PERFORMANCES OF ATMOSPHERIC DENSITY MODELS DURING SATELLITE REENTRY PREDICTION CAMPAIGNS AT SUNSPOT MINIMUM

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ABSTRACT

In order to assess the performances of air density models on the accuracy of satellite reentry predictions in condition of low solar activity, five different thermospheric density models were used, under the same conditions and assumptions, during the reentry predictions campaigns for Cosmos 1025 (2007) and EAS (2008). Three of the models (JR-71, MSISE-90 and NRLMSISE-00) were common to both campaigns, while MSIS-86 was used only for Cosmos 1025 and JB2006 only for EAS. Many reentry predictions were carried out, with each density model, over several weeks preceding the actual reentry date. Then, the corresponding percentage errors in the residual lifetime estimation and the mean residual prediction errors were calculated and compared among them. In both campaigns, the error in the single residual lifetime estimation remained well below 25% for each density model analyzed. The mean residual prediction errors remained below 10% all over the first campaign, with the exception of the last prediction with MSIS-86 and MSISE-90. However, JR-71 resulted to be the best, with mean residual prediction errors below 8% during the campaign and below 5% during the last three days. Also during the second campaign the mean residual prediction errors were, with all the models, well below 10% up to a few days preceding the reentry. Afterwards, they showed a tendency to increase, particularly during the last few hours before the final decay. But in this case the mean residual prediction error was observed to be generally lower when using JB2006.

1. INTRODUCTION

Modeling the trajectory of uncontrolled satellites close to reentry in the Earth's atmosphere is still a challenging task [1] [2]. Residual lifetime estimations and reentry predictions are affected by substantial uncertainties, associated with atmospheric density models, with the forecasts of the relevant solar and geomagnetic activity indices and with tracking data, which for uncontrolled reentries are usually sparse and not particularly accurate. Aerodynamic forces represent the largest non-gravitational perturbations acting on reentering satellites. Their main effect is a gradual decrease in semi-major axis and orbital period until reentry. Estimating the rate of orbital decay with reasonable accuracy is generally quite tricky, due to the difficulties of aerodynamic drag modeling.

The most difficult aspect of drag prediction is the realistic representation of the atmospheric density. A variety of density models have been developed over the past four decades, with typical average uncertainties of 10-20% at low altitudes and substantially more at higher altitudes. However, various research initiatives are in progress to calibrate density models on the observed orbital decay of a number of low perigee satellites and debris. Using density calibration, the intrinsic uncertainties of semi-empirical models should be significantly reduced. As an example, the semi-empirical model Jacchia-Bowman 2006 (JB2006) [3], now upgraded to JB2008 [4], has been recently developed using density correction factors and improved solar irradiance indices.

In an attempt to assess the impact of air density modeling on the accuracy of satellite reentry predictions, two Inter-Agency Space Debris Coordination Committee (IADC) reentry test campaigns, occurred in conditions of low solar activity, were carried out using different thermospheric density models. The first exercise involved the satellite Cosmos 1025 [5], which reentered on 10 March 2007, while the second considered the International Space Station (ISS) debris Early Ammonia Servicer (EAS) [6], which plunged into the Earth's atmosphere on 3 November 2008.

Four models, namely Jacchia-Roberts 1971 (JR-71) [7], Mass Spectrometer Incoherent Scatter 1986 (MSIS-86) [8], Mass Spectrometer Incoherent Scatter Extended 1990 (MSISE-90) [9] and Naval Research Laboratory Mass Spectrometer Incoherent Scatter Extended 2000 (NRLMSISE-00) [10], were compared during the first campaign. JB2006 was considered in the second campaign instead of MSIS-86. For each density model, many reentry predictions were carried out over several weeks preceding the actual reentry date. Then, the corresponding percentage errors in the residual lifetime estimation and mean prediction errors were calculated and compared among them.

2. MODELS, DATA AND ASSUMPTIONS

The Satellite Reentry Analysis Program (SATRAP) [11], originally developed at ISTI/CNR to predict the orbital decay of uncontrolled low Earth satellites, was used to propagate the trajectory. The principal orbit perturbations were taken into account, namely the zonal and tesseral harmonics of the geopotential, up to the 16th degree and order, the luni-solar attraction, solar radiation pressure with eclipses, and aerodynamic drag. Over the years, together with other improvements, several thermospheric density models have been implemented in SATRAP, including all those listed in the introduction.

Concerning the orbital elements of the reentering satellites, the Two-Line Element (TLE) sets [12] provided by the IADC Common and Reentry Database (mas15.esoc.esa.de:8000/) and Space Track (www.space-track.org/perl/login.pl) were used. The daily values (observed and predicted) of the $F_{10.7}$ and A_p solar and geomagnetic activity indexes were obtained from the National Geophysical Data Center (NGDC) of the National Oceanic & Atmospheric Administration (NOAA), while the JB2006 indexes [13] were provided by Space Environment Technologies (www.spacewx.com).

