

REENTRY PREDICTIONS FOR COSMOS 398, FSW-1 5 AND TSS-1R

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ABSTRACT

This paper describes the work done and the results obtained during the reentry prediction campaigns for Cosmos 398, FSW-1 5 and TSS-1R, emphasizing analogies and differences between the three cases. The modelling assumptions are examined and the reentry predictions are compared to show the impact of different orbit propagators and atmospheric models on the final outcome. Ballistic parameter determinations are provided as well, together with an independent mass estimate for Cosmos 398 and FSW-1 5.

Quite surprisingly, the orbital decay of TSS-1R, gravity gradient stabilized by the long tether, was not too difficult to model. In practice, it was possible to show that standard trajectory propagators could be consistently used even in this case, provided that a new effective drag coefficient might be determined and adopted in the computations.

1. INTRODUCTION

After the uncontrolled reentry of the nuclear powered Cosmos 954, on 1978, an ad hoc reentry prediction team was established at CNUCE, an institute of the Italian National Research Council (CNR), to monitor the orbital decay of risky or interesting space objects and to provide timely information to the civil defense authorities. Since 1979, reentry prediction campaigns have been carried out for space stations (Skylab, Salyut 7), nuclear powered spacecraft (Cosmos 1402 and 1900) and other civilian and military payloads.

Between the end of 1995 and the beginning of 1996, the attention was focused on three very interesting uncontrolled satellites: an old Soviet experimental lunar lander (Cosmos 398), a Chinese recoverable capsule (FSW-1 5) and an Italian small space physics spacecraft with a 20 km long tether (TSS-1R). All these space objects - for mass, composition and design - did not present a significant reentry risk, but they were considered very useful to test reentry prediction software and procedures. Moreover, TSS-1R was a quite unusual system, able to reveal, if any,

the limits of standard orbit propagation models and computer codes used to depict the motion of point-like spacecraft. On the other hand, both Cosmos 398 and FSW-1 5 offered the chance to probe our ability to recover information regarding their relevant characteristics, such as mass, size, shape, etc.

The experience of nearly two decades of reentry predictions at CNUCE shows that the very basic parameters of some decaying satellites are often missing, due to the military or classified nature of their primary mission. In these cases it is very important to estimate them, putting together dynamic observables and other pieces of information, in order to assess the potential risk of the event. TSS-1R, whose overall characteristics were well known, added a new dimension to the problem, because it was a truly extended space structure, possibly representative of a growing number of objects to be seen in low earth orbit in the coming years.

2. COSMOS 398

During the sixties, the Soviet Union undertook two projects for the human exploration of the moon: UR-500K/L-1, for the lunar circumnavigation by a crew of two cosmonauts, and N-1/L-3, for the lunar landing of a single cosmonaut (Ref. 1). Neither was completed, but some important accomplishment was earned, like the unmanned lunar circumnavigations and controlled recoveries of the Zond craft. Moreover, several critical components of the moon vehicles were tested in earth orbit; an experimental lunar lander (T2K) was flown three times (Cosmos 379, 398 and 434), between November 1970 and August 1971, following similar mission profiles (Refs. 1 and 2).

Cosmos 398 was launched into a 191 x 258 km orbit, with an inclination of 51.6 deg, on 26 February 1971 (Ref. 2, pag. 39). Two days later the spacecraft performed a first maneuver of 252 m/s (simulating the phase immediately preceding the lunar landing) and, after the separation of the landing platform, a second burn of 1320 m/s (simulating the lift-off from the moon surface). The last impulse left the spacecraft into a 200 x 10905 km orbit, that started a slow decay of 15 years (Cosmos 434 reentered on 12 August 1981 and Cosmos 379 on 21 September

1983, both without rising any world-wide concern). The reentry predictions for Cosmos 398 began at CNUCE at the end of November 1995, following an international alert from the U.S. Space Command, ESA and *Aviation Week & Space Technology* (Ref. 3).

To estimate the potential risk of the event, the mass of the object needed to be evaluated. Assuming a launch mass of 5000-5500 kg (Ref. 1), a mass of 500 kg for the discarded four-leg landing platform and 310 s for the specific impulse of the bi-propellant Block E propulsion module, a final dry mass of 2650-2950 kg was obtained for Cosmos 398, including the roughly spherical pressurized cabin and the propulsion system. This was just the 40% of the figure appeared in some reports and, taking into account the fragile nature of the vehicle, we determined that the corresponding reentry risk was no higher than that coming from the uncontrolled orbital decay of an upper stage of similar mass (an event quite frequent, as a matter of fact!). However, we decided to follow the final days of Cosmos 398 as a drill to test software and operational procedures.

