ORBIT ANALYSIS AND LIFETIME PREDICTION USING RADAR DATA BY REENTRY OF SALYUT-7/KOSMOS-1686

W. Liewehr, H.G. Peters, D. Mehrholz

Research Establishment for Applied Science (FGAN)
Research Institute for High Frequency Physics (FHP)

ABSTRACT

Radar observations of the decayed USSR space station SALYUT-7/KOSMOS-1686 have been frequently performed by FGAN-FHP since 1990. The main objective was to support and advise the German government in all matters concerned with the reentry.
The paper discusses methods for orbit analysis, long and short term lifetime prediction, and spacecraft mass assessment. Typical results like orbital history to identify manoeuvres and changes in attitude are presented. The influence of solar activity on low earth orbits is shown. The robustness and reliability of the analysis methods is demonstrated using radar data from SALYUT-7/KOSMOS-1686 reentry observations.

Keywords: Reentry prediction, orbit analysis, manoeuvre analysis, solar activity, spacecraft parameters, risk assessment, radar observation.

1. INTRODUCTION

The decayed soviet space station SALYUT-7/KOSMOS-1686 was observed frequently by FGAN-FHP's experimental radar system since beginning of 1990. The influence of solar activity, size, shape, attitude, mass, drag coefficient and ballistic coefficient on the orbit was analysed. Long term and short term lifetime predictions were performed. The German government was advised on all matters concerned with the reentry of the space station. For the first time not only analysis results (like during the decay of KOSMOS-1900 in 1988) but also actual radar data were transmitted to ESA-ESOC via DATEX-P (PTT).

2. ORBIT ANALYSIS

2.1 Orbit and Manoeuvres

SALYUT-7 was launched in 1982. Many orbital manoeuvres were performed till its reentry at 7th February 1991 and several spacecraft visited the station. The module KOSMOS-1686 docked in October 1985 and stayed attached to the space station until decay. The last visit of cosmonauts was in May/June 1986, when a crew flew from the more modern space station MIR to SALYUT-7 and back. The altitude of the orbital complex SALYUT-7/KOSMOS-1686 was raised in August 1986 in order to increase the orbital lifetime by many years. Fig. 2.1 shows the history of the semi major axis and the altitude with respect to 6371 km mean earth radius. The time frame covers 19th April 1982 (launch) till 7th February 1991 (decay).

The dashed line in Fig. 2.1 shows the daily measurements of the 10.7 cm solar radiation. The solar activity influences the density of the upper atmosphere and hence the orbit of satellites. The long term variation of the solar activity, the 11-year cycle with maxima in 1980/1981 and in 1990/91, can be recognized. The overall increase in solar activity since 1988 led to an increasing loss of SALYUT-7/KOSMOS-1686's altitude since then. The short term fluctuation with individual maxima exhibits the 27-day rotation period of the sun. A few maxima with extraordinary high solar activity are visible, the strongest one occurred at the end of January 1991 and influenced the orbit of SALYUT-7/KOSMOS-1686 for two weeks.

2.2 Long Term Solar Activity

Fig. 2.2 presents the solar activity since 1977. The diagram covers the current and the last maximum of the 11-year cycle. The current maximum has an average activity slightly larger than the average during the maximum 1980/81. This plot shows two extraordinary high activities: one in 1979 lasting a few days, the other one in January 1991.

Long term influence of solar activity on satellites can be studied by analysing the development of the altitude of the USA satellite RADCAT, launched in 1972 (Obj. Nr. 6212). Since this is a passive radar calibration satellite it can not perform any manoeuvre. The development of the semi major axis since 1977 (Fig. 2.2) demonstrates a stepwise decay: a fast descent during both maxima of the 11-year cycle of the solar activity, a slow descent during the minima of the 11-year cycle.

