REENTRY PREDICTIONS OF THREE MASSIVE UNCONTROLLED SPACECRAFT

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Abstract: *During five months, from September 2011 to January 2012, three campaigns of reentry predictions were carried out for the Inter-Agency Space Debris Coordination Committee (IADC) and in support of the Italian civil protection authorities. The objects involved were three massive spacecraft, UARS (NASA), ROSAT (DLR) and Fobos-Grunt (Roscosmos), which received widespread attention for the marginal risk on the ground associated with their uncontrolled reentry, probably exceeding a human casualty expectancy of 1 in 10,000, i.e. the alert threshold adopted by several agencies in the United States, Europe and Japan. From the technical point of view, the three above mentioned reentry campaigns offered the occasion to model the orbital evolution, fit the semi-major axis, determine the ballistic coefficients and compare some semi-empirical thermospheric density models under varying solar and geomagnetic activity conditions, dealing with spacecraft characterized by quite different configurations, shapes, masses and attitude control. This paper describes the procedures applied to the reentry prediction problem and the results obtained in each campaign, showing the evolution of ballistic coefficients, relative and absolute residual lifetime errors, and reentry windows. For UARS, the average relative residual lifetime error over the campaign was 15%, with a maximum of 28%. For ROSAT the corresponding figures were 3% and 8%, respectively, while for Fobos-Grunt 4% and 8% were found.*

Keywords: *Uncontrolled Reentry, Reentry Predictions, Orbital Evolution, Ballistic Parameter, Reentry Windows.*

1. Introduction

Following the Sputnik 1 launch vehicle reentry on 1 December 1957, a total of 21,956 orbiting objects, ranging from 10 cm to more than 25 m in length, have reentered into the Earth's atmosphere by 1 August 2012. These objects included non-functional spacecraft, together with mission related hardware (3552), rocket bodies (3604), and pieces of cataloged orbital debris (14,800). Only a small percentage (~10%) of the acknowledged spacecraft reentries have been controlled in order to recover crew and material, as in the case of 134 US Space Shuttle landings, or to safely dispose the vehicle into uninhabited areas of the planet, as for unmanned resupply ships (134 Russian Progress, 2 European Automated Transfer Vehicles, 2 Japanese H-2 Transfer Vehicles), Russian space stations (Salyuts, Mir) and some large classified and scientific satellites. A good example of a satellite disposal was the successful de-orbiting into the South Pacific Ocean, on 4 June 2000, of the 15 metric tons Compton Gamma Ray Observatory (CGRO). Nevertheless, the majority of reentries have occurred in an uncontrolled way, with no attempt to handle their impact area on the ground. On the average, a cataloged object has reentered the atmosphere every day since the launch of the first satellite, 55 years ago (Fig. 1).

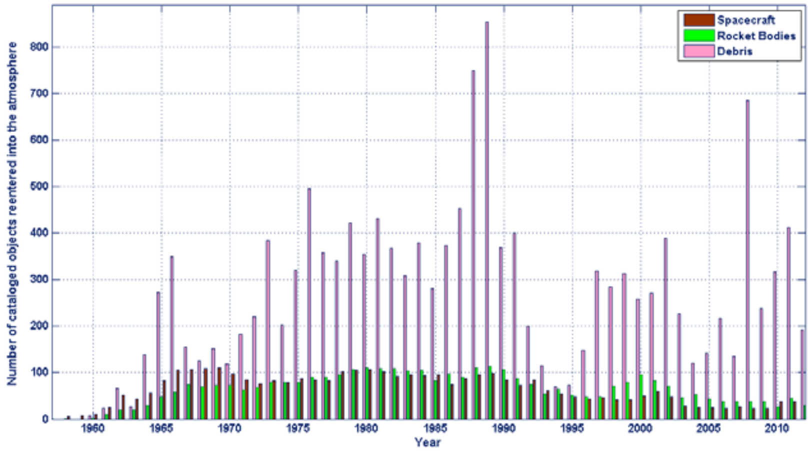

Figure 1. Number of cataloged objects, as of 1 August 2012, which reentered the Earth's atmosphere yearly [with reference to debris, rocket bodies and spacecraft, the average number of reentries per year was 264.30, 64.38 and 63.43, respectively. In all, an average of 392.11 reentries per year was observed, corresponding to 1.07 reentries per day]

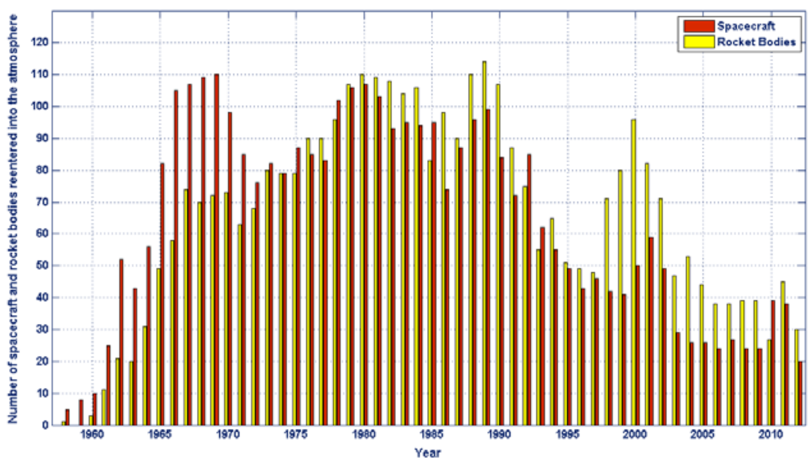

Figure 2. Number of cataloged spacecraft and rocket bodies, as of 1 August 2012, which reentered the Earth's atmosphere yearly

There have been approximately 100 to 200 reentries of spacecraft and rocket bodies each year (Fig. 2), corresponding to a mean rate of reentries on the order of 1-2 large objects per week. In terms of mass, the past reentries have accounted for 70-150 metric tons of man-made materials falling back to Earth each year. However, the majority of these objects did not represent a major hazard, because they largely disintegrated and burnt up in the upper atmosphere, due to aerodynamic heating and loading. Only the occasional reentries of large space structures (e.g. the 75-ton space station Skylab, reentered on 11 July 1979, and the 40-ton space station Salyut-7/Cosmos-1686, plunged into the atmosphere on 7 February 1991), of satellites with radioactive or other toxic materials on board (e.g. the reactor equipped spacecraft Cosmos 954, reentered on 24 January 1978, and the Cosmos 1402 nuclear reactor core, reentered on 7 February 1983), or of objects specifically designed to survive the reentry environment intact (e.g. the FSW 1-5 recoverable capsule, which reentered on 12 March 1996) were deemed instead significant threats.

