RE-ENTRY PREDICTIONS IN SUPPORT OF THE INTER-AGENCY SPACE DEBRIS CO-ORDINATION COMMITTEE TEST CAMPAIGNS

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ABSTRACT

Following the admission of the Italian Space Agency (ASI) in the Inter-Agency Space Debris Co-ordination Committee (IADC), the CNUCE Institute was involved, as the National Technical Contact Point, in the three test re-entry campaigns carried out between 1998 and 2000. The purpose of these campaigns was to test the timely distribution of data and information during high-risk re-entries by means of the IADC international communication network.

During the second campaign, a further analysis was also performed at CNUCE to assess the confidence level of our computed re-entry predictions. Different semi-empirical atmospheric density models were used at the same time to predict the satellite's orbital decay as a function of solar activity conditions and altitude. In particular, the performances of two widely used thermospheric models were investigated and the resulting re-entry forecasts compared.

The aim of this paper is to present the results obtained and the lessons learned during these international exercises.

1. INTRODUCTION

Since 1979, the CNUCE Institute was in charge of the re-entry predictions of potentially dangerous space objects for the Italian civil defence authorities of the Ministry of the Interiors. Following the spectacular orbital decay of Skylab that year, the Institute was involved in the re-entry predictions campaigns for Cosmos 1402, Cosmos 1625, Cosmos 1714, Cosmos 1767, Cosmos 1900, LDEF (at last recovered by a space shuttle), Salyut 7, Progress-M 17, Cosmos 398, FSW-1 5 and TSS 1R.

Special techniques, software and operational procedures were developed specifically for re-entry predictions and are continually upgraded. Moreover, great attention was paid in providing the civil defence authorities with timely and easy to understand information and the activities for the management of re-entry emergencies were included in the operational handbooks adopted by the Italian Department of Civil Defence, as well as in the manual used by the Nuclear Safety Emergency Board to handle all kinds of nuclear emergencies, including those coming from space. On 1994, consolidating the leading role played in the field, a Space Objects Monitoring Service (SMOS) was activated, on the behalf of the Italian Space Agency (ASI), to provide the national agencies and the government with advise and support on space debris and re-entry technical topics.

During the 14th Inter-Agency Space Debris Co-ordination Committee (IADC) meeting, held at the ESA's Space Operations Centre (ESOC) on March 20-21, 1997, the IADC Working Group 2 – Environment and Database – adopted an action item to establish an informational network for the timely efficient distribution of data during high-risk re-entries. In September 1998, the main node of this communication network, located at ESOC, was tested and accepted. Since then, the IADC Common Database and Re-Entry Database are maintained by the ESA's Space Operations Centre in Darmstadt, Germany, and are accessible only to the IADC member organizations.

In the meantime, the Italian Space Agency joined the Inter-Agency Space Debris Co-ordination Committee and our Institute was involved, as the National Technical Contact Point, in the IADC re-entry test campaigns.

So far, three exercises have been conducted using targets of opportunity. The first was the re-entry campaign of the Inspector spacecraft in the second half of October 1998. The second exercise officially began on 10 June 1999 and came to an end with the re-entry of the GFZ 1 satellite on 23 June. The latest was carried out in February-March 2000 using a Russian Soyuz launcher upper stage.

During each test campaign, all the IADC members that were participating actively submitted their re-entry forecasts and/or their own current tracking data (in the NORAD two-line element set format) to the IADC Re-Entry Database. Because in Italy there is not yet a radar

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sensor capable of searching for and tracking a low orbiting spacecraft, our Institute contributed to the campaigns providing only its computed re-entry predictions.

