ORBITAL DECAY AND REENTRY OF THE SALYUT 7 ORBITAL COMPLEX

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We have been actively engaged in the analysis of orbital decay rates and predictions of the reentry times for various satellites. These activities have been focused upon the selection of candidate satellites for retrieval by the Space Shuttle, the calibration of Jacchia-type exospheric temperature and atmosphere models, and reentry hazard analysis. This paper discusses the work associated with reentry predictions made for the Salyut 7/Cosmos 1686 orbital complex. The fidelity of the reentry prediction increased as the date of reentry approached, as expected. Results agreed well with ESOC predictions, which used more detailed and exact methods. However, it is clear that significant improvements are needed. The main problem is the lack of orbital element data in the last few hours prior to reentry. A byproduct of our analysis was an improved estimate of the exospheric temperature during the period of high solar activity which occurred during the last months before reentry.

Keywords: Salyut,reentry,hazard,debris,exospheric temperature

1. INTRODUCTION

Almost every day, a satellite large enough to be tracked by the U.S. Space Command reenters the atmosphere. In general, the satellites break up and burn up upon reentry, and few, if any fragments ever reach the surface. However, large masses may survive the reentry of large satellites, and fall to earth, creating a hazard. Even very small fragments from reentry of radioactive satellites are hazardous, because of dangerous nuclear radiation from the fragments. The reentry of the Soviet nuclear reactor-powered spacecraft, Kosmos 954 on 24 January 1978 was the first hazardous reentry to have occurred. Radioactive debris was spread over a large Canadian area, which was fortunately thinly inhabited. Later, the attention of the world was focussed on Skylab when it reentered over Australia on 11 July 1979. Again, the reentry occurred over areas very thinly populated. In both these cases, the times, places, and footprints of reentry were not forecast accurately. These events made it clear that reentry predictions are important, and that improvements in forecasting accuracy are needed.

In recent times, the large Long Duration Experiment Facility came very close to reentry, and its orbit decay was followed with some apprehension. However, it was retrieved by the Orbiter just weeks before falling to an unrecoverable altitude and eventual reentry. The most recent case of reentry by a potentially hazardous object is the Salyut 7 orbital complex. We made periodic predictions of the reentry time for the complex, using methods that we had previously developed to predict reentry times for various satellites.

2. PREVIOUS REENTRY TIME PREDICTIONS

Old, derelict spacecraft are of interest because of the record they bear in terms of historical and scientific significance. For example a robot observatory launched in the 1960s would provide direct evidence of material degradation over time, a cratering record of meteoroid and orbital debris impacts, etc., if it could be recovered either whole or in part. During 1988, we calculated the projected reentry dates of several potential candidates for retrieval by the Space Transportation System (STS). These candidate satellites, with estimated and actual decay dates, are listed in Table 1. The projected decay date was computed by fitting the orbit decay observed for approximately 20 orbital element sets to a decay calculated from a model, letting the area-to-mass ratio remain a free variable and assuming a constant drag coefficient. The element set data typically spanned approximately a decade of on-orbit time for each spacecraft. This technique produced an ensemble of area-to-mass ratios, which may then be reduced to a mean and standard deviation. The means were utilized, in conjunction with National Oceanographic and Atmospheric Administration (NOAA) predictions of solar activity, to estimate the respective reentry dates.

TABLE 1: Predicted Decay Dates of Retrieval Candidate Satellites

COMMON NAME	USSPACECOM CATALOG NUMBER	EXPECTED DECAY TIME	ACTUAL DECAY TIME
OSO-2	987	Aug - Sep 1989	9 Aug; 1989
SAGE	11270	Sep - Oct 1991	11 Apr, 1989
BHASKARA	11392	Jan - Feb 1989	17 Feb, 1989
Solar Max	11703	Jan - Feb 1992	2 Dec, 1989
ASTRO-B	13829	May - Jun 1989	17 Dec, 1988
LDEF	14898	Mar - Apr 1990	20 Jan, 1990 (retrieval)
USA-13	16328	May - Jun 1989	11 May, 1989

During 1989, we performed detailed analyses for the Solar Maximum Mission (Solar Max or SMM), a Pegasus 2 debris object, an Apollo boilerplate mockup capsule test article, and the Long Duration Exposure Facility (LDEF). The distinguishing features of these studies were the large amount of orbital element set data utilized, as well as daily updates of the 10.7 cm solar flux activity.