From the analysis of past reentries, there was evidence that, while a large space object could break up, a not negligible amount of the resulting debris might survive the reentry environment. In general, from 10% to 40% of the mass of the object was likely to strike the surface of the Earth, with the proper percentage value depending upon the design and composition of the object itself. In particular, recovered debris from space hardware reentries proved that components thereof made of materials with high melting temperatures, such as stainless steel, titanium, beryllium, or glass, tend to survive reentry. However, although more than 1400 metric tons of materials are believed to have survived reentry, no case of personal injury caused by reentering debris has been confirmed [1]. Nonetheless, due to a more and more intensive use of the circumterrestrial space, and to a consequent rise in the amount of space hardware, the number of uncontrolled reentries will remain significant in the foreseeable future. Also due to the increase of the world population, the ground casualty risk, even if still small, will presumably show a tendency to grow in the coming years. For this reason, specific guidelines to minimize the risk to human life and property on the ground were defined. Reentries compliant with the NASA-STD 8719.14 [2] must have a human casualty expectancy (i.e. the chance that anybody anywhere in the world will be injured by a piece of debris) lower than 1:10,000. Such alert threshold is now adopted by several organizations in the United States, Europe and Japan.

In terms of mass and number, the uncontrolled reentries of spent upper stages present significantly higher risk on the ground with respect to spacecraft and, except for very specific cases, as the tragic loss of the Columbia space shuttle orbiter (2003), or the demise of Skylab (1979), the bulk of the reentry fragments recovered so far on the ground comes from rocket bodies. However, even though relatively less frequent, the uncontrolled reentries of sufficiently massive or peculiar spacecraft typically dominate the media attention. This was also the case for the satellites UARS, ROSAT and Fobos-Grunt, which reentered without control into the Earth’s atmosphere from September 2011 to January 2012. As a matter of fact, the spent second stage of the Zenit-2 launcher, used to put into orbit Fobos-Grunt, had a mass (close to nine metric tons) which was higher than those of UARS and ROSAT combined, but its uncontrolled reentry, on 22 November 2011, did not receive any media attention at all. The same applied to the Soyuz upper stage, used to put into orbit the manned capsule Soyuz-TMA 3M, which reentered over Western Europe, on Christmas Eve 2011, with a dry mass (more than two metric tons) on the order of that of Fobos-Grunt.

Nevertheless, even though neither UARS, ROSAT nor Fobos-Grunt could be classified as high risk objects, they received widespread attention for the marginal hazard on the ground associated with their uncontrolled reentry, exceeding a human casualty expectancy of 1 in 10,000.

2. Spacecraft Characteristics and Risk Assessment

2.1. UARS

The NASA’s Upper Atmosphere Research Satellite (UARS) was deployed into a 580 km circular orbit by the space shuttle Discovery, on 15 September 1991. It studied the Earth’s atmosphere for 14 years, measuring many key chemicals and gaining knowledge on the erosion of ozone over Antarctica. At the end of its mission, the residual propellant was used to lower the satellite orbit with a series of eight maneuvers, for the purpose of reducing its residual lifetime, according to space debris mitigation guidelines. UARS was decommissioned by NASA in December 2005, leaving the tanks completely empty in order to complete the satellite passivation. Since then, the orbit of UARS continued to decay, only subjected to natural perturbations, in particular to air drag (Fig. 3).

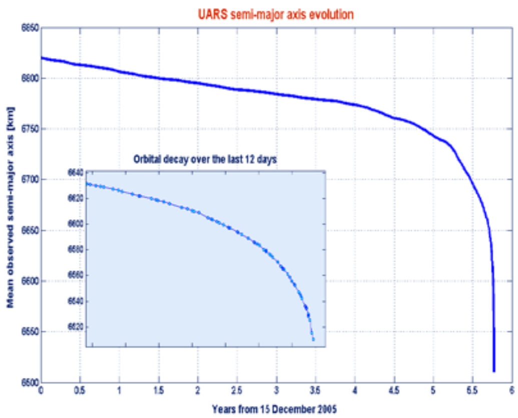

Figure 3. UARS semi-major axis evolution since 15 December 2005

Figure 4. UARS spacecraft configuration (credit: NASA/GSFC)

UARS had a dry mass of 5668 kg, a diameter of 4.6 m, a length of 9.7 m and a quite complex shape, with booms, appendages, protruding structures and a big solar array (Fig. 4). NASA had conducted a detailed reentry risk assessment in 2002, using the Object Reentry Survival Analysis Tool (ORSAT) to estimate spacecraft component demise altitude or location, surviving mass and fragment kinetic energy at ground impact [3]. Assuming a spacecraft breakup altitude of 78 km, a debris footprint length of 788 km had been found, with a total surviving mass of 532 kg concentrated in 26 objects. The heaviest surviving component, an aluminum box, had a mass of 158 kg and a kinetic energy at ground impact of 153 kJ. Impact fragment velocities had been found in the 14-108 m/s range, while a total casualty expectancy of 1:3560, later on updated to ~1:3200 for the population distribution in 2011, had been estimated, taking into account the orbit inclination of 57°.