A further analysis was also performed at CNUCE during the second campaign to verify, and maybe improve, the confidence level of our re-entry forecasts. In particular, the dependence of the re-entry and orbital decay predictions on the air density model used was investigated. In order to reduce the number of variables in the classical relation to compute the aerodynamic drag force, the GFZ 1 satellite, having a spherical shape and perfectly known physical characteristics, was selected. Therefore, four different atmospheric density models (Jacchia-Roberts 1971 (JR-71) [1], Mass Spectrometer Incoherent Scatter 1986 (MSIS-86) [2], Mass Spectrometer Incoherent Scatter Extended 1990 (MSISE-90) [3], Thermospheric Density 1988 (TD-88) [4]) were used at the same time to analyze its orbital decay, from the launch to the re-entry epoch (19 April 1995 - 23 June 1999). For the sake of brevity we refer to [5] for a complete discussion of all the results obtained. The re-entry predictions during the IADC campaign (10-23 June 1999), using the JR-71 and the MSIS-86 models, are instead presented in this paper.

2. RE-ENTRY PREDICTIONS

2.1 The Orbital Predictor

On 1994-1995, the JPL's trajectory predictor ASAP [6], formerly installed at CNUCE, was extensively modified and upgraded to provide high accuracy re-entry predictions. The resulting software, SATRAP [7], included a broad selection of atmospheric density models (exponential, 1976 US Standard Atmosphere; JR-71, MSIS-86, MSISE-90, TD-88) and the possibility to directly process, in a correct and consistent way [8], the NORAD Two-Line Elements (TLE), which, for uncontrolled satellite re-entry, are often the only source of orbital information generally available. SATRAP uses the Cowell's method to solve the equations of motion and a single step 8th order Runge-Kutta method for their numerical integration.

SATRAP has been used during the IADC re-entry campaigns and the following orbital perturbations were considered: zonal and tesseral harmonics of the geopotential up to the 16th degree and order, third body attraction of the moon and the sun, solar radiation pressure (with eclipses) and, of course, aerodynamic drag. The atmospheric density was computed according to the JR-71 model, during the IADC inaugural and latest exercises (Inspector spacecraft and Soyuz launcher upper stage), and to the JR-71 and MSIS-86 models, during the second campaign (GFZ 1).

2.2 Sources of Orbital Data

For each re-entry campaign, a few IADC member organizations, equipped with their own observational facilities, submitted current tracking data in the two-line element set format. These data were stored in the IADC Re-Entry Database and could be accessed by authorized IADC members. The most frequently issued were the TLE provided by NASA. These elements constituted the main source of our orbital data.

2.3 Sources of Environmental Data

Apart from the 1976 US Standard Atmosphere and, of course, the exponential formulation, the SATRAP's atmospheric density models need two different environmental inputs: the 10.7 cm solar flux ($F_{10.7}$) and a planetary geomagnetic index (K_p or A_p). This information is contained in the IADC Common Database, that provides the monthly mean of the $F_{10.7}$ and A_p indices, from 1957 to 2099, as well as their daily-observed values during the last three months.

However, a database including information on the solar and geomagnetic activity is also maintained at CNUCE, in support of the Space Objects Monitoring Service. Beginning in June 1987, this database contains the observed values of the 10.7 cm daily solar flux, as well as the daily planetary geomagnetic index A_p. Both are obtained, via mail or Internet, from the NOAA National Geophysical Data Center (NGDC) in Boulder, Colorado. The current and 27-day outlook indices are instead acquired from the NOAA Space Environment Center (SEC), which provides real-time monitoring and forecasting of solar and geophysical events. Generally, these are only preliminary values and are updated as the final ones become available through the NGDC. Finally, the predicted solar flux data until 2018 are those computed by K. H. Schatten and distributed via the EnviroNET online service of the NASA Goddard Space Flight Center (GSFC).

The CNUCE database was used to describe the solar and geomagnetic activity during the IADC test campaigns. But frequent comparisons with the IADC Common Database were carried out to verify the consistency of the data.

2.4 Ballistic Parameter Estimation

To improve the accuracy of the re-entry prediction process, the ballistic parameter B of a satellite need 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 associated to the physical characteristics of the satellite, to its attitude and, for a given atmospheric model, to the air density. Therefore, for each object and atmospheric density model, B must be adjusted, to reduce the impact of the above-mentioned uncertainties.

In this study, we assumed A and M to be constant for each satellite, while adjusted drag coefficients were obtained by fitting with SATRAP the observed evolution of the mean semi-major axis resulting from the historical two-line elements record.