The ballistic parameter B, defined as

$$B = C_D \cdot A/M \tag{1}$$

where C_D, A and M are, respectively, the satellite drag coefficient, cross-sectional area and mass, was obtained by fitting, in a least squares sense, the semi-major axis decay inferred from the TLEs [14] [15]. In other words, for each atmospheric density model, B was adjusted in order to maximize the agreement with the air drag revealed by the tracking data, i.e. the historical TLE record, over the selected time span. The semi-major axis root mean square (rms) residuals R were computed according to the relationship [14] [15]

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

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. The fits were carried out using the software code CDFIT, specifically developed at ISTI/CNR and adopting the same force model as the orbit propagator SATRAP.

The percentage error in the estimation of the residual lifetime PE_{RL} was computed as follows:

$$PE_{RL} = 100 \frac{(T_{PRED} - T_{REF})}{(T_{REF} - T_{IN})} \tag{3}$$

where T_{PRED} is the predicted reentry time, T_{REF} is the reference ("actual") reentry time, T_{IN} is the time corresponding to the epoch of the TLE used as the initial state to be propagated and $T_{REF} - T_{IN}$ represents the residual lifetime. The mean percentage prediction error *MPE*, from the current prediction time T_{IN} up to the reentry reference epoch T_{REF}, was instead estimated as follows:

$$MPE = \sum_{n=1}^{N_P} \frac{|PE_{RL}|}{N_P} \tag{4}$$

where N_P is the number of predictions issued in the current $T_{REF} - T_{IN}$ interval.

3. THE COSMOS 1025 REENTRY CAMPAIGN

The object chosen for the IADC reentry test campaign 2007-1 was the Soviet satellite Cosmos 1025 (US Catalog No. 10973; COSPAR ID: 1978-067A), a Tselina-D non operational spacecraft originally used for electronic intelligence gathering. Launched on 28 June 1978 from Plesetsk with a Tsyklon 3 rocket, its initial orbit had an altitude of 640 × 668 km and an inclination of 82.49°. The mass of the satellite was presumably 1880 kg, while its radar cross section was about 8.5 m^2. The reentry occurred on 10 March 2007 and, based on the final assessment of the US Space Surveillance Network (SSN), it reached the 80 km atmospheric interface at 12:56 UTC, corresponding at 13:02 UTC at the conventional reentry reference altitude adopted by IADC, i.e. 10 km [16]. The solar and geomagnetic activity in the couple of months preceding the reentry are shown in Figs. 1 and 2, respectively.

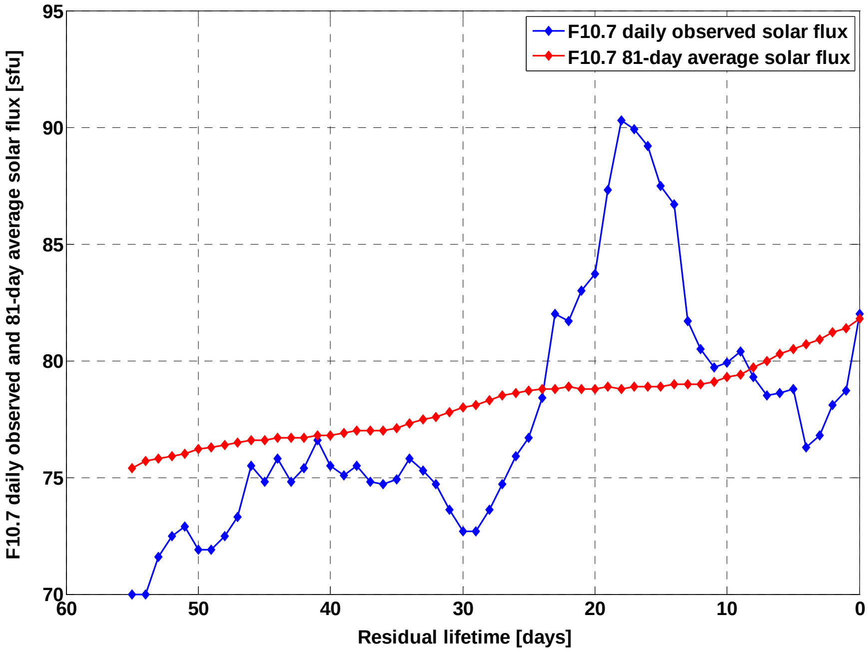

Fig. 1. Solar flux at 10.7 cm during the couple of months preceding the Cosmos 1025 reentry.

During the campaign, launched when the satellite altitude was below 290 km, 30 reentry predictions were carried out by ISTI/CNR. The corresponding ballistic parameters obtained with the four atmospheric density models used for the analysis, by retro-fitting the available TLEs, are shown in Fig. 3. As expected, there was no significant difference between MSIS-86 and MSISE-90 (they are basically the same above an altitude of approximately 90 km), but a consistent increase of *B* during the campaign was shared by all the models. The rms residuals in semi-major axis resulting from the fits are instead presented in Fig. 4. They were basically comparable during the time span considered, even though, again not surprisingly, a much better agreement in amplitude and phase was observed among the two MSIS models (i.e. MSIS-86 and MSISE-90).

