ON THE ACCURACY OF SATELLITE REENTRY PREDICTIONS

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ABSTRACT

In January 2002, the Inter-Agency Space Debris Coordination Committee (IADC) promoted a fourth reentry test campaign, choosing an old Russian upper stage as a study case. As in the past, ISTI – formerly CNUCE – was involved, acting as the Italian Space Agency (ASI) technical contact, in the modeling aspects of the reentry predictions, while other IADC members, namely NASA, Rosaviakosmos and ESA, also provided periodic orbits determinations based on ground sensor data. The test campaign took place in a period of high solar activity, during the second peak of the cycle 23 maximum. This was a good opportunity to investigate the behavior of the models available or developed at ISTI, in terms of atmospheric density description, extreme ultraviolet radiation input, ballistic parameter estimation and orbit propagation. In order to evaluate the intrinsic reentry prediction uncertainties, the orbital decay of the test object was fitted, and predictions were made for it, using three different thermospheric density models and two independent sets of orbit determinations (American and Russian two-line elements). The results obtained were compared in order to provide a quantitative assessment of the level of accuracy that may be expected in similar situations.

INTRODUCTION

Since 1979, ISTI (formerly CNUCE), an Institute of the National Research Council (CNR) based in Pisa, has been responsible for the re-entry predictions of potentially risky space objects for the Italian civil defense authorities. In 1994, consolidating the leading role in the field, a Space Objects Monitoring Service (SMOS) was activated, on behalf of the Italian Space Agency (ASI), to provide the national agencies and the government with advice and support on space debris and re-entry technical topics. In 1998, the Italian Space Agency was admitted into the Inter-Agency Space Debris Co-ordination Committee (IADC) and ISTI was involved, as the National Technical Contact Point, in the IADC re-entry test campaigns. In this framework, special techniques, software tools and operational procedures are continually being developed and upgraded.

SATRAP, the SATellite Reentry Analysis Program (Pardini and Anselmo, 1994), used at ISTI to predict the orbital decay of uncontrolled low earth satellites, includes at present a selection of four semi-empirical atmospheric density models – Jacchia-Roberts 1971 (JR-71); Thermosphere Density model 1988 (TD-88); Mass Spectrometer Incoherent Scatter model 1986 (MSIS-86); Mass Spectrometer Incoherent Scatter Extended model 1990 (MSISE-90) – along with the possibility to directly process the US Space Command (USSPACECOM) Two-Line Elements (TLEs) which, for uncontrolled reentries, are often the only source of orbital information available.

Aerodynamic forces represent the largest non-gravitational perturbation acting on low altitude satellites, causing their orbital decay, unless they are provided with an on-board propulsion system for periodic re-boost. It is well known that there are significant differences between the thermosphere density models implemented in SATRAP, as they are based on distinct data sets, covering different time periods and geographical areas. Another intrinsic limitation of each model is the use of the $F_{10.7}$ cm radio flux and some geomagnetic planetary indices (A_P or K_P) as proxy indicators to represent the solar and geophysical influences on the earth's atmosphere. Consequently, the inadequacies of the atmospheric models, the difficulty in predicting the solar-terrestrial interactions affecting the air density at high altitudes and, to a lesser extent, the initial state vector uncertainties continue to significantly affect the accuracy of residual lifetime estimations and reentry predictions.

The uncertainties associated with the density models implemented in SATRAP, in conditions of low or moderate solar activity, have been investigated elsewhere (Pardini and Anselmo, 2000; Pardini and Anselmo, 2001b). The overall uncertainty of the reentry predictions relative to a set of space objects, which reentered the atmosphere in a period close to the maximum of the present solar cycle 23, has also been estimated (Pardini and Anselmo, 2002), but this study assumed a perfect knowledge of the solar and geomagnetic indices through an "a posteriori" analysis of the orbital decay.