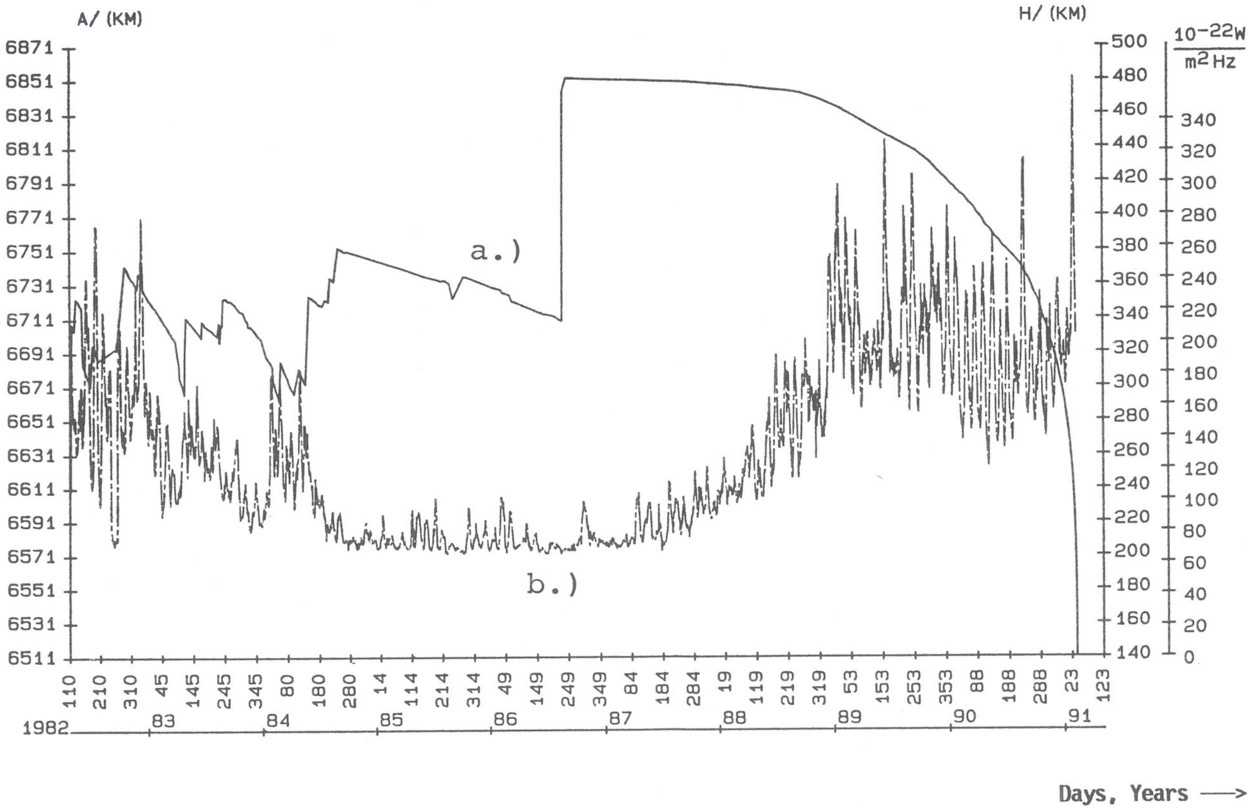

Fig. 2.1: a.) History of the semi major axis and altitude, SALYUT-7; b.) Solar activity (10.7 cm radiation); 19 April 1982 (launch) - 7 February 1991 (decay).