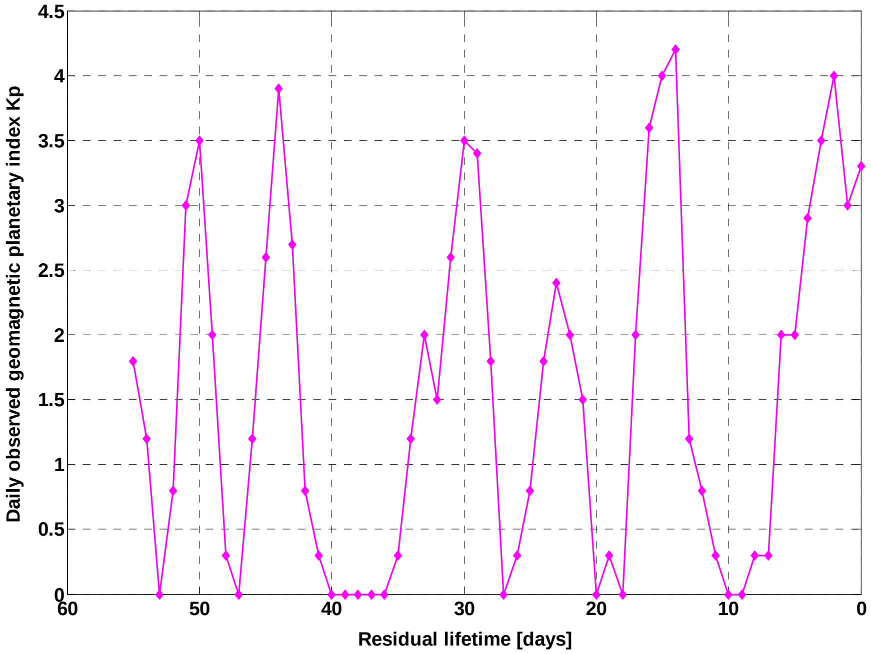

Fig. 2. Geomagnetic activity during the couple of months preceding the Cosmos 1025 reentry.

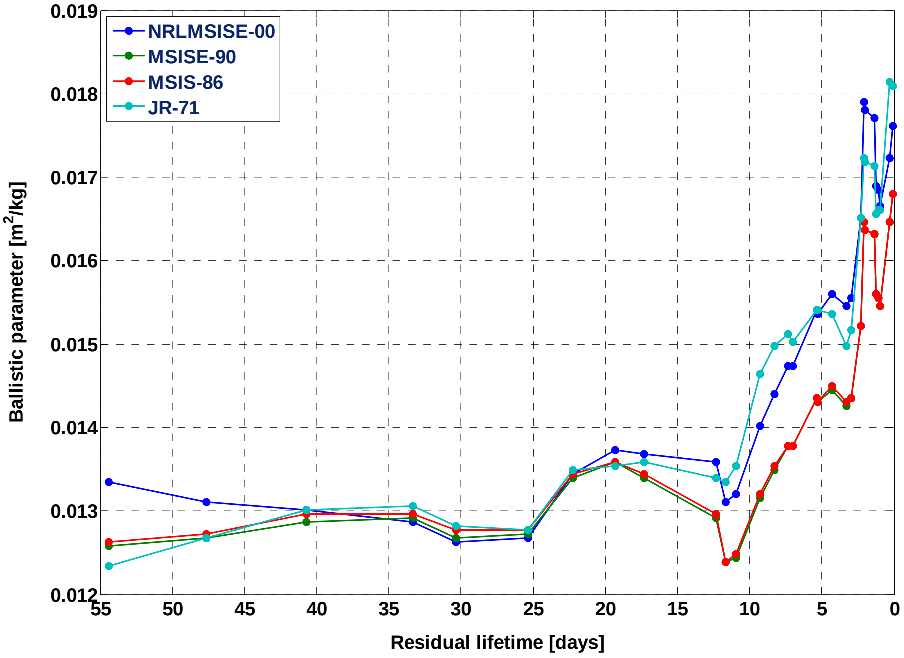

Fig. 3. Cosmos 1025 ballistic parameter estimations.

Fig. 5 shows the evolution of the relative error in the estimation of the residual lifetime. In the first part of the campaign, up to 8.3 days before reentry, corresponding to perigee altitudes in between 276 and 220 km, all the models displayed a similar behavior and JR-71 was generally close to NRLMSISE-00. But in the second part of the campaign, up to 0.28 days before reentry, corresponding to perigee altitudes in between 220 and 150 km, JR-71 closely matched the performances of MSIS-86 and MSISE-90, while NRLMSISE-00 provided quite different results.

Only during the last 7 hours of orbital lifetime, below 150 km, a better agreement between JR-71 and NRLMSISE-00 was reestablished.