3. SALYUT 7/COSMOS 1686 REENTRY

3.1 Data Flow

The United States Space Command (USSPACECOM), headquartered at Cheyenne Mountain Air Force Base near Colorado Springs, Colorado, collects observations of orbiting objects in low earth orbit (LEO) and deep space through its world-wide Space Surveillance Network (SSN) composed of radars and electro-optical sensors. From these observations, the USSPACECOM daily assembles the so-called Two Line Element (TLE) sets, whose format is depicted in figure 1 for distribution to SSN operational sites, NASA/Goddard Space Flight Center, and other official users. Elements sets for Salyut 7 were obtained from historical snapshots of the catalog archived by the Orbital Debris Project at NASA Johnson Space Center and, following reboost of the Salyut 7 complex, thrice weekly from Goddard Space Flight Center. Elements were separately maintained for the Cosmos 1686 spacecraft by USSPACECOM since this was originally an independently-orbiting object and had the possibility of returning to that status; however,these were not utilized in the analysis performed.

where A and P are the apogee and perigee heights at time t_i, respectively, and the subscripts m and o refer to modeled and observed data. Data from the SESC were used to specify the solar flux, and hence the atmospheric density as a function of altitude, at each time.

Mueller's DECAY atmospheric drag/general perturbations computer model (Ref. 1) incorporates as its atmosphere model the Jacchia 1971 atmosphere, simplified somewhat for quick execution time through the use of Lineberry's representation of the log of the density as a truncated Laurent series in altitude and exospheric temperature (Ref. 2). DECAY classifies the orbit of the Salyut complex as being of type I, i.e., an orbit whose decay may reasonably be described by the analytical expressions of King-Hele. Lunar-solar perturbations are neglected, as are those due to the geopotential. While this model was developed to statistically describe the orbital decay behavior of large numbers of satellites, tests have demonstrated good correlations (+/- 20% for long-lived orbits) with the more advanced orbit propagators ASOP and DSTROB resident at NASA/JSC.

The estimates of the mean area-to-mass ratio and its standard deviation were improved from 2.9×10^{-3} m^2/kg and 2.3×10^{-3} m^2/kg (6 November, 1990) to 3.1×10^{-3} m^2/kg and 4×10^{-4} m^2/kg (28 January, 1991). While these numbers assume a constant drag coefficient, itself a function of altitude, satellite shape, and satellite attitude, the orbital complex was undergoing a significant change in its attitude between 17 and 21 January (Ref. 3). In addition, atmospheric effects may be masked to some extent because of the relative response of the atmosphere to the solar flux at altitude and latitudes traversed between the two dates cited, and a larger historical archive of two-line orbital elements was available at the latter date. Despite these competing effects, the assumed Gaussian distribution in ballistic coefficient displayed a remarkable shift towards the peak over the time period discussed.

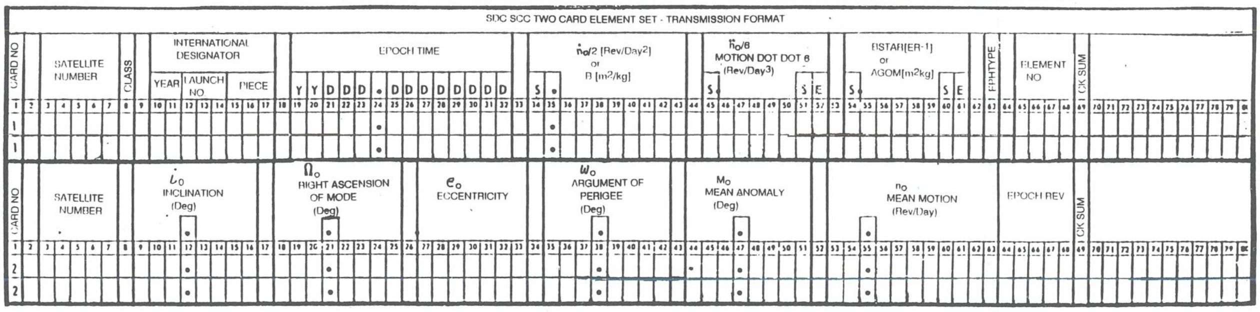

Figure 1. Two Line Element set format

Daily observations of the Ottawa 10.7 cm solar flux were obtained from the NOAA's Space Environment Services Center (SESC) located in Boulder, Colorado. The SESC also provided monthly estimates of the 13-month smoothed solar flux, with 90% confidence limits, from date of issue to December, 1995.