2.2. ROSAT

The DLR’s ROentgen (X-ray) SATellite (ROSAT) was launched from Cape Canaveral with a Delta II rocket on 1 June 1990 and placed into a 575 km circular orbit to study astronomical sources in the extreme ultraviolet and X ray bands of the spectrum. After 8 years of data collection, much more than originally envisaged, the orbit of the abandoned satellite was left to progressively decay due to the action of air drag (Fig. 5). ROSAT had a dry mass of 2426 kg, dimensions of 2.2 × 4.7 × 8.9 m, a quite compact shape and solar array configuration and just one boom aligned with the longitudinal axis (Fig. 6).

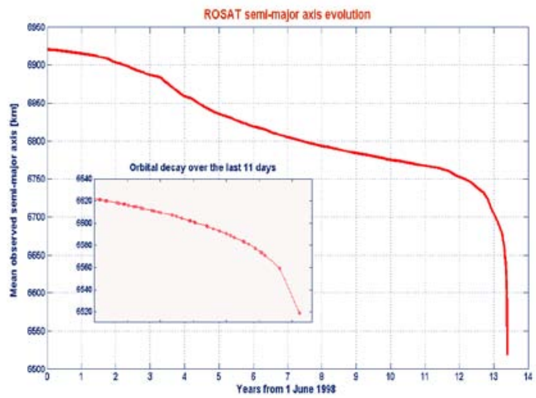

Figure 5. ROSAT semi-major axis evolution since 1 June 1998

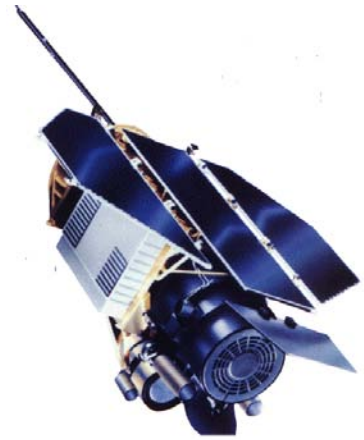

Figure 6. ROSAT spacecraft configuration (credit: NASA)

Since 2001, DLR had funded very detailed reentry fragmentation assessments using progressively improved versions of the Spacecraft Atmospheric Reentry and Aerothermal Breakup (SCARAB) tool [4], the last one carried out during 2011 with SCARAB 3.1L, which included a newly developed ablation model. With a breakup model based on stress and structural integrity checks (not a fixed altitude as in ORSAT), thermal analysis with 2-D heat conduction and six degrees-of-freedom equations of motion, a total surviving mass of ~1700 kg, concentrated in 18 objects, had been found, corresponding to a casualty area of about 20 m^2. The predicted length of the ground impact footprint was about 1200 km. The heaviest surviving component, a Zerodur® (lithium aluminosilicate glass-ceramic) mirror with Carbon Fiber Reinforced Plastic (CFRP) housing, had a mass of ~1500 kg, i.e. more than 88% of the total. Taking into account the orbit inclination of 53º and the updated world population distribution, a final casualty expectancy of ~1:3000 had been estimated, significantly less than the original assessment of ~1:2000.

2.3. Fobos-Grunt

The Roscosmos' spacecraft Fobos-Grunt (Фобос-Грунт), also spelled Phobos-Grunt in English, was launched from Baikonur with a Zenit-2 rocket on 8 November 2011. Initially placed into a 208 × 344 km orbit, it should have left the gravitational sphere of influence of the Earth, directed towards Mars and its main moon Phobos, after a couple of big firings of the integrated Fregat upper stage. But, unfortunately, the probe remained trapped in orbit around the Earth, probably because heavy charged cosmic rays corrupted the proper operation of two processors of the TsVM22 on-board computer, preventing the execution of the mission as planned, escape maneuvers included. Any attempt to regain control of the probe from the ground, circumventing the computer problem, was unsuccessful, but Fobos-Grunt, with a slow spin rate around the sun-pointing longitudinal axis (safe mode) and solar panels deployed, remained alive for at least a couple of weeks. In particular, until the morning of 22 November 2011, the probe continued to modify its orbit, raising the perigee to 215 km and reducing the semi-major axis decay to approximately 55% of the value due to air drag. The analysis carried out by the authors to explain such behavior was presented in [5]. Since 22 November 2011, the orbital decay registered was essentially compatible with natural perturbations alone (Fig. 7).

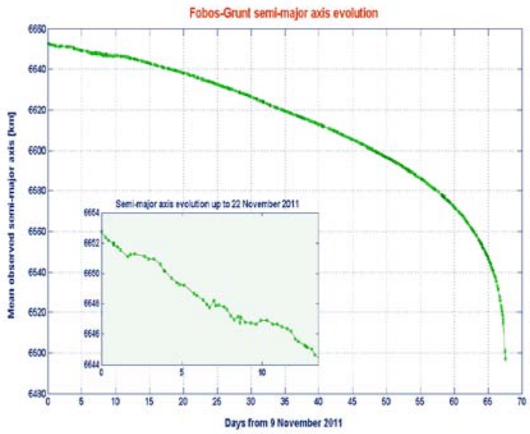

Figure 7. Fobos-Grunt semi-major axis evolution since 9 November 2011

Figure 8. Configuration of the Fobos-Grunt spacecraft (credit: Lavochkin Association)

The failed probe had a total mass at launch of 13,525 kg and dimensions of 3.76 × 3.76 (7.97 m with the solar arrays deployed) × 6.32 m (Fig. 8). Historically, it was the 12th most massive space object reentering the atmosphere uncontrolled, but more than 82% of the total mass, i.e. about 11,150 kg, consisted of very toxic liquid hypergolic propellants, namely UDMH (unsymmetrical dimethylhydrazine), MMH (monomethylhydrazine) and NTO (dinitrogen tetroxide, N_2O_4). The dry mass of Fobos-Grunt, which carried on board also a tiny amount (10 μg) of the radioactive isotope Cobalt-57, was therefore around 2350 kg, a value not uncommon among spacecraft and upper stages usually reentering without control.

Concerning the potential risk that some of the toxic propellant could have been able to reach the ground, some analysts made a parallel with the USA-193 experience [6]. However, in this case, most of the experts thought that the freezing of the propellant was very unlikely and that, anyway, the high altitude melting of the exposed aluminum tanks would have caused the dispersion of both fuel and oxidizer, without risk for the ground.