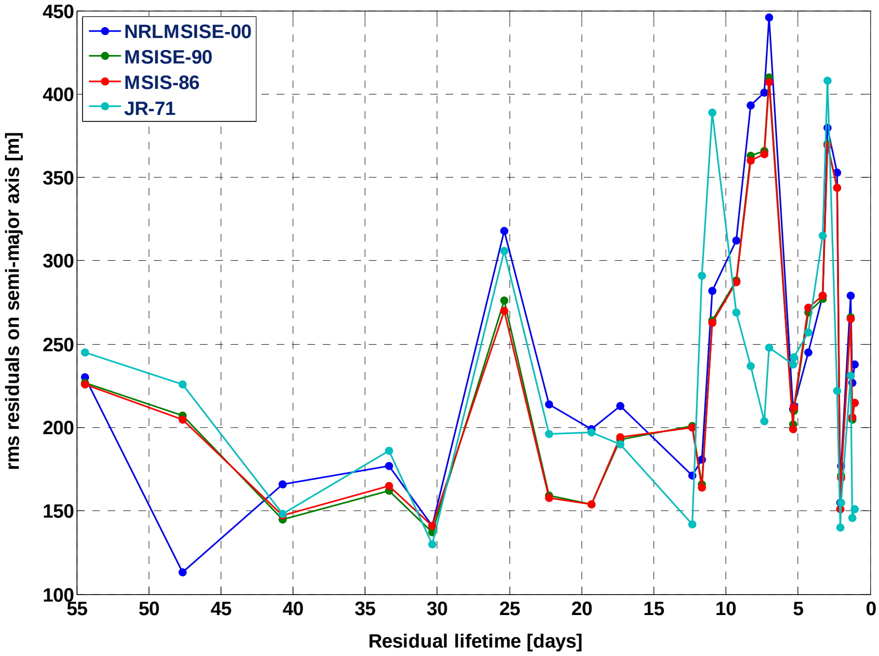

Fig. 4. Cosmos 1025 semi-major axis rms residuals of TLEs fits.

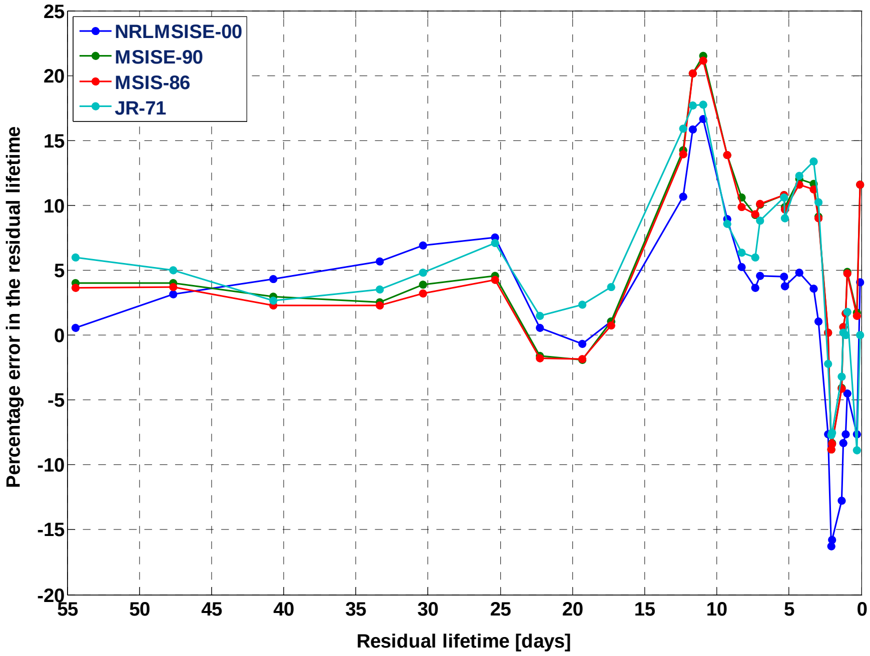

Fig. 5. Evolution of the relative error in the residual lifetime estimation of Cosmos 1025.

Considering the mean residual relative error *MPE*, from the current prediction time T_{IN} up to the reentry reference epoch T_{REF}, the results obtained are shown in Fig. 6. Up to approximately 12 days before reentry, corresponding to a perigee altitude of about 230 km, JR-71 and NRLMSISE-00 were very close and provided the best mean residual relative errors, between 6% and 8%. During the following part of the campaign, JR-71 was the model systematically providing the best mean residual relative errors (< 6% during the last 5 days), while NRLMSISE-00 was the worst in 60% of the cases. As expected, MSIS-86 and MSISE-90 gave very similar results; both followed, until the very end, the evolution exhibited by JR-71, but with a higher mean residual error.

In conclusion, during the Cosmos 1025 reentry campaign, all the atmospheric density models used, under exactly the same conditions and assumptions, provided comparable results, but JR-71 was, overall, slightly the best in terms of mean residual reentry prediction errors.