2.5 Re-entry Condition and Window

For each satellite, the drag coefficient able to reproduce the past observed semi-major axis decay was used in SATRAP to propagate the last TLE available. Therefore, the satellite was supposed to re-enter the atmosphere when it reached an altitude of 90 km over the terrestrial reference ellipsoid. According to this re-entry condition, a predicted re-entry time was then computed.

Nevertheless, as the aerodynamic drag force depends on a variety of different parameters, which cannot be accurately estimated, a re-entry window was obtained by assuming a variation of the drag coefficient by plus or minus 20%.

3. IADC RE-ENTRY TEST CAMPAIGNS

The first time the IADC member organizations had access to the IADC Re-Entry Database, through their Technical Points of Contact, was on 15 October 1998, for the first exercise: the re-entry of the German Inspector spacecraft (1997-058D; NORAD catalog number: 25100). It was not a risky object, but only a small spacecraft of opportunity. It had a launch mass of 68.5 kg, a length of 90 cm and a hexagonal cross-section, with diameter between 44.8 cm and 51.7 cm. Following a post-event assessment of the US Space Command, the re-entry of the Inspector spacecraft occurred on 1 November 1998, at 19:49 UTC.

The second IADC exercise officially began on 10 June 1999, to follow the re-entry of the German GFZ 1 satellite (1986-017JE; NORAD catalog number: 23558). This geodetic research satellite had a spherical shape, with a diameter of 21.5 cm and a mass of 20 kg. This campaign was declared off after the German FGAN's TIRA radar system did not observe a predicted pass of the GFZ 1 satellite at, approximately, 02:26 UTC, on 23 June 1999. The last acquisition occurred during the previous orbit, at 00:56 UTC.

The re-entry of a Russian Soyuz launcher upper stage (1999-058E; NORAD catalog number: 25947) was the subject of the third IADC exercise, on 25 February 2000. This object had a cylindrical shape, with a diameter of 2.7 m and a length of 8.2 m. Its empty mass was 2300 kg. Unfortunately, its final orbital data were not submitted to the IADC Re-Entry Database and our last prediction was based on a TLE about 14 hours older than the predicted re-entry time. The actual re-entry occurred at 05:50 UTC, on 4 March 2000.

4. RESULTS

For each object, the re-entry prediction process involved the following steps:

- acquisition of the historical and current TLE (from the Orbital Information Group – OIG – of NASA/GSFC and/or IADC Re-Entry Database);
- update of the CNUCE database including solar and geomagnetic activity data (from SEC of NOAA/NGDC and/or IADC Common Database);
- selection of an atmospheric density model and calibration of the drag coefficient by fitting the past observed semi-major axis decay;
- propagation of the last TLE (maintaining constant the previously computed C_D) as far as the re-entry condition was satisfied;
- determination of the re-entry window, by assuming a drag coefficient variation of ± 20%.

4.1 Inspector

According to the post-event assessment of the US Space Command, the actual re-entry time of the Inspector spacecraft was 19:49 UTC, on 1 November 1998. Our re-entry prediction results are summarized in Table 1 and in Fig. 1. In Table 1, *PERL* indicates the Percentage Errors on the Residual Lifetime (a negative/positive sign implies that the computed re-entry time preceded/followed the actual one), while *PN* is the associated re-entry Prediction Number.

The average drag coefficient found was 1.95, with a standard deviation of 3.9%. The absolute error on the residual lifetime was lower than 14%, but during the campaign there was a systematic trend to anticipate the re-entry date. Also a post-event estimation gave a re-entry time 12 minutes in advance with respect to the actual one.