According to Russian sources, a total surviving mass of 200 kg, all coming from the dry fraction of the probe and distributed among 20-30 fragments, should be expected. Taking into account the orbit inclination of 52º and the world population distribution, a casualty expectancy just exceeding the alert threshold of 1:10,000 was consequently estimated. However, it should also be mentioned that different reentry scenarios were simulated as well, using SCARAB, by Hyperschall Technologie Göttingen (HTG). The surviving mass, number of fragments and footprint length strongly depended on the assumptions used, with casualty expectancy in between 1:5000 and 1:3000, and debris footprint length of 900-1200 km.

3. Reentry Predictions

Since the accidental reentry of the nuclear powered satellite Cosmos 954, on January 1978, self-contained reentry prediction capabilities were established and maintained at the facilities of the Italian National Research Council (CNR) in Pisa, to provide support to the civil protection authorities in case of new emergencies. Moreover, with the Italian Space Agency (ASI) joining the Inter-Agency Space Debris Coordination Committee (IADC), the Space Flight Dynamics Laboratory of ISTI/CNR was involved, as National Technical Point of Contact, in the fifteen reentry test campaigns carried out so far since 1998, including the three reentries at issue. However, while one IADC exercise is generally conducted each year to improve the level of international cooperation and to test the functionality of prediction tools, irrespective of the risk involved, specific criteria have instead to be satisfied to activate a reentry prediction campaign of national concern. Such criteria, consisting in the over-flight of the Italian territory, and the apparent overtaking of the casualty expectancy alert threshold (1:10,000), were met, more or less marginally, by UARS, ROSAT and Fobos-Grunt. Therefore, reentry predictions were carried out for each spacecraft, both in the framework of the IADC cooperation [7] and for civil protection applications [5].

The satellite trajectory was propagated with the last version (5.0) of the Satellite Reentry Analysis Program (SATRAP) [8] [9], including zonal and tesseral harmonics of the geopotential up to the 16^{th} degree and order (EGM96 model [10]), luni-solar attraction, solar radiation pressure with eclipses and aerodynamic drag. In conditions of transitional and continuum flux, the satellite drag coefficient was estimated in terms of the Knudsen number and the spacecraft characteristic length. In all three reentry campaigns, the GOST-2004 [11] atmospheric density model was used, even though JR-71 [12], JB2006 [13] and NRLMSISE-00 [14] were applied as well to the Fobos-Grunt orbital decay analysis.

Concerning the solar and geomagnetic activity indices, the daily observed values were obtained from the NOAA's National Geophysical Data Center and the Jan Alvestad Solar Terrestrial Activity Report, while forecasts were obtained from the NOAA’s Space Weather Prediction Center and the British Geological Survey. Observations and predictions of the additional indices used by the JB2006 model were provided by Space Environment Technologies (SET), courtesy of W. Kent Tobiska. Fig. 9 shows the evolution of the solar activity during the three reentry campaigns, while Fig. 10 shows the corresponding geomagnetic activity.

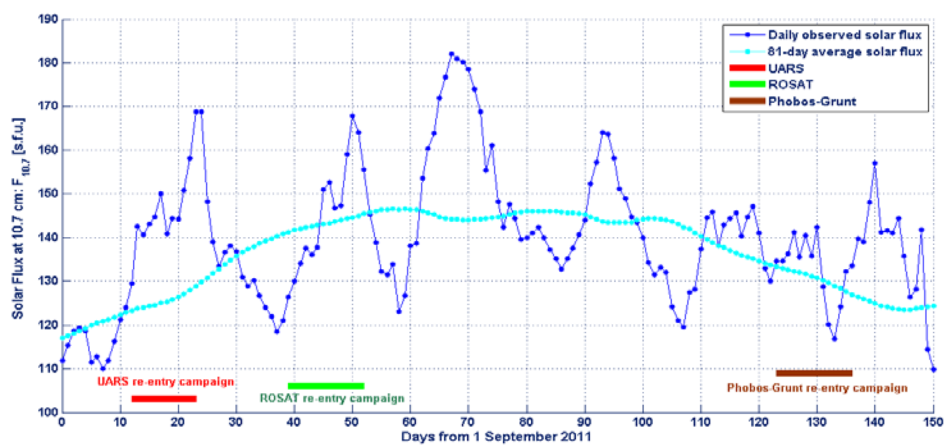

Figure 9. Evolution of the solar flux at 10.7 cm during the three reentry campaigns

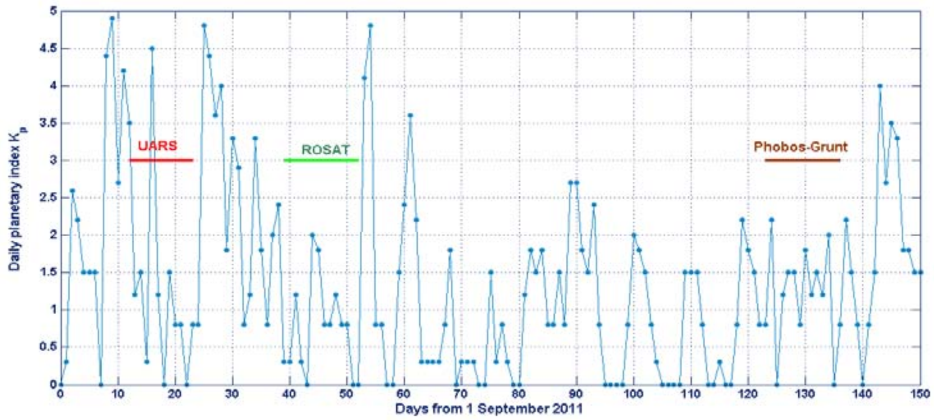

Figure 10. Daily planetary geomagnetic index K_p during the three reentry campaigns

The main source of orbital information was in the form of Two-Line Element (TLE) sets issued by the US Strategic Command through the Space-Track website. Additional orbit determinations based on Russian, European and Japanese sensors were available in the Common and Reentry Database of the Inter-Agency Space Debris Coordination Committee, maintained at the ESA's European Space Operations Centre (ESOC).