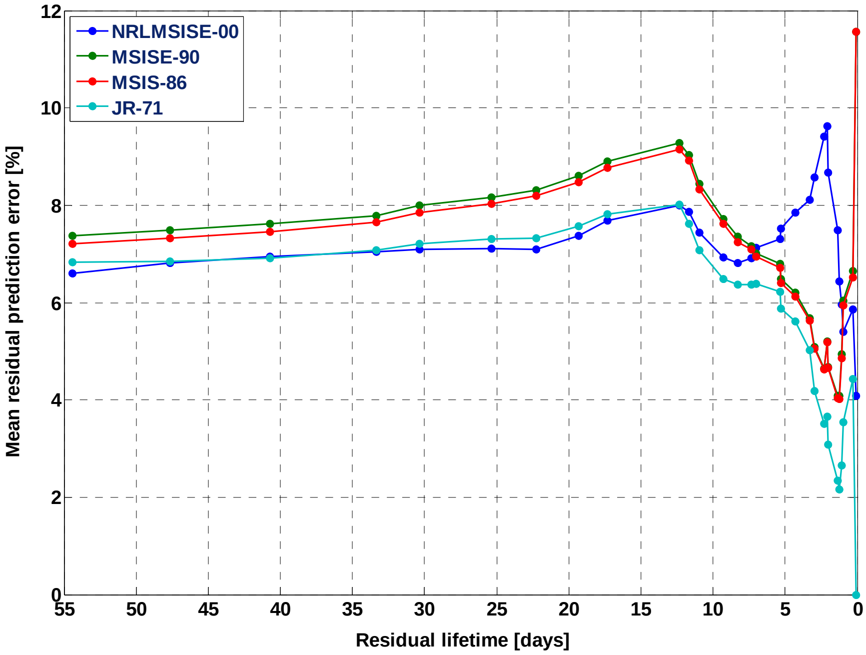

Fig. 6. Evolution of the mean residual relative error in the reentry epoch of Cosmos 1025.

4. THE EAS REENTRY CAMPAIGN

The object chosen for the IADC reentry test campaign 2008-1 was the Early Ammonia Servicer (US Catalog No. 31928; COSPAR ID: 1998-067BA), thrown overboard from the International Space Station on 23 July 2007 (therefore with an orbital inclination of 51.6°), having completed its mission. EAS consisted of two nitrogen tanks that had provided compressed gaseous nitrogen to pressurize the ammonia tank and replenish it, as needed, in the thermal control subsystems of ISS. It also contained additional stocks of ammonia for the American Early External Ammoniac Thermal Control System.

The tank had been launched on STS-105 with Discovery in August 2001. The empty mass was 640 kg, with dimensions of 2.5 m × 1.2 m × 1.7 m. The reentry occurred on 3 November 2008 and, based on the final assessment of the US Space Surveillance Network, it reached the 80 km atmospheric interface at 04:51 UTC, corresponding at 04:58 UTC at the conventional reentry reference altitude adopted by IADC, i.e. 10 km [16]. The solar and geomagnetic activity in the month preceding the reentry are shown in Figs. 7, 8 and 9, respectively.

During the EAS campaign, initiated when the satellite altitude was below 250 km, 34 reentry predictions were carried out by ISTI/CNR. In the first 7 predictions, issued between 28 and 13 days before orbital decay and corresponding to initial perigee altitudes between 239 and 216 km, only JR-71, MSISE-90 and NRLMSISE-00 were used. In the remaining 27 predictions, as soon as the updated set of specific solar indices needed (Fig. 8) became available, courtesy of Space Environment Technologies, JB2006 was used in addition to the other three models.

The ballistic parameters obtained with the four atmospheric density models used for the analysis, by retro-fitting the available TLEs, are shown in Fig. 10. Overall, the trends were similar among the four models, with JB2006 generally providing intermediate values between those obtained with JR-71 and those obtained with MSISE-90 and NRLMSISE-00. These last two showed a quite close agreement, not surprising by considering the common origin, while JR-71, with a few exceptions, systematically presented higher values of *B*, reflecting an intrinsic lower atmospheric density with respect to the other models, in particular MSISE-90 and NRLMSISE-00.