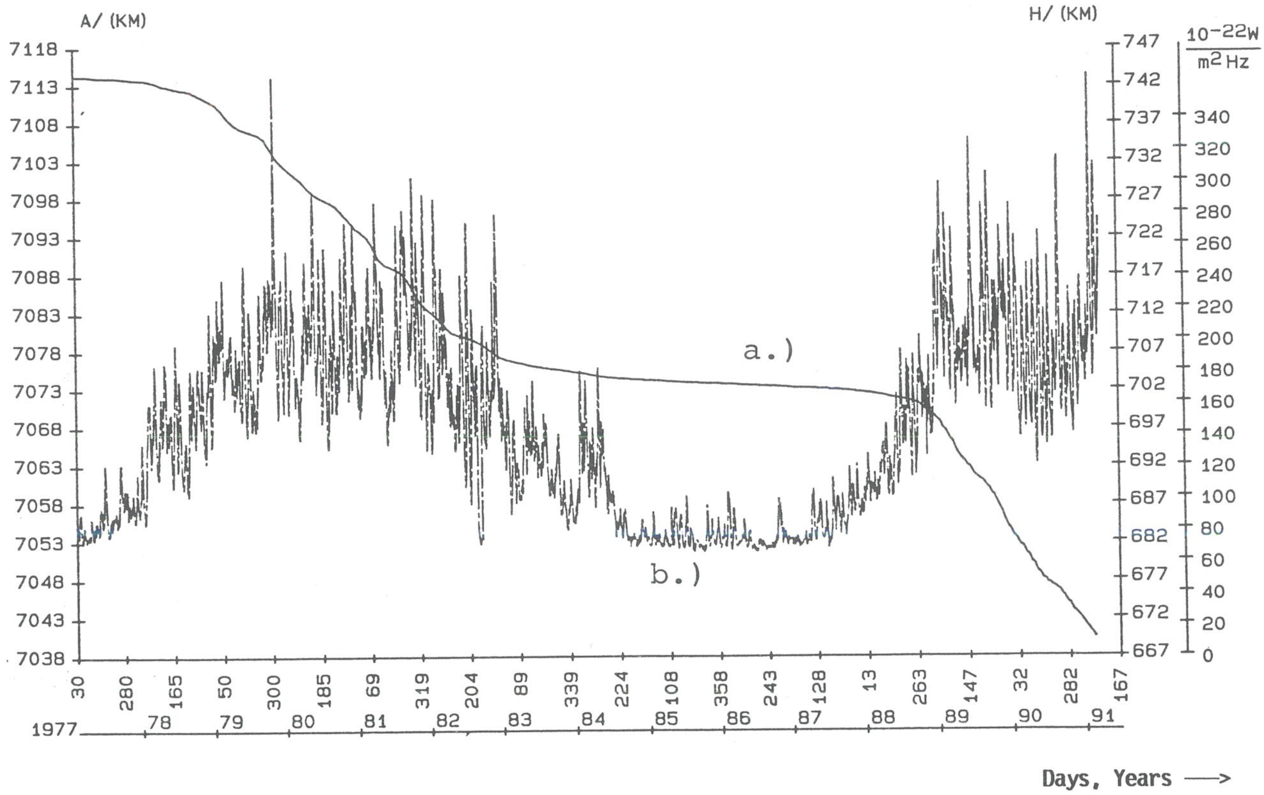

Fig. 2.2: a.) History of the semi major axis and altitude, RADCAT; b.) Solar activity (10.7 cm radiation).

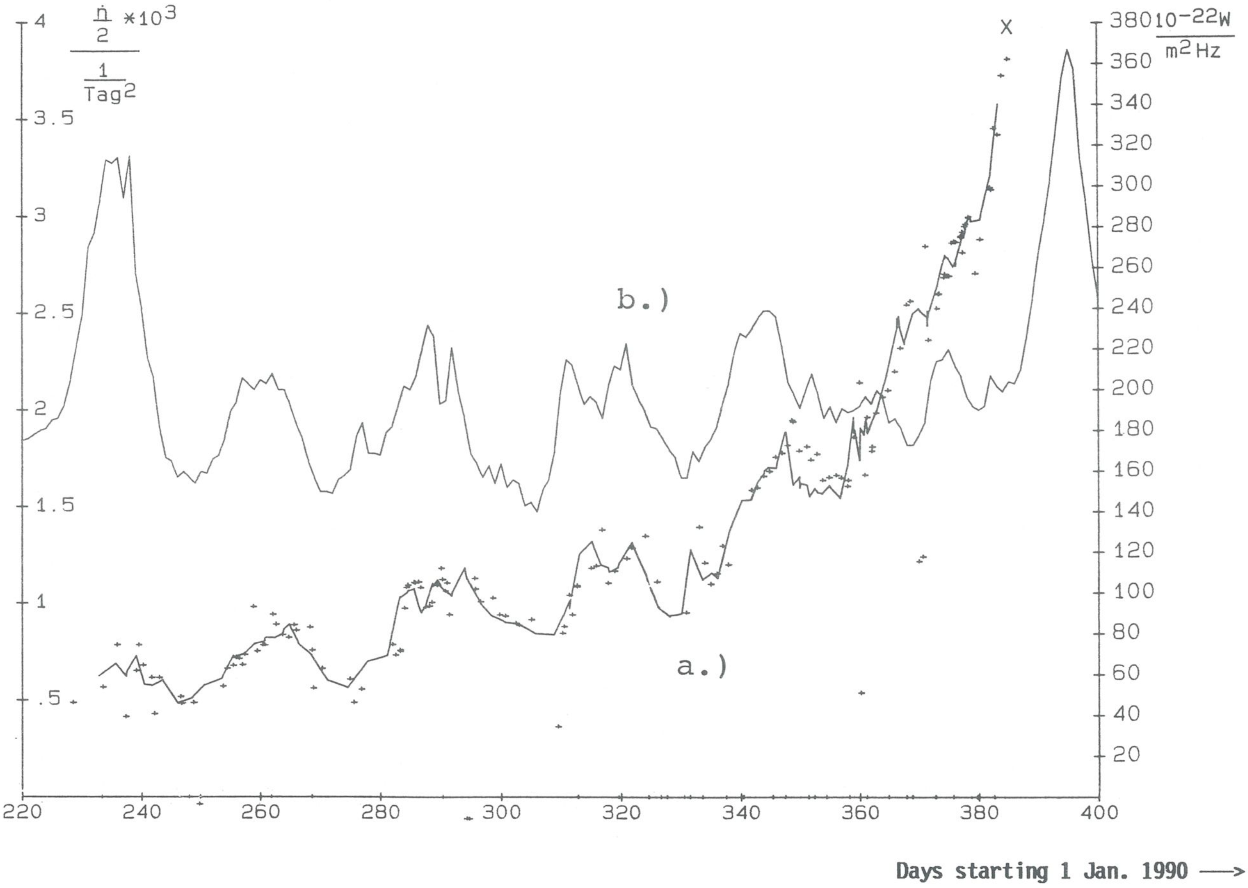

Fig. 2.3.1: a.) Determination of dn/dt; b.) Solar activity (10.7 cm radiation).