The ballistic parameter $B = C_D \cdot A/M$, where C_D is the satellite drag coefficient, A the average cross-sectional area and M the mass, was obtained by fitting, in a least squares sense, the semi-major axis decay obtained from the TLEs. For this purpose, the software tool CDFIT 5.0 [9], including the same models of SATRAP 5.0, was used.

For each reentry prediction, the relative error (*RE*) in the estimation of the residual lifetime was determined according to:

$$RE = 100 \times \frac{T_{com} - T_{ref}}{T_{ref} - T_{in}} \quad (1)$$

where T_{com} is the predicted reentry time, T_{ref} is the reference reentry epoch, T_{in} is the time corresponding to the last available two-line element which was propagated, and the difference $T_{ref} - T_{in}$ indicates the residual lifetime. The satellite was assumed to have reentered the atmosphere as soon as it came down to the conventional geodetic altitude of 10 km adopted by the IADC, and the reentry times (T_{com} and T_{ref}) were referred to this reentry condition. The running mean prediction error (*MPE*) in the estimation of the residual lifetime was computed as follows:

$$MPE = \sum_{n=1}^{N_P} \frac{|RE|}{N_P} \quad (2)$$

where N_P is the number of reentry predictions between the current residual lifetime and the reference reentry epoch.

3.1. UARS

During the UARS reentry campaign, both American and Russian TLEs were used, even though, in the last couple of days, only the American elements were available. The prediction activity was carried out during the last 12 days of satellite lifetime, following several months of situation monitoring and evaluation. In total, 25 reentry predictions were issued during the official campaign, marked by 81-day average and daily solar flux at 10.7 cm on the rise and by a couple of geomagnetic storms in the first half.

The evolution of the ballistic parameter determined with CDFIT 5.0, shown in Figure 11, probably mainly reflects the attitude evolution of the spacecraft, characterized by a complex shape. During the first 10 days of the campaign the ballistic parameter slightly increased by less than 10%, but during the last 48 hours it experienced a drop of nearly 40%, quite complicating the prediction work. The standard deviation during all the campaign was 13% of the mean value.

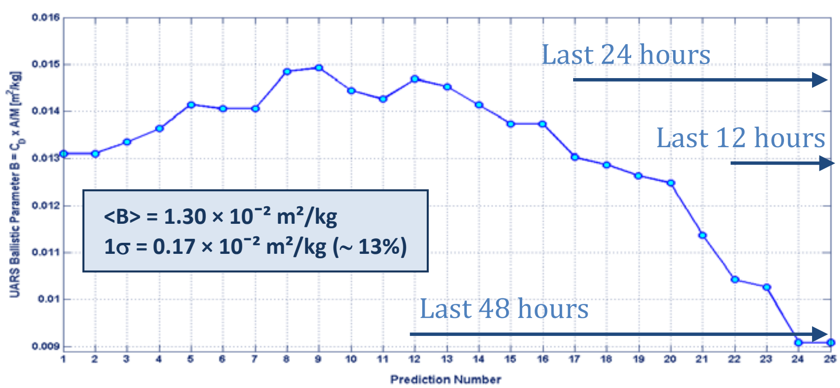

Figure 11. Evolution of the UARS ballistic parameter during the reentry campaign

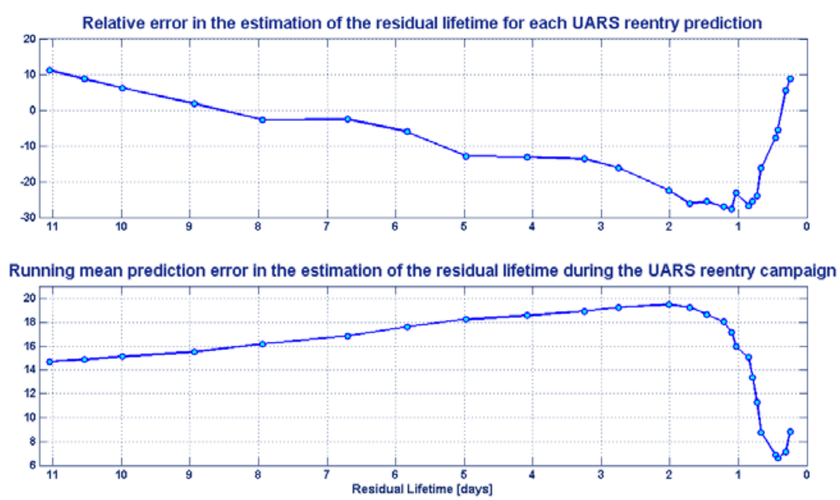

Figure 12. Residual lifetime prediction error budget for the UARS campaign (Reference reentry epoch at 10 km: 24 September 2011, 04:07 UTC)

The residual lifetime prediction error budget for the UARS campaign is summarized in Fig. 12. In 19 out of 25 predictions a shorter residual lifetime (negative relative error) was estimated, 9 times with relative absolute errors >20% (during the last 2 days). The maximum relative absolute errors were close to 28% and occurred around one day before reentry. Considering the running average of the relative prediction errors, the mean relative residual lifetime error was close to 15% over the campaign, about 20% during the last 2 days, about 15% during the last day and less than 10% during the last 16 hours.

3.2. ROSAT

During the ROSAT reentry campaign, in addition to the American and Russian space surveillance systems, DLR and ESA provided TLEs as well using the German Tracking & Imaging Radar (TIRA). In the last couple of days there was a blackout in the flux of American TLEs, but most of the gaps were filled with elements issued by Russia, DLR and ESA. However, during the last 14 hours, the TLEs issued by DLR were not fully consistent with the Russian and ESA elements and, consequently, they were not included in the analysis. The problems encountered in the orbital data flux and consistency so close to the ROSAT reentry created a certain amount of operational disruption, but at the end the situation was successfully managed, thanks to the high level of international cooperation on the subject.