In January 2002, the IADC promoted a fourth reentry test campaign, choosing an old Russian upper stage as a case study and, as in the past three exercises (Pardini and Anselmo, 2001a), ISTI was involved in the modeling aspects of the reentry predictions. Since it took place during the second peak of the cycle 23 maximum, the new campaign was also a good opportunity to assess the performance of the air density models available at ISTI and to evaluate the intrinsic uncertainties of our reentry predictions. The orbital decay of the test object was fitted, and predictions were made for it, using three different thermospheric density models (JR-71, MSIS-86, TD-88) and two independent sets of orbit determinations (American and Russian two-line elements). Twelve reentry predictions were produced using each atmospheric model. The computed reentry time was then compared with the time estimated through a post-event assessment issued by the US Space Command.

While the USSPACECOM Two-Line Elements (TLE) were used for predictions 1 to 11 and also to represent and fit the past orbital decay, only the Russian elements – those stored in the IADC Re-entry Database and only accessible to authorized IADC members – were employed during the last prediction, since they were the only orbital information available before the reentry of the stage in the atmosphere. The USSPACECOM elements were chosen, because appropriate conversion routines (Hoots and Roehrich, 1980) are implemented in SATRAP, but it was not known 'a priori' whether these routines were fully compatible with the Russian two-line elements. For this reason, an 'a posteriori' analysis was carried out at the end of this IADC campaign. This analysis consisted in using both American and Russian elements to describe the historical orbital decay, to compute the drag coefficients and to predict the reentry time for particular situations. This study confirmed that using American or Russian elements – in the TLEs format – led to comparable results.

THE FOURTH IADC REENTRY TEST CAMPAIGN

Test Object

The fourth IADC exercise officially began on January 9, 2002, with the aim of following the final orbital decay of a Russian Vostok (SL-3/A-1) upper stage, registered under COSPAR ID 1978-094B and USSPACECOM catalog number 11056. It was cylindrical in shape, with a diameter of 2.7 m, a length of 3 m and an empty mass of about 1400 kg. Its final acquisition was carried out by the Russian Space Surveillance System, which provided the last two-line elements set – on 19 January 2002, at 21:33 UTC – when the mean altitude of the upper stage was already less than 114 km. Subsequently, a post-event assessment by the US Space Command confirmed that the actual reentry occurred on January 19, 2002, at 22:09 UTC.

Models and Assumptions to Predict the Orbital Decay and the Reentry Time

Orbital Data

Twelve reentry predictions were carried out at ISTI for this IADC campaign. Apart from the twelfth prediction, where the Russian orbital data were propagated, the USSPACECOM two-line elements, which were acquired from the NASA/GSFC Orbital Information Group (OIG), were used throughout the campaign. The observed time evolution of the mean semi-major axis was computed by converting these elements to an osculating position and velocity with the appropriate models (Hoots and Roehrich, 1980).

Atmospheric Density Models

The atmospheric density was computed according to the models JR-71, MSIS-86 and TD-88 (for the purposes of this study, MSIS-86 and MSISE-90 were practically identical, so only the former was used, but the results obtained are applicable to both). These models need two different environmental inputs to represent the effects on the atmosphere of the solar-terrestrial interactions: a solar flux index and a planetary geomagnetic index. At the moment, the daily observed 10.7 cm radio flux ($F_{10.7}$) and the A_P (or K_P) geomagnetic index are used in SATRAP. Their past values are obtained from the NOAA National Geophysical Data Center (NGDC), while their current and forecast values are acquired from the NOAA Space Environment Center (SEC), both located in Boulder, Colorado. The fourth IADC campaign occurred in a period of high solar activity, where the values of the $F_{10.7}$ index were those illustrated in Table 1.