As a source of orbital data we used the Two-Line Element (TLE) sets maintained at the NASA Goddard Space Flight Center by the Orbital Information Group. The updated element sets were converted into osculating cartesian elements and used as initial conditions for orbit and reentry predictions. Two computer codes were applied to Cosmos 398: the SATellite Reentry Analysis Program (SATRAP), specifically developed at CNUCE for the study of decaying space objects (Ref. 4), and the EPHEM program (Ref. 5) of the Goddard Trajectory Determination System (GTDS).

Both of them used the Cowell method for the integration of the equations of motion and included the main orbital perturbations: geopotential harmonics, air drag, luni-solar attraction and direct solar radiation pressure (with eclipses). Several atmospheric models could be selected, to describe the air density variation as a function of the solar flux at 2800 MHz and geomagnetic activity: in this case, the Jacchia-Roberts model was selected in SATRAP, while Harris-Priester was adopted in GTDS (Ref. 5).

To improve the precision of the prediction process, the ballistic parameter B of the satellite needed to be independently determined and updated. Defined by the relation

$$B = \frac{C_D A}{2M},$$

where C_D is the drag coefficient, A the effective cross-section and M the mass, the ballistic parameter incorporates the uncertainties on the physical characteristics of the satellite, the attitude and, for

a given atmospheric model, the air density. Therefore, for each object and prediction model, B must be experimentally adjusted, to reduce the impact of the above mentioned uncertainties.

Updated ballistic parameters were determined daily, taking the values able to reproduce the observed semimajor axis decay or nodal transit times over a time span of one or more days. Generally, the most recent estimate so obtained was then used, together with the last orbit available, to produce a new reentry prediction.

The days (and months) immediately preceding the Cosmos 398 reentry were very quiet in terms of solar and geomagnetic activity (the solar flux at 2800 MHz remained just above 70 standard units). However, a sudden and sharp decay rate increase was observed in the TLE data on December 9, but no simple explanation was found for it. Cosmos 398, at last, reentered on the Southern Atlantic Ocean at 20:40 UTC of 10 December 1996, observed by an American DSP early warning spacecraft.

The a posteriori reentry prediction errors as a function of the propagation run time are shown in Fig. 1, both for SATRAP and GTDS. The average reentry prediction error was 9.4% for SATRAP and 7.0% for GTDS. However, an abrupt degradation of the predictions quality was observed the very last day (16.4% error for SATRAP and 12.1% for GTDS); during the preceding week the results were quite better, with an average error of 4.4% for SATRAP and 3.5% for GTDS.

The mean ballistic coefficients obtained where:

$$\begin{aligned} \text{SATRAP} &< B > = 0.00294 \pm 0.00026 \text{ m}^2/\text{kg}; \\ \text{GTDS} &< B > = 0.00261 \pm 0.00019 \text{ m}^2/\text{kg}. \end{aligned}$$

The total surface area of Cosmos 398 was computed to be 33 m^2 (from the figures at pages 20 and 21 of

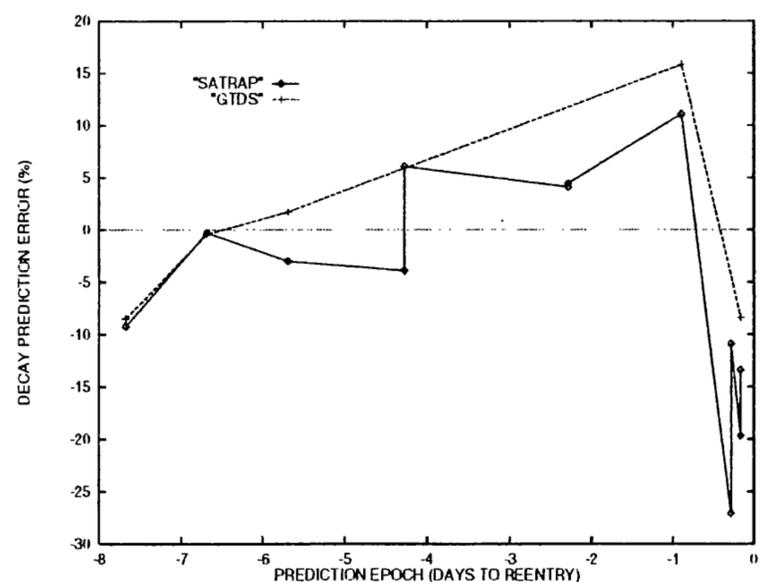


Figure 1. Cosmos 398: reentry prediction errors as a function of the propagation run time.