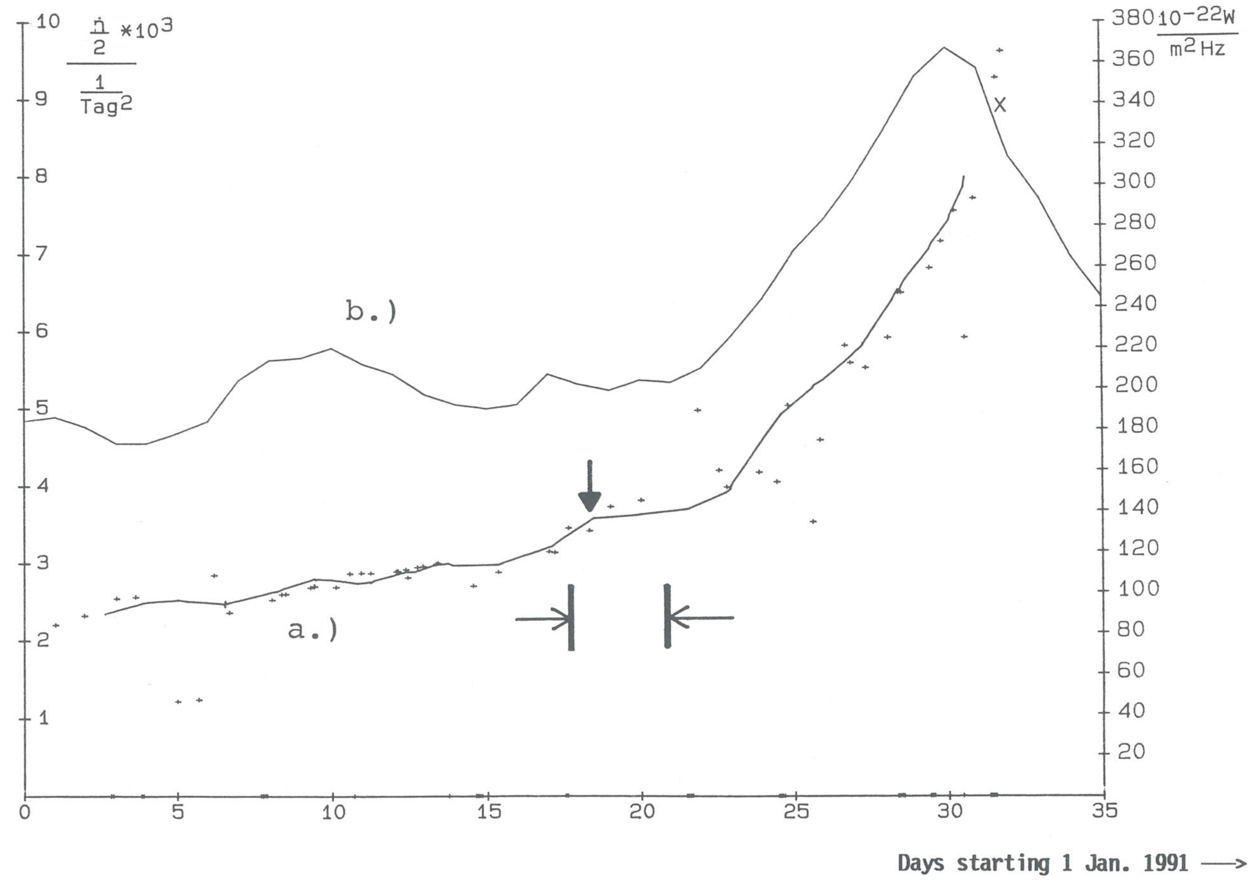

Fig. 2.3.2: a.) Determination of dn/dt in January 1991; b.) Solar activity (10.7 cm radiation).

