	7/08/1989	-44	7/04/1989	+ 7
MAY 1989	87.8	3/01/89	7/03/1989	----	6/17/1989	----
		4/02/89	6/29/1989	- 4	6/18/1989	+ 1
		5/02/89	6/30/1989	- 3	6/23/1989	+ 6
		6/02/89	7/04/1989	+ 1	7/01/1989	+14

Table 4. Solar cycle data.

CYCLE NO.	START OF CYCLE	PERIOD (YEARS) MIN. TO MIN.
1	1755.083	11.333
2	1766.417	9.000
3	1775.417	9.250
4	1784.667	13.583
5	1798.250	12.250
6	1810.500	12.750
7	1823.250	10.583
8	1833.833	9.667
9	1843.500	12.417
10	1855.917	11.250
11	1867.167	11.750
12	1878.917	11.167
13	1890.083	11.917
14	1902.000	11.500
15	1913.500	10.000
16	1923.500	10.167
17	1933.667	10.417
18	1944.083	10.167
19	1954.250	10.500
20	1964.750	11.667
21	1976.417	10.250
22	1986.667	--

MEAN CYCLE PERIOD $P = 11.028$ YR

STANDARD DEVIATION $1\sigma = 1.19$ YR
$2\sigma = 2.38$ YR

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16. Abstract

This study analyzed long-term orbital lifetime predictions. Predictions were made for three satellites: the Solar Max Mission (SMM), the Long Duration Exposure Facility (LDEF), and the Pegasus Boiler Plate (BP). A technique is discussed for determining an appropriate ballistic coefficient to use in the lifetime prediction. The orbital decay rate should be monitored regularly. Ballistic coefficient updates should be done whenever there is a significant change in the actual decay rate or in the solar activity prediction.

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