Table 1

RE-ENTRY PREDICTIONS FOR THE INSPECTOR SPACECRAFT

PN	*PERL* %	C_D	Epoch of the Last TLE	Predicted Re-entry Time
1	- 12.2	1.98	1998/10/15, 01:43	1998/10/30, 16:03
2	- 1.8	1.77	1998/10/19, 00:00	1998/11/01, 14:00
3	- 14.0	1.99	1998/10/19, 22:25	1998/10/31, 00:25
4	- 12.7	2.03	1998/10/20, 22:19	1998/10/31, 07:29
5	- 12.8	2.03	1998/10/22, 04:09	1998/10/31, 11:09
6	- 12.6	2.03	1998/10/22, 20:33	1998/10/31, 13:33
7	- 10.6	2.00	1998/10/26, 06:23	1998/11/01, 03:10
8	- 4.1	1.90	1998/10/27, 06:08	1998/11/01, 14:17
9	+ 1.9	1.89	1998/10/28, 05:52	1998/11/01, 21:54
10	- 1.4	1.92	1998/10/29, 05:33	1998/11/01, 18:35
11	- 1.9	1.93	1998/10/30, 05:11	1998/11/01, 18:39

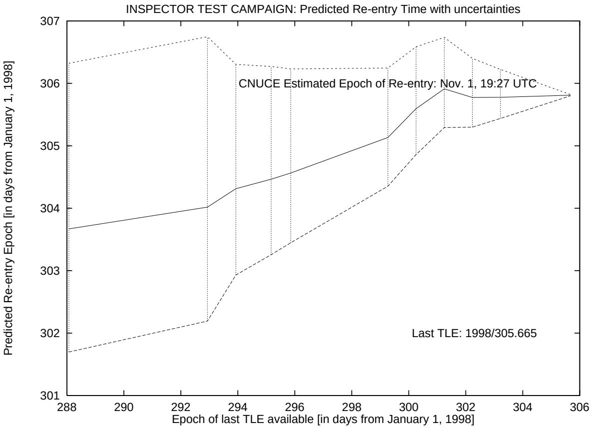

Fig. 1. Inspector Re-Entry Time Windows

4.2 GFZ 1

The GFZ 1 satellite re-entered the atmosphere on 23 June 1999, presumably between 00:56 and 02:26 UTC. The re-entry found by ESA/ESOC using the last FGAN's tracking data was 01:21 UTC. We assumed this time as the actual re-entry epoch. The results of our campaign are summarized in Table 2 (predictions using JR-71), Table 3 (predictions using MSIS-86) and Fig. 2.

When using the JR-71 model, the average drag coefficient obtained was 2.31, with a standard deviation of 14%. On the other hand, by using MSIS-86 the situation was not better. The average drag coefficient resulted to be 2.47 and its standard deviation was again 14%. Also the residual lifetime computation was affected by a quite large, and unusual, uncertainty. The error reached +27.8% in the fifth prediction using JR-71 (Table 2) and +34.9% in the sixth one with MSIS-86 (Table 3). Both models gave similar results, with mutual discrepancies smaller than 10%, even though MSIS-86 postponed, systematically, the re-entry time with respect to JR-71 (Fig. 2). Our post-event assessment gave a re-entry epoch delayed by 19 minutes with respect to the ESA/ESOC estimation.

Table 2

RE-ENTRY PREDICTIONS FOR THE GFZ 1 SATELLITE (JR-71)

JR-71 Atmospheric Density Model				
PN	*PERL* %	C_D	Epoch of the Last TLE	Predicted Re-entry Time
1	- 7.3	2.33	1999/06/09, 20:23	1999/06/22, 02:01
2	- 4.0	2.23	1999/06/15, 01:55	1999/06/22, 17:40
3	- 1.6	2.20	1999/06/16, 05:55	1999/06/22 22:40
4	+ 19.7	2.10	1999/06/21, 04:55	1999/06/23, 10:05
5	+ 27.8	2.10	1999/06/21, 15:09	1999/06/23, 10:51
6	+ 25.4	2.10	1999/06/22, 08:41	1999/06/23, 05:34
7	- 11.7	3.08	1999/06/22 13:04	1999/06/22 23:55

Table 3

RE-ENTRY PREDICTIONS FOR THE GFZ 1 SATELLITE (MSIS-86)