The prediction activity was carried out during the last 11 days of satellite lifetime, following several months of situation monitoring and evaluation. In total, 18 reentry predictions were issued during the official campaign, marked by 81-day average and daily solar flux at 10.7 cm on the rise and relatively quiet geomagnetic conditions.

The evolution of the ballistic parameter determined with CDFIT 5.0, shown in Fig. 13, was much smoother than that observed in the UARS case, probably due to the quite compact configuration of the spacecraft. Over the campaign, the ballistic parameter standard deviation was just 2% of the mean value and the decrease of *B* observed in the last 19 hours was only 8%.

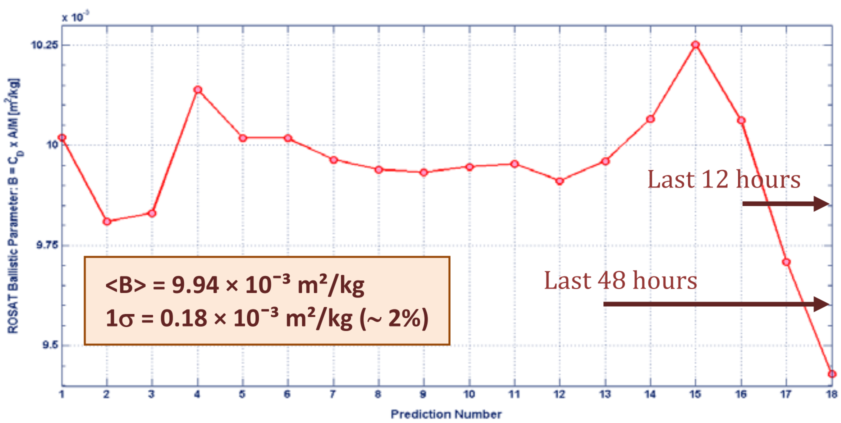

Figure 13. Evolution of the ROSAT ballistic parameter during the reentry campaign

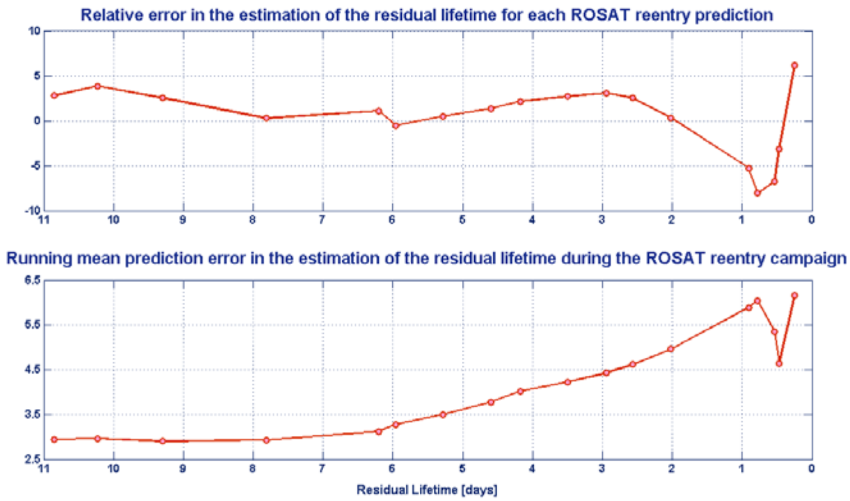

Figure 14. Residual lifetime prediction error budget for the ROSAT campaign (Reference reentry epoch at 10 km: 23 October 2011, 01:57 UTC)

The residual lifetime prediction error budget for the ROSAT campaign is summarized in Fig. 14. In 13 out of 18 predictions a longer residual lifetime (positive relative error) was estimated. The maximum relative absolute error was about 8% and occurred around 19 hours before reentry. Considering the running average of the relative prediction errors, the mean relative residual lifetime error was about 3% over the campaign, about 5% during the last 2 days, and about 6% during the last day.

3.3. Fobos-Grunt

During the Fobos-Grunt reentry campaign, the American and Russian TLEs were the main source of orbital information, even though both DLR and ESA issued a few element sets (none in the last 36 hours) based on the observations of the German TIRA radar. The prediction activity was carried out during the last 13 days of satellite lifetime, but the situation had been monitored and evaluated since the probe failure to leave the Earth orbit. In total, 20 reentry predictions were issued during the official campaign, marked by declining 81-day average solar flux at 10.7 cm and relatively quiet geomagnetic conditions.

The evolution of the ballistic parameter determined with CDFIT 5.0, shown in Fig. 15, was relatively regular, with a small decreasing secular trend and a long period oscillation, probably due to the quite compact configuration of the spacecraft and to the sun-pointing attitude it maintained for most of the time. All over the campaign, the ballistic parameter standard deviation was just 4% of the mean value, the general decrease of *B* was around 10%, and during the last 12 hours it remained quite stable.

The residual lifetime prediction error budget for the Fobos-Grunt campaign is summarized in Fig. 16. In 15 out of 20 predictions a shorter residual lifetime (negative relative error) was estimated. Overall the maximum relative absolute error was about 8%, 6% during the last 2 days and less than 3% during the last day. Considering the running average of the relative prediction errors, the mean relative residual lifetime error over the campaign was about 4% and generally maintained a decreasing trend until the end, with less than 3% during the last 3 days and less than 1.5% during the last 24 hours.