Ref. 1), corresponding to an average cross-section of 8.25 m^2 for a random tumbling object. Assuming $C_D = 2$, the following independent mass estimates were obtained:

$$\text{SATRAP} \quad M = 2578 \div 3078 \text{ kg} ;$$

$$\text{GTDS} \quad M = 2946 \div 3409 \text{ kg} .$$

They resulted in good agreement with the computations presented at the beginning of the section and with the information later provided by Russian sources (Ref. 6).

3. FSW-1 5

The satellite FSW-1 5, part of the Chinese recoverable satellite program (Ref. 7), was launched on 8 October 1993 into a low earth orbit, with an inclination of 57 deg, by a Long March 2C booster from the Jiuquan Center in the Gobi desert (Ref. 8). The spacecraft, with a mass of 2100 kg, was dedicated to photoreconnaissance and micro-gravity experiments (Refs. 7 and 9). On October 18, when Chinese ground controllers commanded the reentry sequence, the 1200 kg equipment module remained in low orbit, while the recoverable capsule was injected by its retro-rocket package into a 179 x 3031 km ellipse, with an inclination of 56.5 deg.

The equipment module reentered over the Pacific Ocean (near Peru) on 28 October 1993, but a first lifetime estimation made at CNUCE, using the predicted solar flux, indicated that the capsule, propelled in the wrong direction, would stay aloft for about 2.4 years. So we started a long monitoring of the orbital decay, issuing any few months new reentry predictions. The object was not considered particularly dangerous (computing a solid rocket motor burn of 650 m/s, the estimated dry mass of the capsule was in the 600-750 kg range), but it was designed for recovery and the possibility of an impact with the ground as a single piece at 50 m/s could not be absolutely ruled out (Ref. 10). During 1994 and 1995 the predicted reentry date remained quite stable, between the end of 1995 and the beginning of 1996; on 1 November 1995 an intensive campaign of reentry predictions was at last under way.

Several computer codes (including all the relevant perturbations) and atmospheric models were used since the FSW-1 5 anomaly occurred: FOP (with a modified Jacchia-Roberts air density model), GTDS (Harris-Priester), SATRAP (Jacchia-Roberts), LOP (exponential model adjusted at the perigee to agree with Harris-Priester for 65 standard units of solar flux) and ASAP (U.S. 1976 Standard Atmosphere

adjusted with a 0.7 weight factor to account for low solar activity). The first three were used during the 1993-1995 period, while the last three were utilized during the five months preceding the actual reentry. FOP (Ref. 11) and LOP (Ref. 12) employed the variation of parameters method in the formulation of the equations of motion and averaging techniques to propagate the trajectories. GTDS, SATRAP and ASAP (Ref. 13) used instead the Cowell's method to numerically integrate the equations of motion.

The a posteriori reentry prediction errors as a function of the propagation run time are shown in Fig. 2. The average reentry prediction errors were 7.2%, 11.5% and 3.7%, respectively, for SATRAP, LOP and ASAP. The Chinese capsule decayed from orbit over the Southern Atlantic Ocean at 4:05 UTC of 12 March 1996 and, according to U.S. Space Command sources, some fragments survived the conditions of reentry. During the last months of lifetime the solar flux at 2800 MHz remained stable around 70-75 standard units and also the geomagnetic activity was generally low.