NASA Johnson Space Center supplied the thrice weekly updates of element sets to the European Space Operations Center (ESOC) upon receipt from the archiving center at Goddard Space Flight Center. NASA/JSC also aided the coordination of element set shipment, via the BITNET computer network, the Nuclear Risk Reduction Center and the US Department of State, to the Soviet authorities.

3.2 Estimation of Ballistic Coefficient

As discussed briefly above, the ballistic coefficient may be computed by assuming a constant drag coefficient C_D and varying the area-to-mass ratio so as to minimize the merit function $F(t_i)$ defined by:

$$F(t_i) = \frac{1}{N}\sum_{i=1}^{N}\left[\left(A_m(t_i) - A_o(t_i)\right)^2 + \left(P_m(t_i) - P_o(t_i)\right)^2\right] \quad (1)$$

3.3 Reentry Predictions

Figure 2 depicts the matrix of solar activity and ballistic coefficient values identified and evaluated as a function of time for the 28 January 1991 prediction. In each case, the solid line represents the mean area-to-mass ratio with the predicted solar flux and its 90% confidence values. The dotted lines represent the various solar flux models applied to the mean minus one standard deviation area-to-mass, while the "dot-dash" lines depict the various solar models applied to the mean plus one standard deviation area-to-mass ratio. The reader is cautioned that several lines overlap and that an earlier reentry time indicates either a large solar flux, a large area-to-mass ratio, or both.

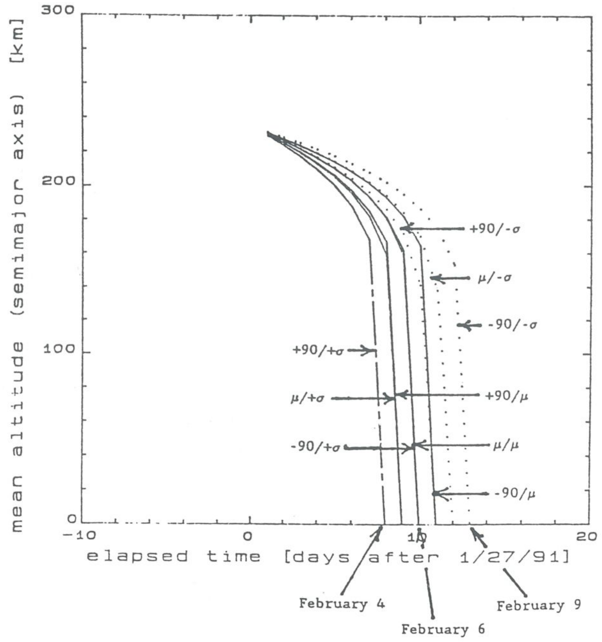

Figure 2. Reentry matrix predictions made on 28 January 1991. The legends +90/μ/-90 refer to mean solar activity and 90% confidence limits; +σ/μ/-σ refer to mean ballistic coefficient and standard deviations employed.

A series of five reentry predictions were made, as shown in Table 2. The first two estimates incorporated only the mean ballistic coefficient and the mean and 90% confidence limit solar flux predictions. The remaining estimates introduced the effect of a standard deviation in ballistic coefficient.

TABLE 2: NASA/ESA Reentry Predictions

NASA prediction	ESA bulletin no.	Time window	predicted re-entry (times UCT)
1. (90/10/07)		-31/ +58 d	1991/02/01
2. (90/11/26)		-11/ +27 d	1991/01/31
	#01 (90/12/03)	±11 d	1991/02/01
	#02 (90/12/10)	±10 d	1991/02/04
	#03 (90/12/21)	± 9 d	1991/02/06
	#04 (91/01/04)	± 8 d	1991/02/07
3. (91/01/06)		-5/ + 8 d	1991/02/01
	#05 (91/01/16)	± 6 d	1991/02/06
	#06 (91/01/25)	-4/ + 6 d	1991/02/06
4. (91/01/27)		-2/ + 3 d	1991/02/06
	#07 (91/01/30)	± 2 d	1991/02/06 16:00
	#08 (91/02/02)	±18 h	1991/02/06 22:00
5. (91/02/03)		±12 h	1991/02/07 12:00
	#09 (91/02/04)	±11 h	1991/02/07 01:37
	#10 (91/02/05)	± 8 h	1991/02/07 02:23
	#11 (91/02/06)	± 4 h	1991/02/07 04:33