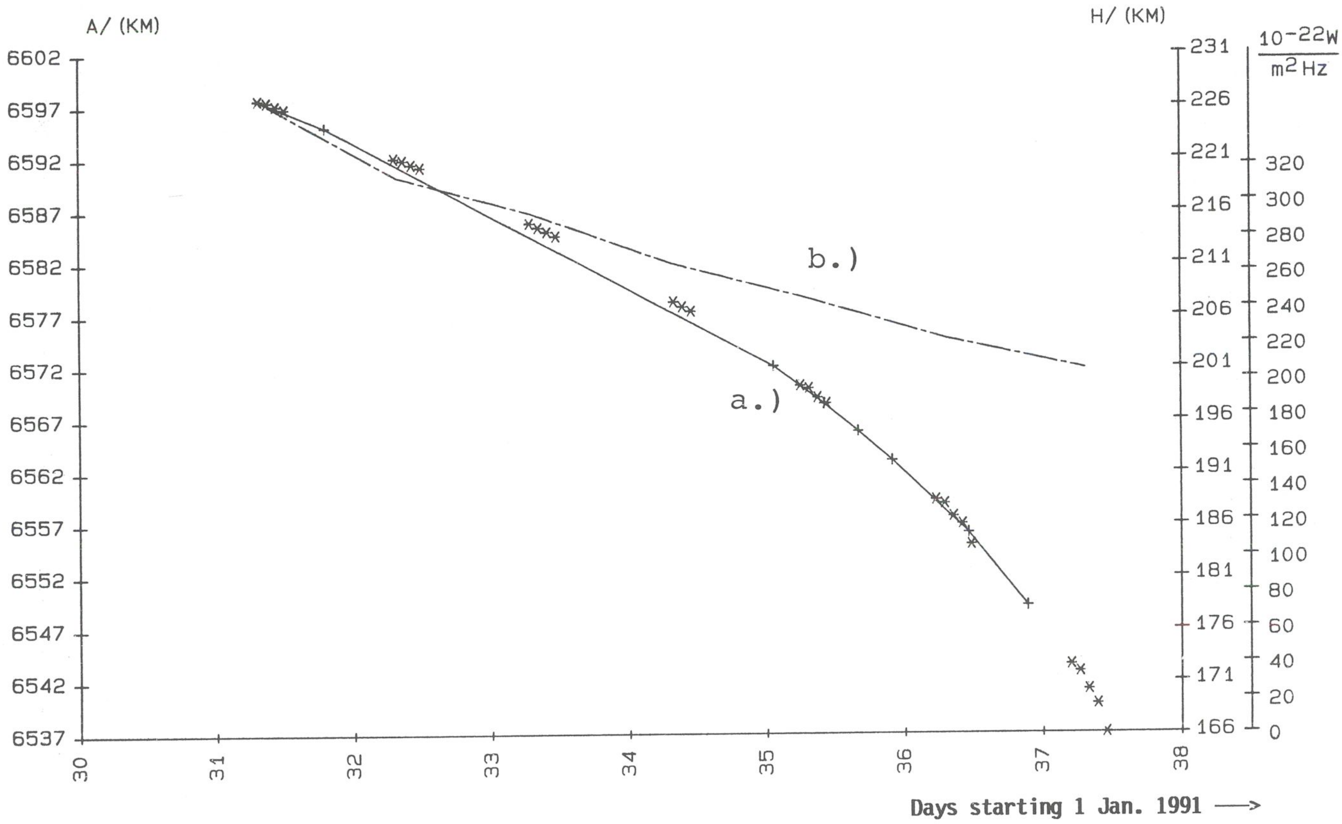

Fig. 2.3.3: a.) Altitude of SALYUT-7/KOSMOS-1686 during the week before decay;
b.) Solar activity (10.7 cm radiation).