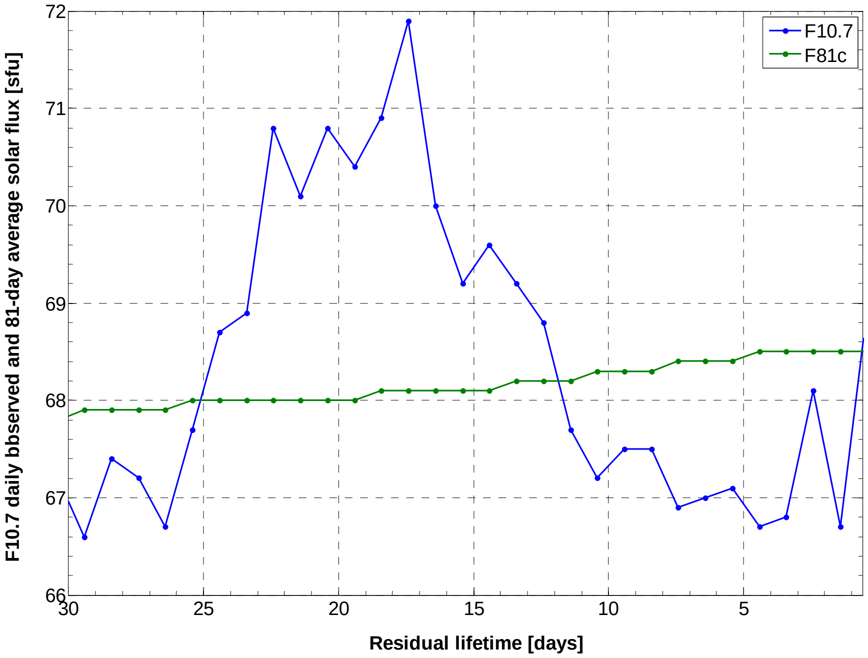

Fig. 7. Solar flux at 10.7 cm and 81-day average during the month preceding the EAS reentry.

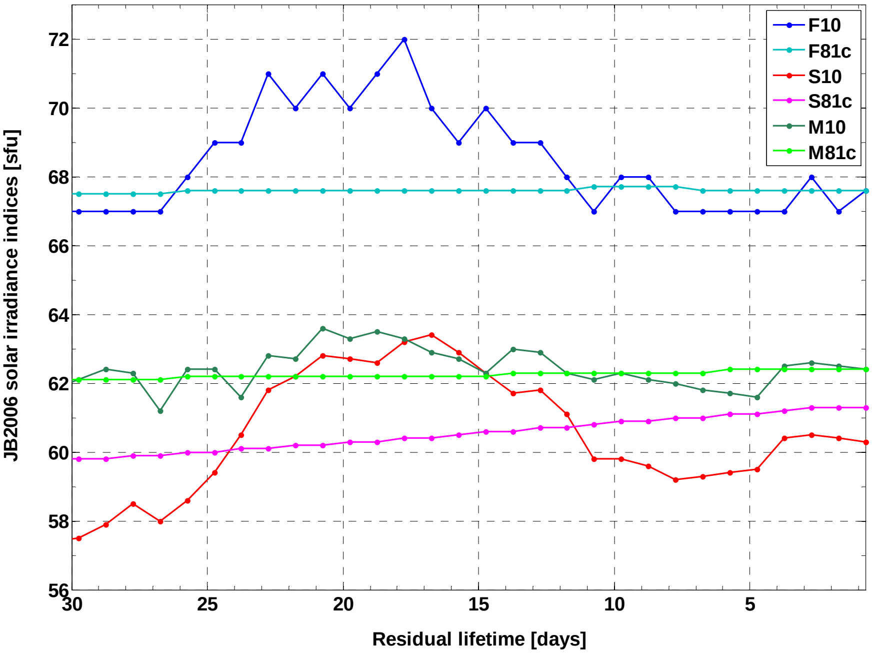

Fig. 8. JB2006 solar irradiance indices during the month preceding the EAS reentry.

The rms residuals in semi-major axis resulting from the TLEs retro-fits are presented in Fig. 11. Even during this reentry campaign they were basically comparable among the models and followed the same trend. JR-71 gave the smallest residuals in 39.4% of the fits, while the corresponding figures for the other models were 27.3% for JB2006, 18.2% for NRLMSISE-00 and 15.1% for MSISE-90.

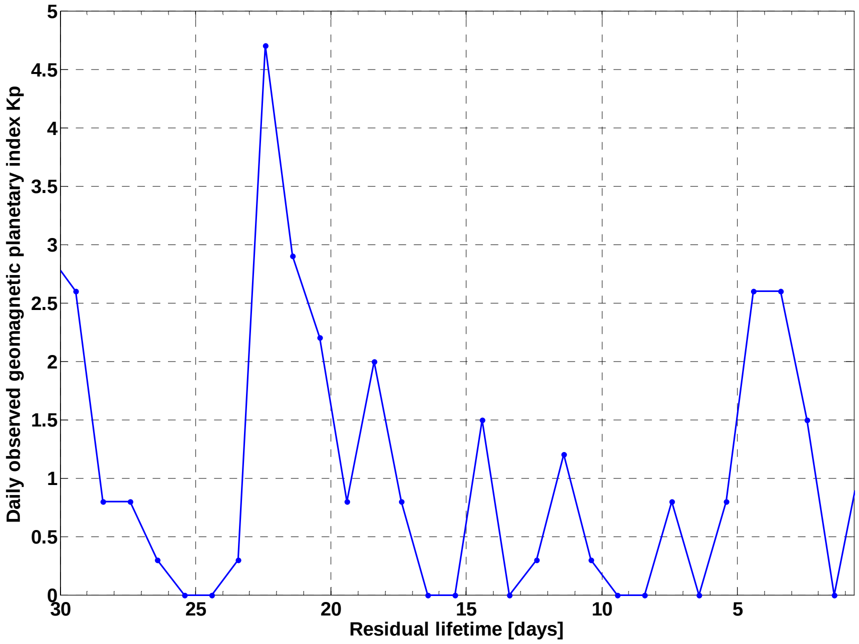

Fig. 9. Geomagnetic activity during the month preceding the EAS reentry.