Table 1. Daily observed $F_{10.7}$ solar flux during the 4th IADC campaign [9-20 January 2002]

Day	9	10	11	12	13	14	15	16	17	18	19	20
$F_{10.7}$	228.5	224.6	228.9	233.3	240.7	229.0	218.3	216.1	211.8	210.5	213.7	222.2

Ballistic Parameter

For each atmospheric density model, the ballistic parameter B, defined according to the relationship

$$B = \frac{C_D A}{2M} \tag{1}$$

(where A, M and C_D are, respectively, the satellite average cross-section, mass and drag coefficient), was estimated by backward fitting with SATRAP, in a least squares sense, the semi-major axis decay described by the historical two-line elements. A constant mass-to-area ratio of 170 kg/m^2 was assumed in this study and the drag coefficient was computed according to Eq. (1). Therefore, the value of C_D able to reproduce the past observed semi-major axis decay was used in SATRAP to forward propagate the last TLE available. The computed drag coefficients are shown in Table 2 and in Figure 1 for the density models JR-71, MSIS-86 and TD-88. In Table 2, PN indicates the prediction number, the second column gives the epoch of the last available TLE to be propagated, while the drag coefficients for each density model (columns 4-6) were obtained by retro-fitting the semi-major axis decay over the time span displayed in the third column (i.e. 10.24 days for the first prediction). For the twelfth prediction – in which the last Russian TLE was used – the same drag coefficients employed for the eleventh prediction were applied (i.e. no retro-fit was carried out at this point).

Table 2. Drag coefficients

PN	Epoch of the Last TLE Available	Retro Fit [days]	Drag Coefficients		
			JR-71	MSIS-86	TD-88
1	10 Jan., 04:19	10.24	2.17	1.93	2.40
2	11 Jan., 05:41	9.04	2.15	1.90	2.51
3	14 Jan., 05:09	7.03	2.07	1.84	2.27
4	15 Jan., 04:55	6.02	2.02	1.81	2.01
5	16 Jan., 04:38	6.01	1.98	1.78	1.86
6	17 Jan., 05:47	5.69	1.92	1.73	1.75
7	18 Jan., 05:24	3.02	1.93	1.74	1.79
8	19 Jan., 04:55	1.17	2.08	1.95	1.99
9	19 Jan., 10:47	1.41	2.09	1.97	2.01
10	19 Jan., 15:40	1.61	2.07	1.97	2.02
11	19 Jan., 16:52	1.66	2.05	1.97	2.03
12	19 Jan., 21:33	1.66	2.05	1.97	2.03

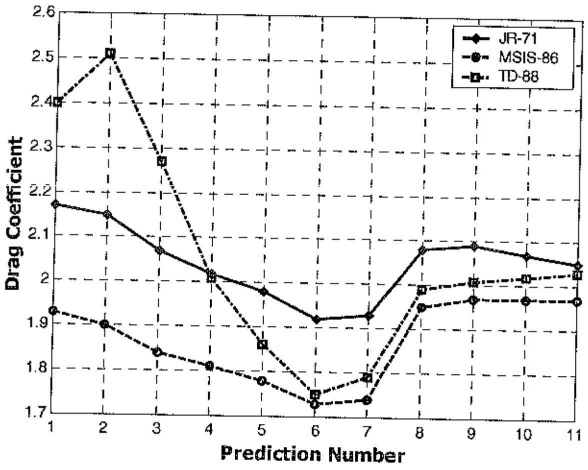

Fig.1. Drag coefficients obtained by retro-fitting the semi-major axis decay.

The semi-major axis root mean squares (rms) residuals (R) were computed according to the relation

$$R = \sqrt{\frac{\sum_{i=1}^{N}\left[a_{i\_obs} - a_{i\_com}\right]^2}{N}} \tag{2}$$

where a_{i_obs} and a_{i_com} are, respectively, the observed and the computed semi-major axis at the same epoch and N is the number of observations available, i.e. the number of TLEs used in the fitting. In nearly all the fit intervals the values obtained with JR-71 and MSIS-86 were comparable (Table 3 and Figure 2), while the use of TD-88 typically resulted in higher values.