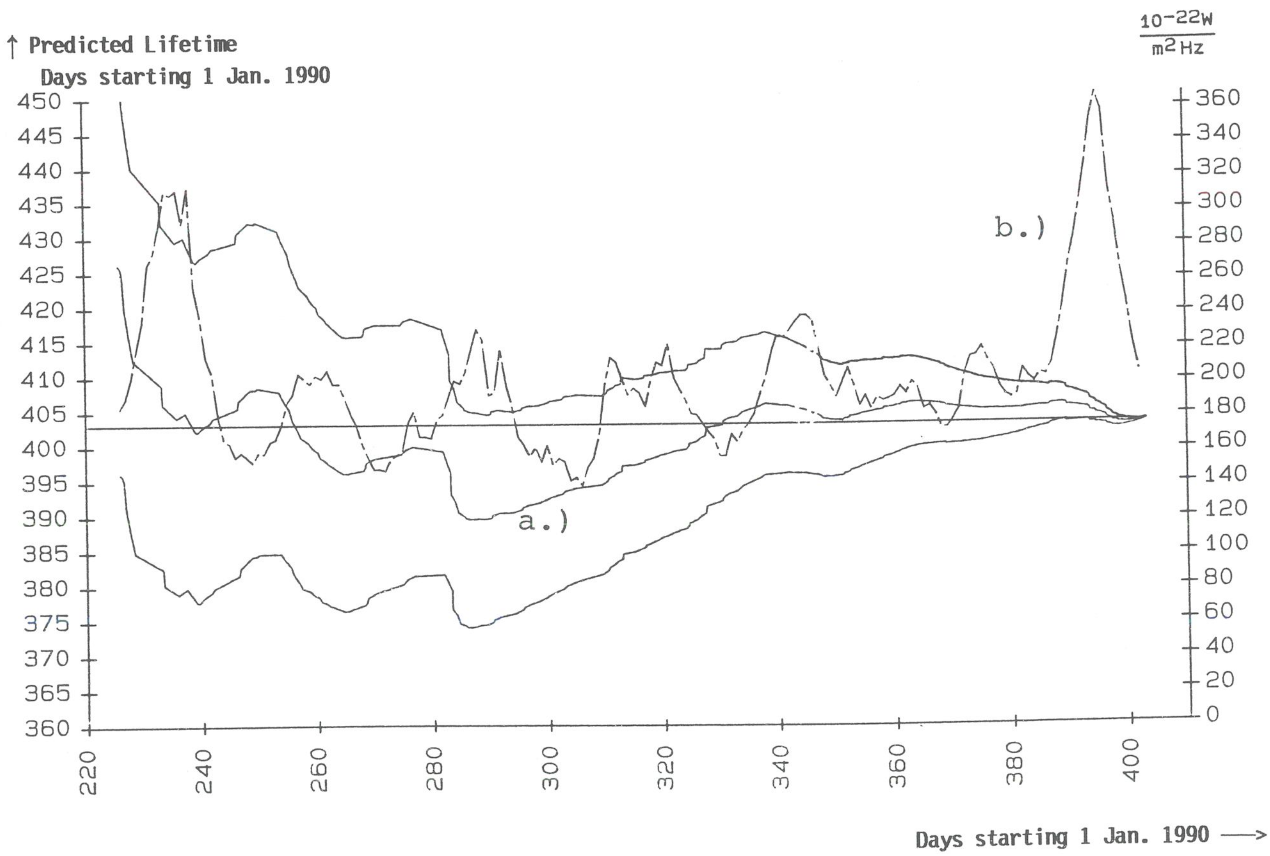

Fig. 3.1: a.) History of lifetime predictions, 6 month before decay;
b.) Solar activity (10.7 cm radiation).

If long term lifetime predictions are made during a minimum of the 11-year cycle of the solar activity, like the minimum in 1986, the next rise in the solar activity has to be taken into account. Otherwise the predictions will give lifetimes, which are far too long.

2.3 Development of Mean Motion

2.3.1 The derivative of mean motion. The derivative of the mean motion dn/dt depends upon solar activity and its influence on upper atmosphere density; it is crucial for determination of:

- orbital lifetime,
- ballistic coefficient,
- spacecraft mass.

Fig. 2.3.1 (solid line a.)) gives the result of the FGAN-FHP correction algorithm for dn/dt from two-line elements (TLE) computed from FGAN-FHP radar data and from TLE received from NASA. The original NASA data for dn/dt, taken from the TLE, are marked with a "+". Quite often there are differences between NASA data and corrected dn/dt.
Line b.) exhibits the solar activity. There is a good correlation between the solar activity plot and dn/dt plot. The influence of the 27-day sun rotation period can easily be recognized in the variation of dn/dt.
Working with TLE from NASA, FGAN-FHP always uses corrected dn/dt data in order to predict observability, lifetime, ballistic coefficient, and to control the radar system.

Fig. 2.3.2 shows dn/dt on an enlarged time scale for the time period of January 1991. The "+" indicate as before the original NASA data for dn/dt. Line b.) exhibits the solar activity with the already mentioned extraordinary high peak. All variations in dn/dt, except the slower increase of dn/dt between 17th and 21st of January (marked with an arrow), can be explained by variations of the solar activity. Between 17th and 21st of January 91 no measurements were performed. It is assumed that the development of dn/dt in this time frame stems from a change in the ballistic coefficient: the orbital complex SALYUT-7/KOSMOS-1686 had ceased its gravity gradient stabilised attitude and started a complex slow rotation. This analysis result was confirmed by comparison of the radar images (Ref. 1), which were computed from high resolution radar data from 17th and 21st January 1991. Until 17th of January the space station was gravity gradient stabilised with KOSMOS-1686 pointing to the earth. Since 21th January 1991 the images show the space station in many different orientations.