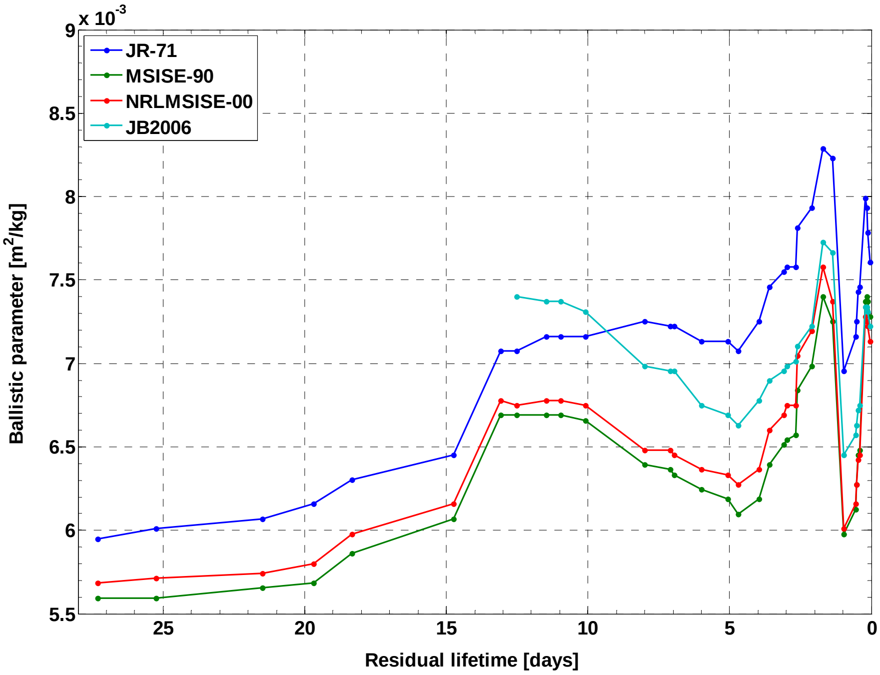

Fig. 10. EAS ballistic parameter estimations.

Fig. 12 shows, for each density model, the evolution of the relative error in the estimation of the residual lifetime. In the first part of the campaign, up to 13 days before reentry, JB2006 was still not operational and the other models displayed a similar behavior, with MSISE-90 very close to NRLMSISE-00. In the second part of the campaign, the behavior of all the models remained similar, but in general MSISE-90 resulted to be closer to NRLMSISE-00 and JR-71 closer to JB2006.

Regarding the mean residual relative error *MPE*, from the current prediction time T_{IN} up to the reentry reference epoch T_{REF}, the results obtained are shown in Fig. 13. Up to approximately 13 days before reentry, corresponding to a perigee altitude of about 216 km, all the three models used were quite close, but JR-71 systematically provided the best mean residual relative errors, between 6% and 8%. As soon as JB2006 was put into action, it resulted the best by a significant margin, in terms of mean residual relative errors, until approximately 0.5 days before reentry, corresponding to a perigee altitude of about 148 km. During the final 12 hours, the best model was, instead, MSISE-90, which had been slightly the worst until 5 days before orbital decay; the highest mean residual relative errors were associated, at this point, at JR-71.

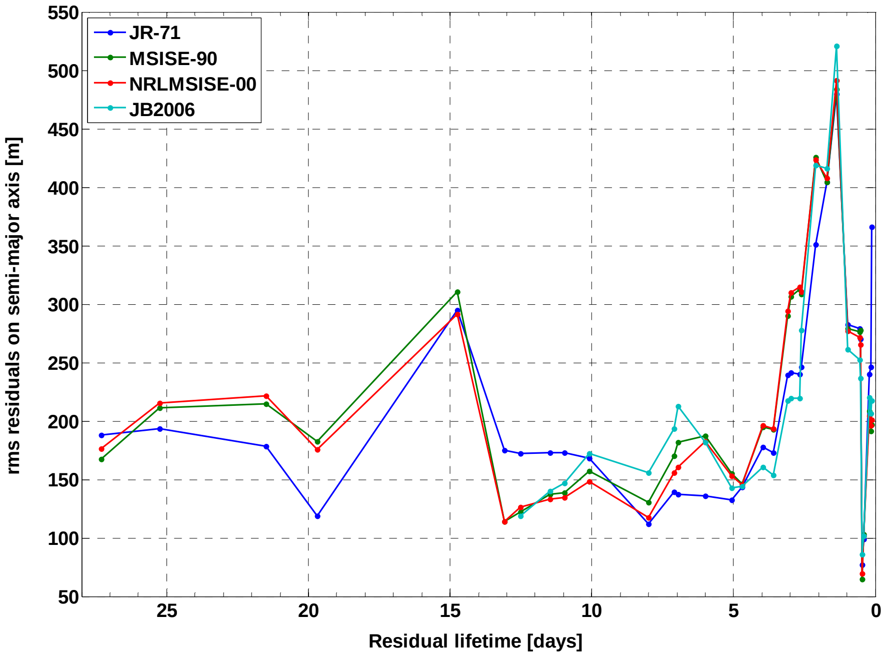

Fig. 11. EAS semi-major axis rms residuals of TLEs fits.