Table 3. Semi-major axis residuals [rms]

PN	Epoch of Last TLE Available	Retro Fit [days]	Residuals [m]		
			JR-71	MSIS-86	TD-88
1	10 Jan., 04:19	10.24	90	148	534
2	11 Jan., 05:41	9.04	135	144	326
3	14 Jan., 05:09	7.03	244	209	1099
4	15 Jan., 04:55	6.02	349	312	856
5	16 Jan., 04:38	6.01	431	380	856
6	17 Jan., 05:47	5.69	241	212	410
7	18 Jan., 05:24	3.02	210	216	235
8	19 Jan., 04:55	1.17	136	104	105
9	19 Jan., 10:47	1.41	134	160	172
10	19 Jan., 15:40	1.61	205	151	189
11	19 Jan., 16:52	1.66	362	155	269
12	19 Jan., 21:33	-	-	-	-

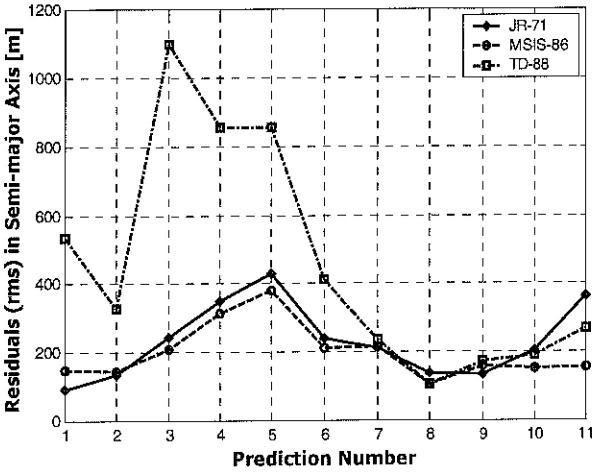

Fig. 2. Semi-major axis residuals (rms) of the least squares retro-fits of the semi-major axis decay.

Reentry Predictions

For each atmospheric density model and corresponding computed drag coefficient, a reentry time was estimated by propagating the last TLE available with SATRAP (including all the relevant perturbations: zonal and tesseral harmonics of the geopotential, up to the 8th degree and order, third body attraction of the moon and the sun, solar radiation pressure, with eclipses, and aerodynamic drag). The satellite was assumed to have reentered the atmosphere as soon as it came down to a geodetic altitude of 80 km, and the reentry time was referred to this reentry condition. Nevertheless, as the aerodynamic drag force depends on a variety of different parameters, as A, C_D and the local air density, which generally cannot be accurately estimated and predicted, a reentry window was also obtained by assuming a variation in the drag coefficient of ±20% (reentry predictions from 1 to 9), reduced to ±15% for predictions 10 to 12.

Results

Errors in the Estimation of the Residual Lifetime

The actual reentry time based on the post-event assessment of the US Space Command, i.e. January 19, 2002, at 22:09 UTC, was adopted as the reentry reference date (T_{ref}), which our results had to be compared to. For each prediction, the satellite TLE was propagated until the reentry condition was satisfied. The resulting reentry time (T_{com}) was then compared with the actual one. The percentage error (PE_{rl}) in the estimation of the residual lifetime was computed according to the following relationship

$$PE_{rl} = \frac{T_{com} - T_{ref}}{T_{ref} - T_{in}} \tag{3}$$

where T_{in} is the time corresponding to the last TLE propagated (initial epoch) and the difference $T_{ref} - T_{in}$ indicates the residual lifetime. Table 4 and Figure 3 show the results obtained for each reentry prediction and density model.

Apart from the last prediction, where the initial perigee altitude was less than 114 km – which was near to the reentry condition assumed in this study – the maximum absolute percentage errors obtained by using the models JR-71, MSIS-86 and TD-88 were 8.4%, 17.7% and 52.0%, respectively. However, during the last orbits, errors of a few percent may be due to the definition (down to 10 km) and uncertainty (± 7 minutes) of the USSPACECOM reentry time.