MSIS-86 Atmospheric Density Model				
PN	*PERL* %	C_D	Epoch of the Last TLE	Predicted Re-entry Time
1	- 4.7	2.48	1999/06/09, 20:23	1999/06/22, 10:25
2	- 2.4	2.40	1999/06/15, 01:55	1999/06/22, 20:43
3	+ 0.4	2.37	1999/06/16, 05:55	1999/06/23 02:02
4	+ 25.0	2.25	1999/06/21, 04:55	1999/06/23, 12:27
5	+ 33.5	2.25	1999/06/21, 15:09	1999/06/23, 12:49
6	+ 34.9	2.25	1999/06/22, 08:41	1999/06/23, 07:09
7	- 3.3	3.30	1999/06/22 13:04	1999/06/23 00:56

In effect, the GFZ 1 satellite did not behave in a regular way, typical of other observed spherical satellites. Even though for most of the time displayed a quite normal decay behavior, in certain occasions a significant increase of the drag coefficient, without any obvious explanation, was recorded. However, during the day preceding the atmospheric re-entry, when one of such a large C_D increases was again detected, the German FGAN's TIRA radar system obtained a return signal suggesting that the satellite had entered a spinning motion [9].

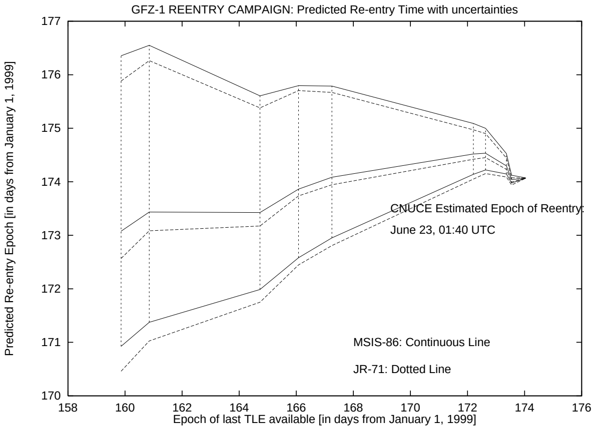

Fig. 2. GFZ 1 Re-Entry Time Windows

4.3 Soyuz Launcher Upper Stage

The Soyuz upper stage re-entry occurred on 4 March 2000, at 05:50 UTC, according to a post-event assessment of the US Space Command. Our results for this campaign are summarized in Table 4 and Fig. 3.

The average drag coefficient found was 1.93, with a standard deviation of 5.4%. The decay behavior was quite regular and the absolute error on the residual lifetime was never larger than 8%. The percentage error distribution was nearly symmetrical around the actual re-entry date, with a lower and a higher extreme of -7.7% and + 5.8%, respectively. Anyway, a slight tendency to anticipate the re-entry epoch was observed also in this case (Table 4). The post-event assessment gave instead a re-entry time delayed by 12 minutes with respect to the actual one.