A measure of the fidelity of our predictions may be made by comparison with those predictions reported by ESOC through their "Re-entry Bulletin" (Ref. 4). ESOC utilized (Ref. 5) the FOCUS-2 orbit propagator down to 150 km altitude; this code numerically integrates the analytically-averaged equations of motion and incorporates atmospheric drag (MSIS-77/86 density models, harmonic cross-section variation analysis, diurnal bulge model, and solar and geomagnetic forecast models including standard deviations), geopotential (GEM-10 or others up to degree 23), lunar-solar, and solar radiation pressure (oblate earth, cylindrical shadow) perturbations. Below 150 km, the USOC program numerically integrates the perturbed equations of motion with a variable stepsize Runge-Kutta method. Perturbations are the same as those utilized by FOCUS-2 with the addition of an extended atmospheric density model and a variable drag coefficient C_D.

Table 2 compares the ESOC and NASA/JSC reentry predictions as a function of time. One sees that in all cases, the NASA/JSC predictions are comparable to those made by the ESOC using the more advanced orbit propagation methods discussed above.

3.4 Fragmentation and Ground Hazard

A NASA program relevant to the fragmentation and subsequent dispersion of debris from the Salyut 7 complex observes (Ref. 6) the reentry of shuttle external tanks (ETs). These large liquid fuel tanks are approximately a factor of two larger than Salyut/Cosmos in size, possess a similar mass, and like the orbital complex are hollow insulated aluminum structures. Sensors deployed during the reentry and breakup of the STS-31 ET include the Air Force Maui Optical Site (AMOS) 1.6 m telescope, the Maui Optical Tracking and Identification Facility (MOTIF) 1.2 m telescope with stopped aperture, and two video cameras of 19.3 cm and 31.75 cm aperture bourne on the NC-135 ARGUS aircraft. Observations by these sensors indicate that ET breakup occurred at an altitude of 75.571 km. Debris relative velocities range between 238 m/s and 1502 m/s for the initial debris cloud, with large pieces possessing relative velocities of 37.528 m/s to 461 m/s. These observations are consistent with radar observations of 26 previous ET breakups. Twenty-two of these missions utilized an ET with an active tumble valve (TV), a device designed to prevent atmospheric skip during reentry; these missions displayed a mean breakup altitude of 71.14 km with a standard deviation of 2.93 km. The remaining four missions, with inactive TV, had a mean breakup altitude of 73.30 km with a standard deviation of 1.60 km. Thus, fragmentations of the ET are restricted to a relatively narrow altitude band. Analysis indicates further that fragmentation of the ET is due primarily to the melting of structural components, not aerodynamic loading of components. Thus, the Salyut complex probably fragmented at an altitude of approximately 72 km over South America due to the heating and subsequent melting of major structural members.

The Mueller atmospheric decay routines utilized in this work propagate orbits to the atmospheric interface at 90 km altitude; due to the "averaged" atmosphere model used and information regarding the geographical sub-satellite location of interface penetration was not recoverable from the Mueller Model. Therefore, while the DECAY code outputs an impact time, the geographic location and altitude of the impact is breakup and no predictions were made as to the probable location of impact in this study.

The US embassy in Buenos Aires collected such information as was available in Argentina regarding the location and disposition of found debris (Ref. 7). Eight debris objects were reported, as described in Table 3 by official Argentine sources and forwarded by the US embassy to the US Department of State. In general, the objects reported appear to be either aerodynamically efficient or fairly massive, implying a relatively small ballistic coefficient. Observationally, this would tend to place the smaller debris fragments to the west of the reported debris and more massive objects, e.g. film safes, to the east of the debris fall.

TABLE 3: Salyut Debris in Argentina

location, degrees		description
latitude, S	longitude, W	
33.00	60.40	circular piece, 90 cm diameter, 5 cm thick
33.29	61.29	metallic sphere of approximately 1 m diameter
35.59	64.35	1 m^2 plate inscribed with "62-23-0-82-2-3"
30.33	65.56	30 cm rectangle; tubular piece of unknown length (semi-buried); 3 m diameter, 100 kg plate
33.00	59.00	20 cm square fragment
32.00	60.00	fragment; no other details