Due to the complex slow rotation the drag coefficient c_d and the average reference area changed, resulting in a change of the ballistic coefficient. This caused a slower increase of dn/dt, which is equivalent to an increase in lifetime.

2.3.2 Altitude during the last week before decay. After each radar observation a TLE is computed from tracking radar data. Altitudes were derived from the mean motion contained in the TLE of FGAN (*) and of NASA (+). In Fig. 2.3.3 the altitude of the space station during the last week of its flight up to the last passage observable from the FGAN-FHP radar (10:58 UTC - 11:01 UTC on 6th of February, 1991) is plotted. The altitudes derived from NASA data and from FGAN-FHP radar data fit very well. Due to the observation scenario (Ref. 1) only 5 or 6 consecutive passages were detectable by FGAN every day, followed by an observation gap of about 16 hours. This situation is typical for satellite observation from only one single station. The dashed line exhibits the decreasing solar activity after the extraordinary high activity at the end of January 1991.

3. LIFETIME PREDICTION

3.1 Basics

The lifetime prediction is based on an improved and computerised King-Hele method (Refs. 2-3). The most important input variable is dn/dt. The corrected data for dn/dt were always used. The atmospheric model was CIRA-72 which needs 10.7 cm solar radiation as input parameter.

3.2 Lifetime Predictions for SALYUT-7/KOSMOS-1686

Fig. 3.1 gives the history of lifetime predictions (line a.)) and the solar activity (line b.)) during the last 6 months before decay. Lifetime predictions were based on single TLE sets. Line a.) stands for the weighted mean value of the single assessments. This result was used to advise the German government and to inform ESA-ESOC. The lines above and below line a.) are the ±15% uncertainties of the weighted mean value. With this uncertainty the actual reentry date was within the limits for the predicted decay during the last 6 months. For predicting the lifetime of this individual satellite, unusual high uncertainties arose from spin and precession of the complex shaped space station, from the subsequent variation in the drag coefficient and average reference area, and also from the large variations in solar activity resulting in strongly varying density of the upper atmosphere.