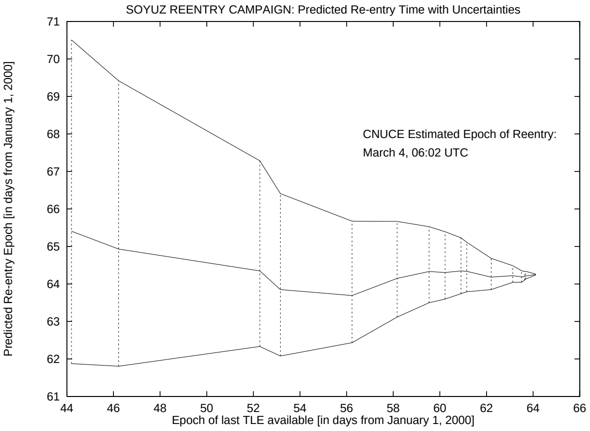

Fig. 3. Soyuz Stage Re-Entry Time Windows

Table 4

RE-ENTRY PREDICTIONS FOR THE SOYUZ LAUNCHER UPPER STAGE

PN	*PERL* %	C_D	Epoch of the Last TLE	Predicted Re-entry Time
1	+ 5.8	1.96	2000/02/13, 04:43	2000/03/05, 09:43
2	- 4.3	2.14	2000/02/14, 05:03	2000/03/03, 10:03
3	+ 3.8	1.96	2000/02/15, 05:21	2000/03/04, 22:21
4	+ 0.9	2.05	2000/02/21, 06:43	2000/03/04, 08:20
5	- 3.6	2.14	2000/02/22, 03:50	2000/03/03, 20:23
6	- 6.9	2.05	2000/02/25, 05:35	2000/03/03, 16:35
7	- 1.5	1.92	2000/02/27, 04:04	2000/03/04, 03:35
8	+ 1.9	1.82	2000/02/28, 12:57	2000/03/04, 07:57
9	+ 1.6	1.83	2000/02/29, 05:21	2000/03/04, 07:21
10	+ 3.1	1.83	2000/02/29, 21:44	2000/03/04, 08:21
11	+ 3.0	1.83	2000/03/01, 03:41	2000/03/04, 08:04
12	- 2.9	1.87	2000/03/02, 04:54	2000/03/04, 04:23
13	- 2.0	1.90	2000/03/03, 03:03	2000/03/04, 05:17
14	- 7.2	1.88	2000/03/03, 12:08	2000/03/04, 04:34
15	- 7.7	1.88	2000/03/03, 15:11	2000/03/04, 04:42
16	- 5.5	1.88	2000/03/03, 16:18	2000/03/04, 05:05

5. CONCLUSIONS

The three test campaigns demonstrated the utility and the functionality of the IADC Re-entry Database as an international information exchange network for the timely distribution of data during a satellite re-entry. From our point of view, we had again the possibility to test and improve our re-entry prediction models and assumptions.

Some conclusions and suggestions, derived from the analysis of our IADC campaign results, are briefly presented in the following. As far as the orbital decay of the Inspector spacecraft and Soyuz upper stage are concerned, no anomalous behavior was recorded, but this was not true for GFZ 1. The maximum absolute error on the residual lifetime was lower than 8% for the Soyuz upper stage, whose orbital decay was characterized by high solar activity levels and very stable re-entry predictions.

For the Inspector spacecraft the maximum absolute error was lower than 14%, while for GFZ 1 it reached 35%. In both cases, a general tendency to anticipate the re-entry epoch was observed (Figs. 1 and 2), probably due to a deficiency in the air density computation. In fact, as our previous work [5] confirms, the JR-71, MSIS-86, MSIS-90 and TD-88 models seem to overestimate the local air density below an altitude of about 400 km, both for low and moderate solar activity conditions (like those encountered by the above considered objects during their orbital decay), then anticipating the re-entry predictions. On the other hand, the accuracy of the JR-71 model improves considerably at moderate to high solar activity levels, explaining the better behavior displayed by the Soyuz upper stage orbital decay.

In addition, the GFZ 1 satellite deserves a special remark. In this case, in fact, a significant variation of the drag coefficient was recorded, as shown by the large standard deviations (14%) associated to the predictions with both the atmospheric models. In the two days preceding the re-entry, the residual lifetime was affected by large errors, decisively greater than those generally observed. The two atmospheric models used (Tables 2 and 3) provided similar results, with discrepancies of less than 10%. Apart during the last two days, the tendency to anticipate the re-entry epoch was observed using both the air density models (Fig. 2). But the re-entry predictions using MSIS-86 were slightly more accurate, confirming again the conclusions of [5], where, for low to moderate solar activity conditions, MSIS-86 resulted the best model to compute the air density below 400 km.

Even if in this case the rotational dynamics of the object may have played a not negligible role, such large fluctuations, both of the drag coefficient and the residual lifetime, may reflect the limited capability of the models to adapt to varying environmental conditions, and/or the inadequacy of the solar flux at 10.7 cm as a proxy indicator of the extreme ultraviolet radiation influence on the atmosphere. A possible improvement of the IADC Common Database would be the adoption of solar flux proxies directly correlated to the sun ultraviolet irradiance, as the $E_{10.7}$ index, produced by the SOLAR2000 project [10] in substitution of the $F_{10.7}$ index. This upgrading might allow the reduction of the error in the calculation of the air density, then improving the re-entry predictions.

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