Reentry Predictions and Windows

For each computed reentry time, a reentry window was also estimated, by assuming a percentage variation of

Table 4. Percentage error in the residual lifetime estimation

PN	Residual Lifetime [days]	Percentage Error on the Residual Lifetime [%]		
		JR-71	MSIS-86	TD-88
1	9.743	- 8.418	- 5.909	- 16.957
2	8.686	- 8.371	-4.765	- 22.026
3	5.708	- 8.114	- 2.190	- 26.630
4	4.718	- 5.211	1.163	- 16.750
5	3.730	- 1.787	4.338	0.223
6	2.682	1.553	9.813	9.580
7	1.698	2.985	14.846	16.073
8	0.718	- 4.352	7.157	20.696
9	0.474	- 3.813	10.409	29.765
10	0.270	- 0.515	16.965	48.327
11	0.220	- 0.631	17.666	52.049
12	0.025	33.320	44.440	38.880

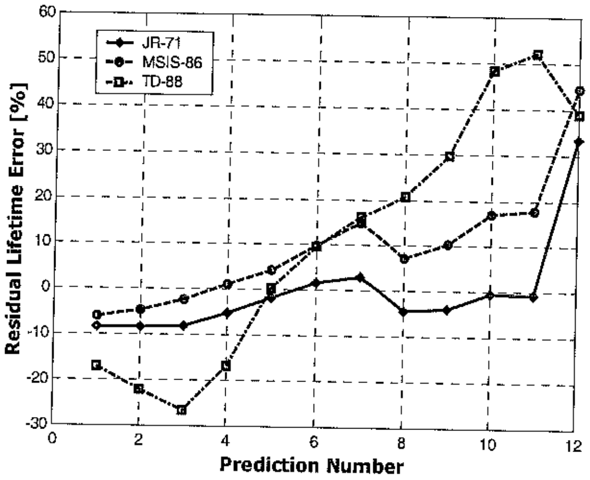

Fig. 3. Percentage error in the residual lifetime estimation.

the drag coefficient of ±20% (predictions 1-9), reduced to ±15% for predictions 10-12. Figure 4 shows the predicted reentry time, with uncertainties (reentry windows), for each density model adopted. The results obtained displayed a reasonably good agreement between JR-71 and MSIS-86, even though MSIS-86 showed a general tendency to postpone the reentry date with respect to JR-71. TD-88, on the other hand, exhibited a more irregular behavior and was typically characterized by larger errors (see Table 4).

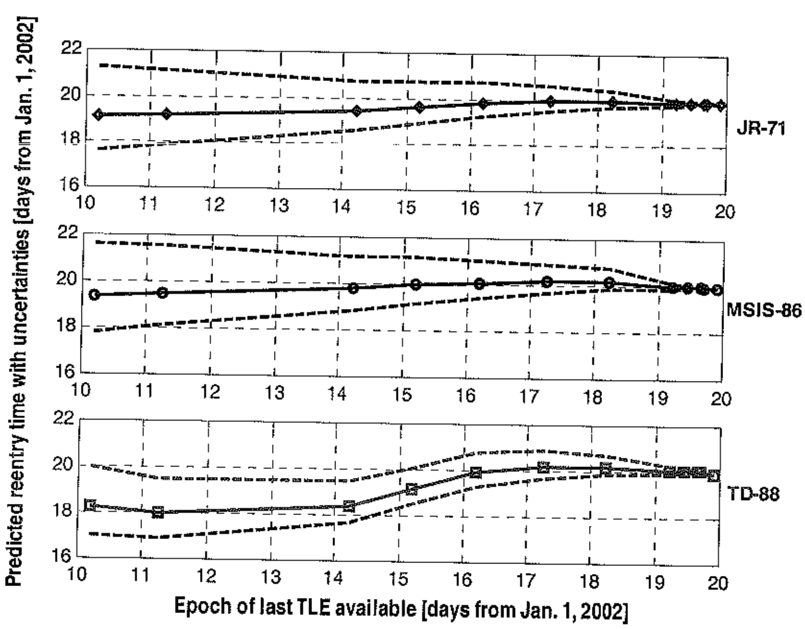

Fig. 4. Predicted reentry time with uncertainties.