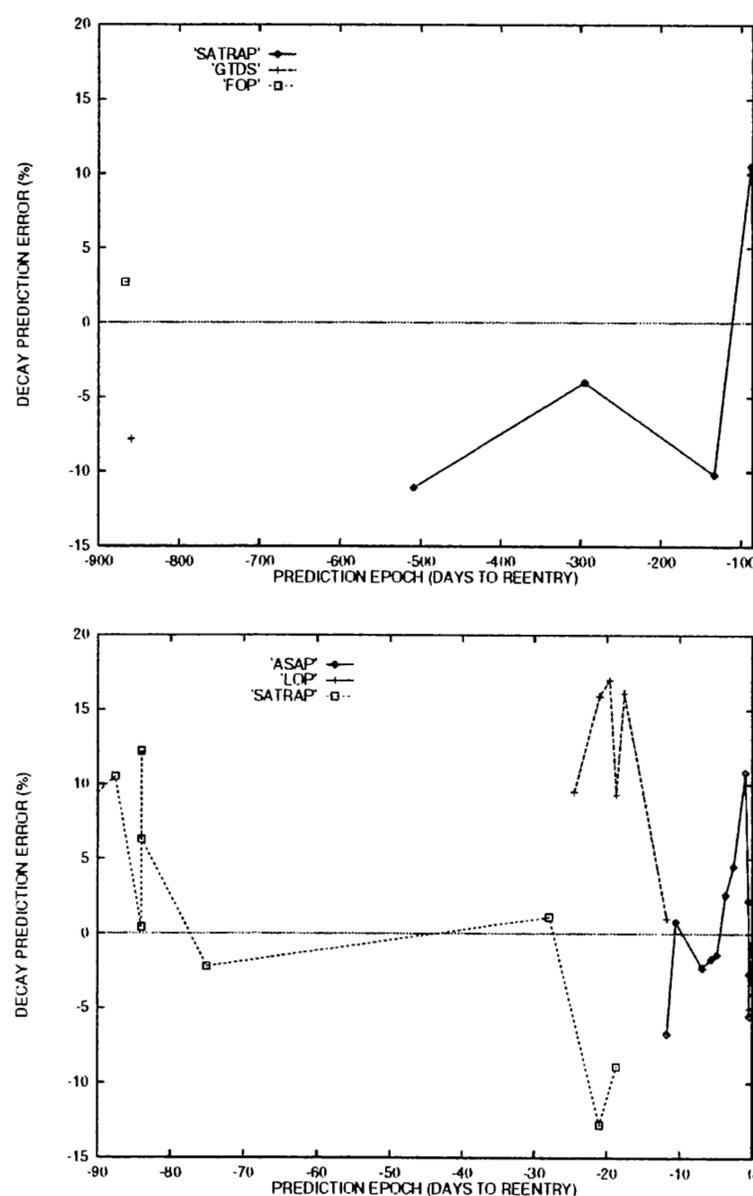


Figure 2. FSW-1 5: reentry prediction errors as a function of the propagation run time.

As for Cosmos 398, independent estimations of the ballistic parameter were performed on a routine basis. The size and shape of the blunt-nose conical capsule were accurately determined by the FGAN/FHP German radar (Ref. 14). From these observations we obtained a total surface area of 8.7 m^2 , corresponding to an average cross-section of 2.17 m^2 for a random tumbling object. Assuming $C_D = 2$ and the values of B recovered with SATRAP, adopting the most accurate atmospheric model, the following independent mass estimate was obtained:

$$M = 650 \pm 50 \text{ kg}.$$

Again, a good agreement with our preliminary estimate and the information later provided by Chinese sources was obtained.

4. TSS-1R

At 2:30 UTC of 26 February 1996 the tether connecting the Italian scientific satellite TSS-1R to the space shuttle Columbia (STS-75) suddenly broke free. As effect of the center of mass shift and tension in the cable, the 518 kg spherical satellite and 19.65 km of tether were injected into a higher orbit of 320 x 425 km, accidentally validating the principle of tether maneuver. The orbital inclination remained the same of Columbia (28.5 deg), but the observed semimajor axis increase corresponded to an equivalent maneuver of about 30 m/s.

CNUCE was activated that same day to estimate the orbital lifetime of the Italian spacecraft. The reentry risk was considered negligible, but the system was very unusual and interesting, and deserved a detailed analysis. After the separation from Columbia, TSS-1R, as confirmed by several optical observations, maintained a gravity gradient stabilization, with the satellite at the top and the attached cable stretching down towards the earth. The cross-section of the satellite was about 2 m^2 ; the tether, with a diameter of 2.5 mm and a linear mass of 8.2 kg/km, had a section of 49.1 m^2 and a mass of 161 kg. Therefore, the total cross-section was 51.1 m^2 , and the overall mass was 679 kg. The center of mass of the system was placed about 2.3 km below the spacecraft, along the tether.

The software available for lifetime estimations and reentry predictions was conceived for point-mass spacecraft, with linear dimensions negligible with respect to the size of the orbit; but in this case such assumptions were no more valid. Due to the lack of time, the challenge was met devising a method to derive an equivalent point-like object able to repro-

duce, when propagated with standard software, the same orbital behavior observed for the center of mass of the actual tethered system.