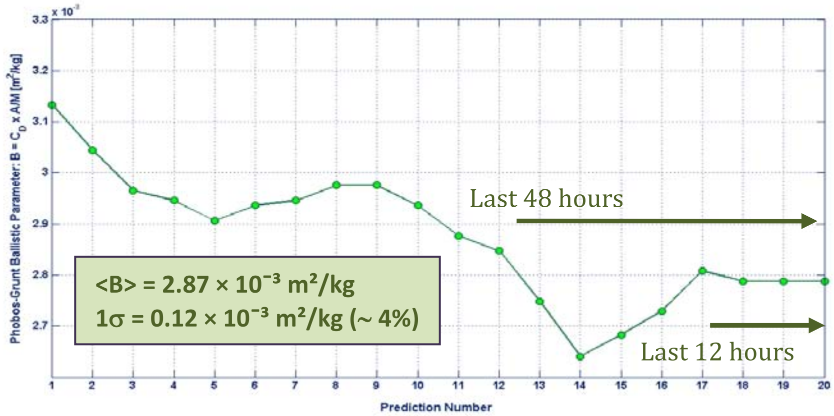

Figure 15. Evolution of the Fobos-Grunt ballistic parameter during the reentry campaign

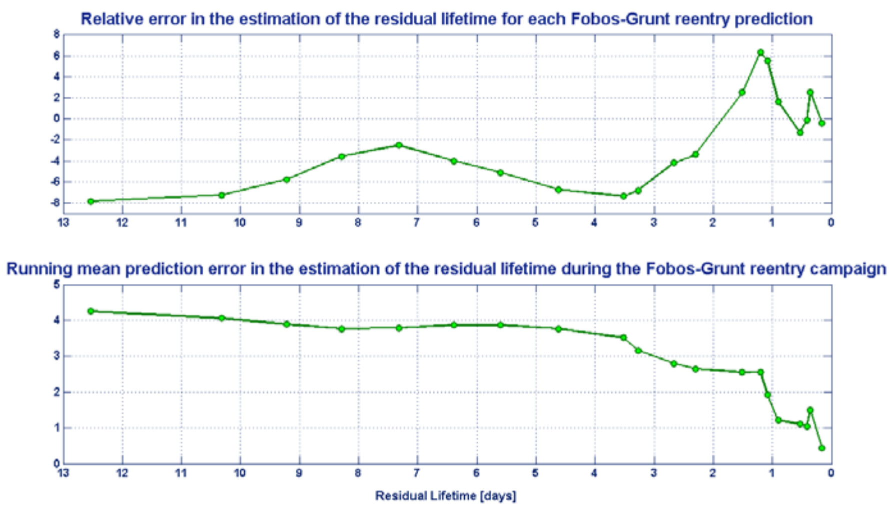

Figure 16. Residual lifetime prediction error budget for the Fobos-Grunt campaign (Reference reentry epoch at 10 km: 15 January 2012, 17:53 UTC)

4. Reentry Uncertainty Windows and Ground Tracks

Predicting the satellite's reentry time and location is a very tricky problem. An uncontrolled spacecraft can reenter anywhere on the Earth, putting all locations within the latitude band, defined by the orbit's inclination, into the danger zone. There is considerable uncertainty in the estimation of the reentry epoch due to unknown and changing atmosphere, solar activity conditions and object's orientation. At about ten days prior to reentry, the time the satellite comes back to Earth can be predicted within a window of about half a week. The time slot of uncertainty reduces as the date of reentry approaches. However, even one day in advance, the estimation may still include a margin of several hours. Shortly before reentry, predictions are issued on the orbit on which the satellite falls back to Earth, making possible to exclude not affected zones. Therefore, in order to provide useful information, especially for civil protection planning and applications, appropriate reentry windows were defined based on past experience.

For UARS they were obtained by varying the fitted ballistic parameter used to propagate the satellite trajectory by ±20%. This variation range was increased to ±25% in the case of ROSAT, while for Fobos-Grunt the uncertainty windows were obtained by directly varying the nominal residual lifetime by ±25%. The amplitudes, in days, and the evolution of the corresponding reentry windows are shown in Fig.17.

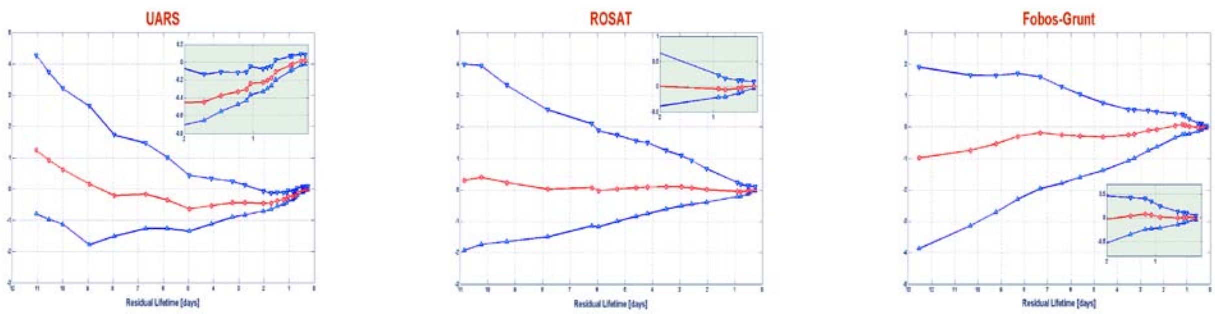

Figure 17. Evolution of reentry predictions (red line) and uncertainty windows (blue lines)

The evolution exhibited by nominal predictions and reentry windows was very smooth and the definitions adopted for the uncertainty windows typically resulted to be completely adequate and quite conservative. This was not the case during the last two days of the UARS campaign, when the fast and significant decrease of the ballistic parameter led to a substantial increase of the residual lifetime (see the inset of Fig. 17 for UARS). In that situation, an uncertainty window obtained by varying the ballistic parameter by ±30% would have resulted in a more regular and conservative evolution of the upper bound, even though the adopted definition was anyway satisfactory, following quite well the object behavior and without introducing discontinuities or boundary violations in contiguous predictions.

The last UARS reentry prediction and uncertainty window was issued about three hours before the satellite plunge into the atmosphere. The ground track corresponding to the last prediction (COIW, i.e. Center Of Impact Window: referred to a conventional geodetic altitude of 10 km) and window (START-END) is shown in Fig. 18.

Later on, by analyzing the data acquired by classified satellite sensors, the US Joint Space Operations Center (JSpOC) was able to estimate that UARS had reentered into the atmosphere on 24 September 2011, at 04:00 UTC ±1 minute. The entry location corresponded to an altitude of 80 km. The pass through the IADC reference reentry altitude of 10 km was approximately 1200 km down track, at 04:07 UTC. Fig. 19 shows the UARS final ground track, entry point at 80 km, and upper limit of debris dispersion, based on the JSpOC post-event assessment.