COMPARISON OF AMERICAN AND RUSSIAN TWO-LINE ELEMENTS

The Russian Space Surveillance System provided the last TLE before the reentry of the Vostok upper stage. This TLE was converted to osculating elements and propagated with SATRAP to predict the final orbital decay, but was not used to compute a new drag coefficient. However, after the IADC campaign, an 'a posteriori' analysis was carried out to verify the compatibility of the Russian elements with the conversion models implemented in SATRAP. The results obtained showed that the Russian TLE provided during the campaign were fully compatible and consistent with the USSPACECOM sets. An additional evaluation consisted in computing the drag coefficients – by fitting the past semi-major axis decay using the American and/or the Russian TLEs – and in predicting the reentry time, using both element sets in analogous time spans. Table 5 displays some of the results obtained: again, the agreement observed was very good.

Table 5. Drag coefficients and reentry predictions using American and/or Russian TLE

	American TLE		Russian TLE		American and Russian TLE	
Density Model	Retro-Fit: 11 Jan 05:41–17 Jan 05:47		Retro-Fit: 11 Jan 01:40–17 Jan 01:52		Retro-Fit: 11 Jan 01:40–17 Jan 05:47	
	C_D	Residuals [m]	C_D	Residuals [m]	C_D	Residuals [m]
JR-71	1.94	315	1.93	232	1.93	259
MSIS-86	1.74	285	1.74	207	1.74	226
TD-88	1.78	539	1.77	448	1.77	485
	Predicted Reentry TLE: 17 Jan 05:47		Predicted Reentry TLE: 17 Jan 01:52			
JR-71	20 Jan 00:04		20 Jan 00:58			
MSIS-86	20 Jan 05:08		20 Jan 05:55			
TD-88	20 Jan 07:38		20 Jan 08:50			

CONCLUSIONS

The results obtained during the fourth IADC campaign highlighted a good agreement between the density models JR-71 and MSIS-86, even though the latter showed a general tendency to postpone the re-entry date with respect to JR-71. On the other hand, TD-88 was typically characterized by a more irregular behaviour and quite large errors. The use of JR-71 resulted in a small uncertainty in the estimation of the residual lifetime. Apart from the last prediction – where the satellite mean altitude was approaching the reentry condition – the maximum absolute percentage error was less than 9%, against an error of 18% using MSIS-86. On the basis of this result, the conclusion is that JR-71 seems to be the best model to compute air density below ~ 250 km (mean altitude corresponding to the first prediction of the campaign) and in conditions of high solar activity (Table 1).

As far as the comparison between American and Russian TLEs is concerned, it can reasonably be concluded that the two sets of elements were fully consistent, leading to very similar results.

REFERENCES

Hoots F.R. and R.L. Roehrich, *Models for Propagation of NORAD Elements Sets*, Spacetrack Report No. 3, Project Spacetrack, Aerospace Defense Command, United States Air Force, Colorado Springs, Colorado, USA, December, 1980.

Pardini C. and L. Anselmo, *SATRAP: SATellite Reentry Analysis Program*, Rapporto Interno C94-17, Istituto CNUCE, CNR, Pisa, August 30, 1994.

Pardini, C. and L. Anselmo, Calibration of Semi-empirical Atmosphere Models Through the Orbital Decay of Spherical Satellites, in *Astrodynamics 1999*, Vol. 103, Part II, Advances in the Astronautical Sciences series, Univelt Inc., San Diego, California, Paper AAS 99-384, pp. 1293-1305, 2000.

Pardini C. and L. Anselmo, Re-entry Predictions in Support of the Inter-Agency Space Debris Co-ordination Committee Test Campaigns, *Proceedings of the 3rd European Conference on Space Debris*, ESOC/ESA, Darmstadt, Germany, 19-21 March 2001, ESA SP-473, pp. 521-526, 2001a.

Pardini, C. and L. Anselmo, Comparison and Accuracy Assessment of Semi-empirical Atmosphere Models Through the Orbital Decay of Spherical Satellites, *Journal of Astronautical Sciences*, Vol. **49**, No. 2, pp. 255-268, April-June, 2001b.

Pardini C. and L. Anselmo, Performance Evaluation of Atmospheric Density Models for Satellite Reentry Predictions with High Solar Activity Levels, *23rd International Symposium on Space Technology and Science*, Paper ISTS 2002-r-08, Matsue, Japan, May 26-June 2, 2002.

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