The principles underlying this approximation are easy to understand. For a given exospheric temperature, over an altitude range of a few tens of km, the air density profile can be quite accurately described by an exponential law with a fixed scale height. Assuming as reference altitude that of the spherical satellite (not too far from the center of mass of the system) and the tether aligned along the local vertical, the total acceleration a_D produced by the air drag on TSS-1R could be expressed, after integration, as

$$a_D = -\frac{C_D}{2M} \left[A_s + A_t \frac{H}{L} \left(e^{L/H} - 1 \right) \right] \rho V^2,$$

where M is the total mass, A_s and A_t the cross-sections of the satellite and the tether, respectively, H and ρ the atmospheric scale height and density at the altitude of the satellite, L the tether length and V the relative velocity of the system with respect to the atmosphere. It can be noticed that the relation obtained is formally equivalent to that adopted for point-like spacecraft, provided that the tether cross-section be scaled by a corrective factor

$$c_f = \frac{H}{L} \left(e^{L/H} - 1 \right).$$

During periods of low solar activity (the flux at 2800 MHz was about 70 standard units) the density scale height of the atmosphere at the altitudes of interest is between 20 and 50 km; the corresponding corrective factors for the 20 km tether were 1.72 for $H = 20$ km, 1.42 for $H = 30$ km and 1.23 for $H = 50$ km. Because H decreases at lower altitude, an increase of the TSS-1R total effective area by 15-40% should be expected as the orbital decay progressed towards the reentry.

On the other hand, the system presented another peculiarity. Most satellites are exposed to free-molecular flow conditions, because the mean molecular free path, of the order of hundreds of meters above 200 km, is quite larger than the typical spacecraft sizes. The non-dimensional ratio between the two lengths is known as Knudsen number and its value is generally larger than 5-10. It has been shown that in free-molecular and hypersonic (the satellite speed exceeds by a large amount the mean molecular speed) regime the drag coefficient assumes values in between 2.0 and 2.5 for a wide spectrum of shapes and surface compositions (Ref. 15). But for TSS-1R these assumptions were no more valid. The very long tether implied a Knudsen number much smaller than 0.1, meaning the prevalence of *slip-flow* or hypersonic continuum flow regimes (Ref. 15).

Therefore the drag coefficient should be closer to 1 and quite stable as function of the altitude. In conclusion, TSS-1R should display an effective ballistic coefficient equal to 60-80% of that of a sphere with the same mass and cross-section.

Following this rough picture of the drag acting on TSS-1R - disregarding structural dynamics phenomena, torques and other complications of the real system - it was clear that standard orbit prediction software for point-mass spacecraft could in effect be used also in this case, and we made it. For logistical (and not technical) reasons we were restricted to use, during the reentry campaign, mainly ASAP (including a U.S. 1976 Standard Atmosphere adjusted with a 0.7 weight factor to account for low solar activity) and, just for a couple of times, LOP (with an exponential model adjusted at the perigee to agree with Harris-Priester for 65 standard units of solar flux).

The a posteriori reentry prediction errors as a function of the propagation run time are shown in Fig. 3. The average reentry prediction error obtained with ASAP was 19.6%; with LOP it was lower (10%), but the data are not statistically significant. Following American calculations (no direct observation was available), used to compute the just mentioned errors, TSS-1R reentered into the atmosphere on 19 March 1996 at about 23:12 UTC, over an area which included Northeast Africa and Southwest Asia. The CNUCE reentry estimate at 70 km of altitude was 22:53 UTC, over an area including the middle Atlantic Ocean and North Africa. The satellite probably burned up completely before hitting the ground, even though the peculiar deceleration profile, with a peak at very high altitude (about 70 km), due to the air-braking effect of the tether, might have produced milder reentry conditions and the survival of some

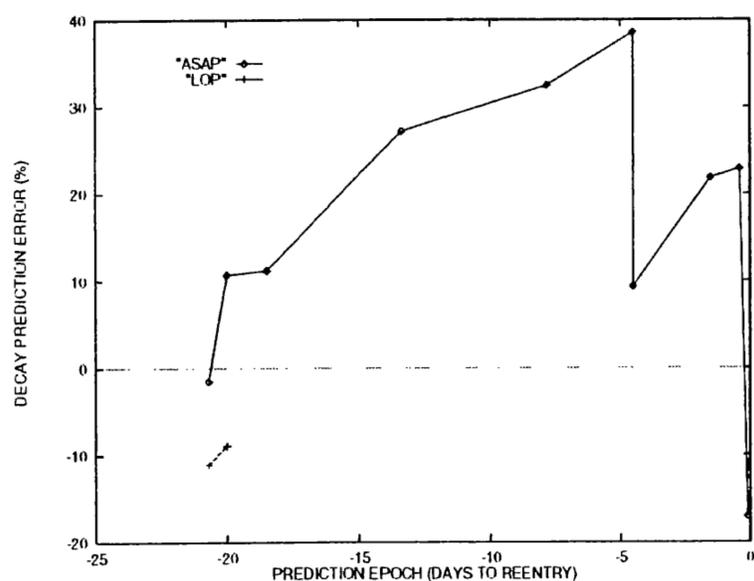


Figure 3. TSS-1R: reentry prediction errors as a function of the propagation run time.

parts. However, over the previous five months, space objects heavier than TSS-1R made an uncontrolled reentry every 5 days, on the average.