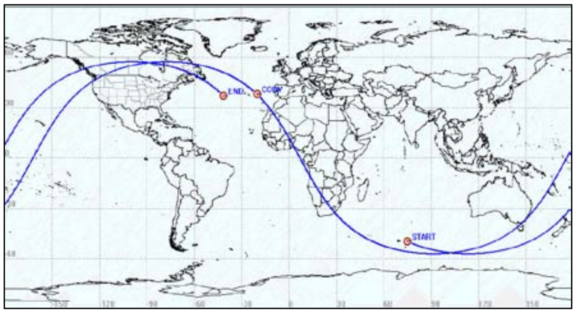

Figure 18. UARS reentry ground track issued 3 hours before the satellite decay

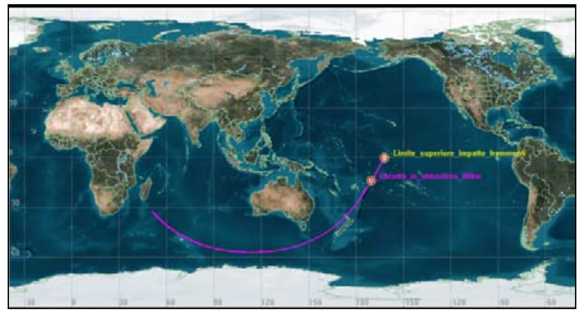

Figure 19. UARS final reentry ground track based on the JSpOC post-reentry assessment

The last ROSAT reentry prediction with a 3-hour wide window (Fig. 20) was obtained just a few tens of minutes before reentry. The JSpOC post-reentry assessment estimated that ROSAT had reentered into the atmosphere, at the geodetic altitude of 80 km, at 01:50 UTC ±7 minutes on 23 October 2011. Using this information and taking into account the claimed uncertainty, the post-reentry evaluation shown in Fig. 21 was obtained for the final ground track, nominal entry (80 km) and impact points, and lower and upper limits of debris dispersion.

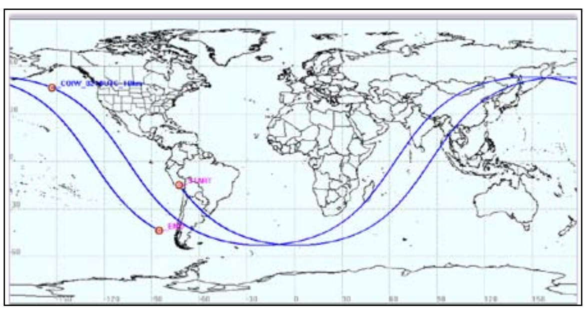

Figure 20. ROSAT reentry ground track obtained a few tens of minutes before reentry

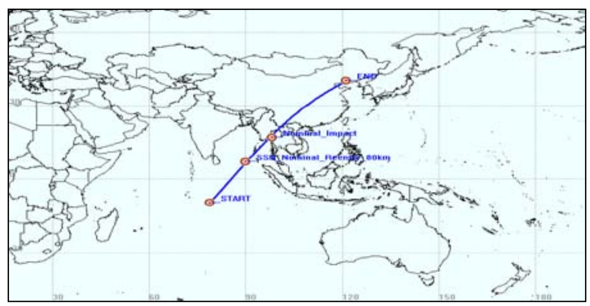

Figure 21. ROSAT final reentry ground track based on the JSpOC post-reentry estimation and uncertainties

The last Fobos-Grunt reentry prediction and uncertainty window was issued approximately one hour before the probe decay, on 15 January 2012. The corresponding ground track is presented in Fig. 22, where the nominal reentry points, at the geodetic altitude of 10 km, obtained with four different atmospheric models, namely JR-71 (17:15 UTC), JB2006 (17:32 UTC), NRLMSISE-00 (17:41 UTC) and GOST-2004 (17:52 UTC), are shown to visualize some of the inherent uncertainties of the prediction process, even adopting exactly the same input data and propagation tools. The JSpOC post-reentry assessment estimated that Fobos-Grunt had reentered into the atmosphere, at the geodetic altitude of 80 km, at 17:46 UTC ±1 minute on 15 January 2012. The estimates from other sources ranged from 17:39 and 18:08 UTC. Taking into account the final orbit determination obtained during the last pass of the probe over the Russian radar sensors, at 17:04 UTC, and refined estimations of the ballistic parameter, a detailed post-reentry assessment was carried out also by the authors at ISTI/CNR. Again, four different atmospheric models were used. The results obtained are summarized in Fig. 23. The ground track shown in

Fig. 23 corresponds to an uncertainty window of ±11.5 minutes around the nominal GOST-2004 prediction, obtained by varying by ±25% the last nominal residual lifetime.

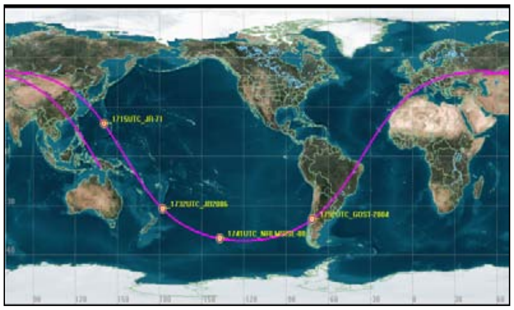

Figure 22. Fobos-Grunt reentry ground track issued approximately 1 hour before the probe decay

Figure 23. ISTI/CNR final assessment of the Fobos-Grunt reentry at the conventional altitude of 10 km

5. Acknowledgments

We are indebted to the IADC Common and Re-Entry Database, maintained at ESA/ESOC, for collecting and making available, during the three campaigns, the orbital elements determined by some of the participating countries equipped with space surveillance sensors. In particular, the contribution of American, German, Russian and ESA sponsored radar observations is acknowledged.

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