4. DECAY ANALYSIS: ESTIMATION OF EXOSPHERIC TEMPERATURE

Analysis of the orbital decay parameters for satellites provides values for the exospheric density which are in effect during orbital decay. The calibration is directly related to the estimation of the ballistic coefficient, or the area-to-mass ratio, of orbiting objects. Assuming a reliable model for the sensible atmosphere in LEO, in this case Mueller's DECAY model (Ref. 1) with Lineberry extensions (Ref. 2), one may (i) derive the object's ballistic coefficient through minimization procedures (Ref. 8), (ii) assuming a constant drag coefficient C_D of 2.2 (Ref. 9), solve for the area-to-mass ratio, and (iii) relating a radar or optical signature to true area, solve for the object's mass. This work (Ref. 8) has enabled estimates to be made of the mass and size distributions found in on-orbit debris clouds. Computer algorithms developed in the course of this work were utilized in the present work. Badhwar (Ref. 10) has used this technique to develop a better fit to the Mueller DECAY model's exospheric temperature function of solar flux from analysis of the orbital decay of LDEF during the period of high solar activity.

The current solar cycle, twenty-two, is one of the most intense solar cycles on record and provides an opportunity to extend the empirical relationships between solar flux at the 10.7 cm wavelength and the exospheric temperature for large values of the solar radio flux. The atmospheric decay of the LDEF was utilized in this study using a parameter minimization technique similar to that used to estimate the ballistic coefficient. In this case, for a given binned value of solar flux, modeled apogee/perigee time histories were fit to the observed time histories derived from orbital element sets; the average exospheric temperature was left as the only free parameter. A comparison with the Jacchia '77 model demonstrates agreement for temperatures below 1100 K and increasing deviations for temperatures above.

Analysis of LDEF orbital elements (Ref. 10) between April 1984 and January 1990 (recovery) covering solar cycles 21 and 22 and an altitude range of 475 to 330 km reveals a best-fit relationship of:

$$T_\infty = T_o [1 - \exp(-\nu \bar{F})] \qquad (2)$$

were T_O is an asymptotic temperature value, υ is a constant, and $\bar{F}$ is the mean daily solar flux smoothed by averaging over six solar rotations. Best-fit values are T_O = 1388.16 +/- 32.32 and υ = 9.393×10^{-3} +/- 0.525×10^{-3}.

A similar analysis was performed for the decay of the Salyut orbital complex. Figure 3 depicts the exospheric temperature as a function of smoothed solar flux for both LDEF and Salyut. Vertical error bars are +/- one standard deviation as given by the least-squares fit. One sees the agreement between LDEF and Salyut, indicating a saturation of the atmosphere for large values of solar flux. The slightly higher values of temperature for the

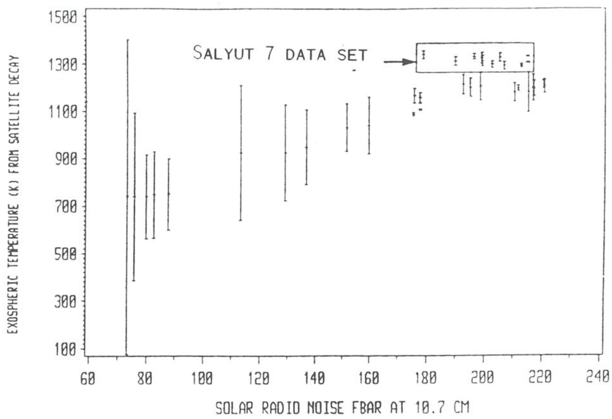

Figure 3. Estimated Exospheric temperature as a function of smoothed solar radio noise

Salyut complex may in part be due to the uncertainties in the area-to-mass ratio or the different inclinations of LDEF and Salyut 7.

5. CONCLUSIONS

The Salyut 7/Cosmos 1686 reentry event provided an opportunity to (i) exercise the computer models describing atmospheric decay and general perturbations, (ii) analyze exospheric temperature saturation as a function of incident solar 10.7 cm flux, and (iii) cooperate with the international community, through the provision of data sets and analysis, concerned with debris and associated hazards presented by debris. Algorithms used to describe the orbital evolution and ballistic coefficient of resident space objects compares favorably with more intricate propagators. Estimation of exospheric temperature and correlation with previous work indicates a necessary revision to the Jacchia treatment of temperatures for large solar flux values. Such analyses will lead, with more data, to a better understanding of the interaction between space objects and the atmosphere, and hazard mitigation for large space structures.

6. ACKNOWLEDGEMENT

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