Adjusting the ballistic coefficient with ASAP to fit the TLEs, an average value of $0.070 \text{ m}^2/\text{kg}$ was obtained. This was the 84% of the corresponding value for a sphere with the same area to mass ratio and $C_D = 2.2$. Excluding the ballistic coefficients obtained the last day, the 70% of the value for the sphere was obtained. The last day of orbital lifetime this value increased to 120%. With LOP - but in this case only two determinations were made - the ballistic coefficient was found to be the 96% of the spherical reference.

Taking into account the strong limitations of the atmospheric models used, the uncertainties of the ballistic coefficient determination, the complications of the tether dynamics and the displacement of the center of mass of the system with respect to the satellite, the agreement between the theoretical computations presented in the first part of this section with the actual values of B obtained from the trajectory data is really surprising. Even though a further analysis with better atmospheric models will be needed to validate the simple physical picture discussed here, it seems to offer a useful tool for preliminary mission design and lifetime estimation of tethered satellites. Moreover, standard orbit prediction codes for point-mass satellites seems adequate to describe the motion of spacecraft with long tethers too, provided that the ballistic coefficient is appropriately rescaled.

5. CONCLUSIONS

Three very different reentries of uncontrolled space objects were studied and analyzed in detail. Several computer codes and atmospheric density models, running on different platforms (mainframe, workstations and personal computers) and under disparate operating systems (MVS, UNIX, MS-DOS), were used and compared. Reentry predictions, uncertainty windows and sub-satellite track maps were produced, issued to the national civil defense authorities and exchanged with other agencies.

The results obtained were satisfactory and new operational procedures, less demanding in terms of manpower, were demonstrated for the first time. Our goal is the transfer of a complete and reliable system for reentry predictions on a laptop personal computer, also able to connect with internet for data exchange, bulletins issuing, access to databases (orbits, space environment data), management of a multimedia web site, etc. The three reentries discussed in this paper offered the occasion to approach a little such

a goal.

Apart the operational aspects, much was learnt of the decaying properties of the three satellites. Each was peculiar for some reason, and therefore an interesting subject of study. Cosmos 398 and FSW-1 5 were particularly useful to test our ability to recover unknown information on the spacecraft from the orbital behavior and other scant and scattered sources. TSS-1R, on the other hand, offered the occasion to study a very special system, able to provide a wealth of new knowledge and experience on a kind of space object that could become very common in the future.

The reentry predictions errors were generally less than 10%, even if in the case of TSS-1R this figure was twice as much. This was probably due in part to the peculiar nature of the object, but we think that the atmospheric model used, probably affected by an error of the same magnitude, was particularly inadequate in this situation. Moreover, the ballistic coefficient was periodically determined from the *past* orbital evolution and then maintained *constant* in the reentry predictions, neglecting the increase to be expected, due to the reduction of the air density scale height, and overestimating the residual lifetime. This seems to be confirmed by the systematic trend to overshoot of the predictions (see Fig. 3) and by the steady growth of the ballistic coefficient as a function of time (up to 100%).

Another property of the reentry prediction results, also observed at CNUCE in previous cases, is the tendency to underestimate the residual lifetime during the last day. Again, this is probably due to the constant value of B used for decay predictions, while the actual drag coefficient decreases for the flow regimes transition. For objects of complex shape, like TSS-1R, the aerodynamic torques may play a role too, reducing the effective cross-section.

A final point to be discussed is the definition of reentry. In our computations, a space object is generally considered reentered when it reaches an altitude over the reference ellipsoid of 80–90 km. But some sensors of the U.S. Space Command, like the IR detectors of the DSP satellites, are able to follow the reentry trajectory at much lower altitudes. This could correspond to a time difference of about 5–10 minutes and to a down range distance of 2000 km. Therefore, the prediction errors obtained the very last day can be significantly affected by such a difference in the reentry time definition.

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