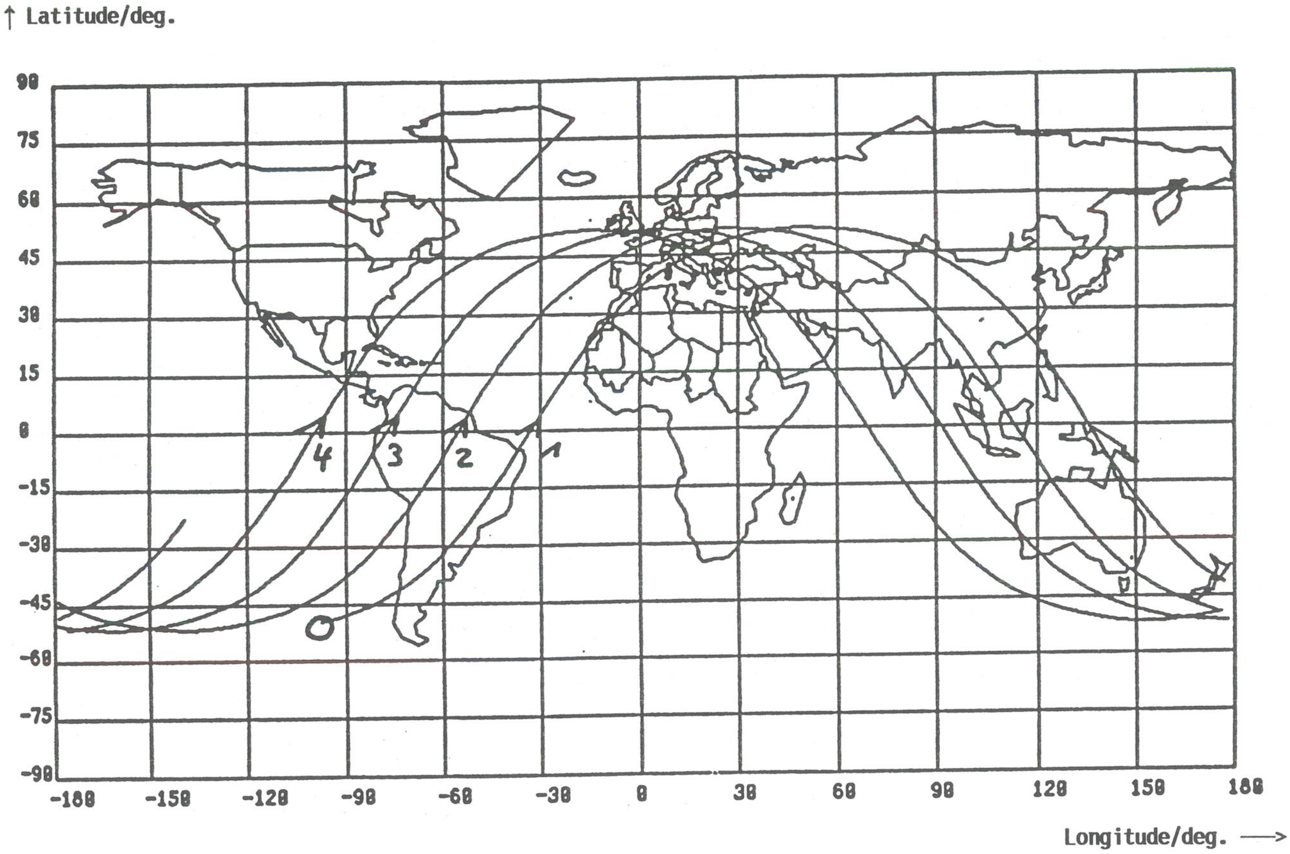

Fig. 3.2: Subsatellite tracks for the period of the last lifetime prediction (03:40 UTC +/- 6 h). Passages prior to the middle of lifetime prediction (circled) not included.

Fig. 4.1: Determination of the ballistic coefficient B (m^2/kg), value averaged over three 27-days solar rotation cycles.

Starting between 17th and 21st January 1991 two effects occurred and were superimposed. Lifetime predictions were shifted to an earlier date. Initially the observed slow rotation caused a change of the ballistic coefficient and of the average reference area resulting in a longer lifetime. The increase in solar activity at 22nd January 1991 however, overcompensated this effect so that the actual lifetime was shorter than that predicted before this event.

A deformation of the solar panel structure of SALYUT-7 was detected (Ref. 1) at the last observable passage (6th February 1991, 10:58 UTC). This caused surely a slight change of the drag coefficient and of the average reference area. Since this happened shortly (16 hours) before decay, there was no remarkable influence on the decay prediction.

3.3 Last Lifetime Prediction and Actual Decay

After the last observable passage at 10:58 UTC on 6th February 1991 there was an observation gap until 04:13 UTC on 7th February 1991. The last prediction one day before decay, passed to the German government and ESA-ESOC was:

decay on 7th of February, 03:40 UTC ±6 hours.

In the afternoon the uncertainty was reduced to ±4 hours. On the day before reentry, the risk of a decay over Germany could not be ruled out due to the uncertainty in the lifetime prediction and the observation gap of more than 16 hours.

The actual decay at 03:44 UTC on 7th February 1991 is marked by the straight line in Fig. 3.1. FGAN tried to observe the next passage (04:13 UTC) after more than 16 hours time gap, but the satellite was not detected. So FGAN informed the German government and ESA-ESOC: SALYUT-7/KOSMOS-1686 had decayed.

The subsatellite tracks for the period of the last lifetime prediction (03:40 UTC ±6 hours) are visible in Fig. 3.2. The circle west of Chile refers to the middle of the time-window of the lifetime prediction. The passages up to 6 hours prior to the middle of the predicted lifetime are not in this map, as there were no passages over Germany or other ESA member states. The actual decay was over Argentina. Half an hour later SALYUT-7/KOSMOS-1686 would have flown over Italy, 1 1/2 hours later over France and Germany.

At FGAN-FHP lifetime predictions can be actualised with every single new TLE. Programs solving the motion equations with numerical integration need always radar data from three or four passages to converge.

4. MASS DETERMINATION

For the risk analysis a mass assessment was performed, to be independent from published values. The mass can be calculated from the ballistic coefficient B. B itself can be determined from the orbital elements (dn/dt is the most important factor) and from the atmospheric density (CIRA-72 model, using the solar activity as input). During gravity gradient stabilisation, the ballistic coefficient was averaged for the period of three 27-days solar rotation cycles (Fig. 4.1). The drag coefficient c_d was calculated by HTG (Refs. 4-5). Spin and precession of the space station were taken into account; c_d=1.8 was averaged over one revolution of precession. Shape, dimensions, and attitude were learned from radar images. The average reference area was A=126 m^2 and the ballistic coefficient B=0.0057 kg/m^2. With $m=c_d \cdot A/B$ spacecraft mass m was assessed to be 40.000 kg ±15%.

5. CONCLUSION

Radar data gained from FGAN-FHP radar observations were a reliable source for determination of all relevant information concerned with the reentry of the soviet space station SALYUT-7/KOSMOS-1686. Risk assessments, lifetime and satellite subtrack predictions were performed. The actual decay was within the predicted lifetime window. This demonstrates the reliability of the applied methods.

6. REFERENCES

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