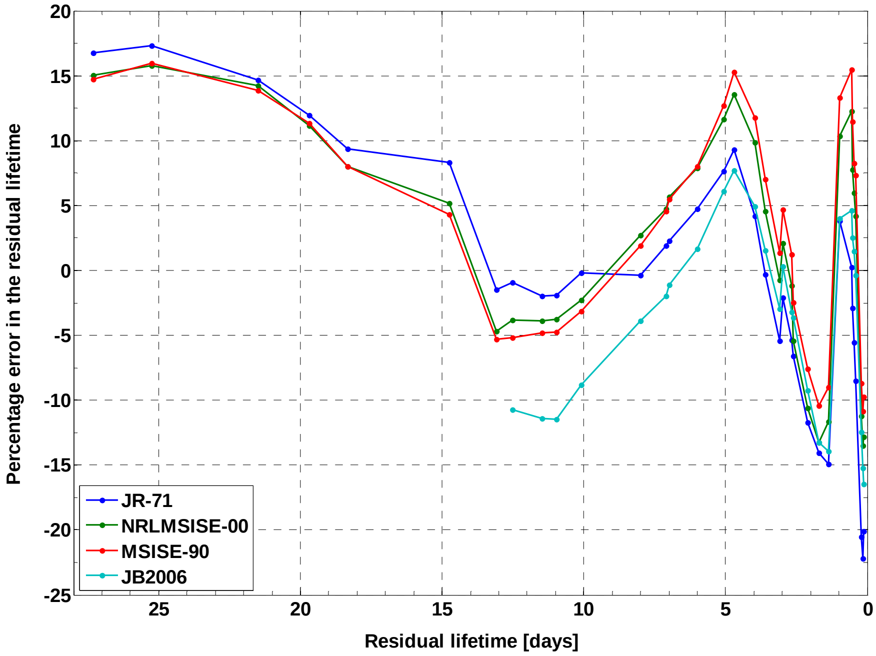

Fig. 12. Evolution of the relative error in the residual lifetime estimation of EAS.

In conclusion, during the EAS reentry campaign, all the atmospheric density models used, under exactly the same conditions and assumptions, provided mean residual relative errors below 10% up to less than three days before re-entry. Afterwards, the relative errors showed a tendency to increase, particularly during the last few hours preceding the final decay. Anyway, from a practical point of view, the final reentry predictions obtained with the various models were very close in absolute terms and compatible among them, as shown in Fig. 14, where all the resulting nominal impact points lie in the JB2006 uncertainty window.

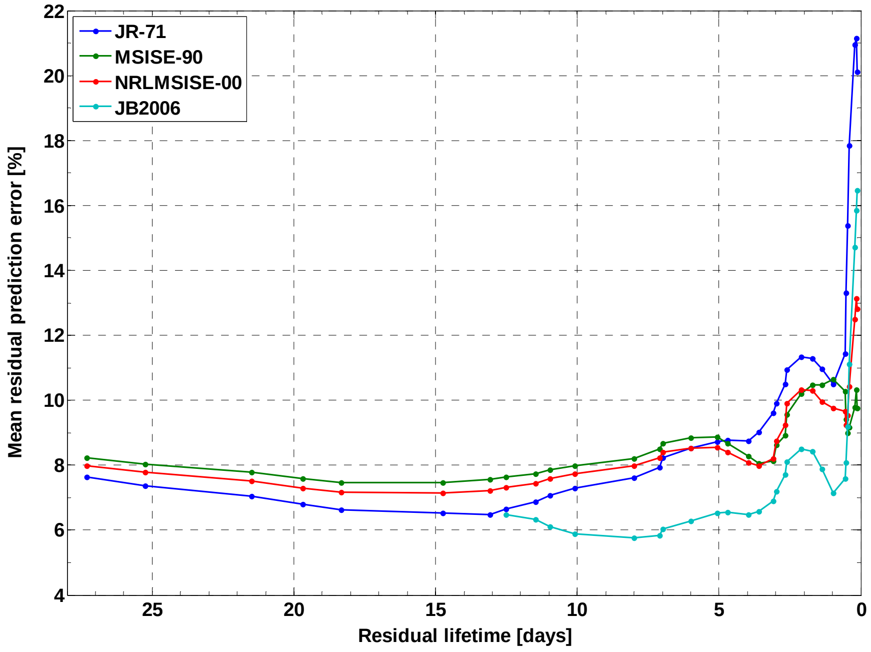

Fig. 13. Evolution of the mean residual relative error in the reentry epoch of EAS.

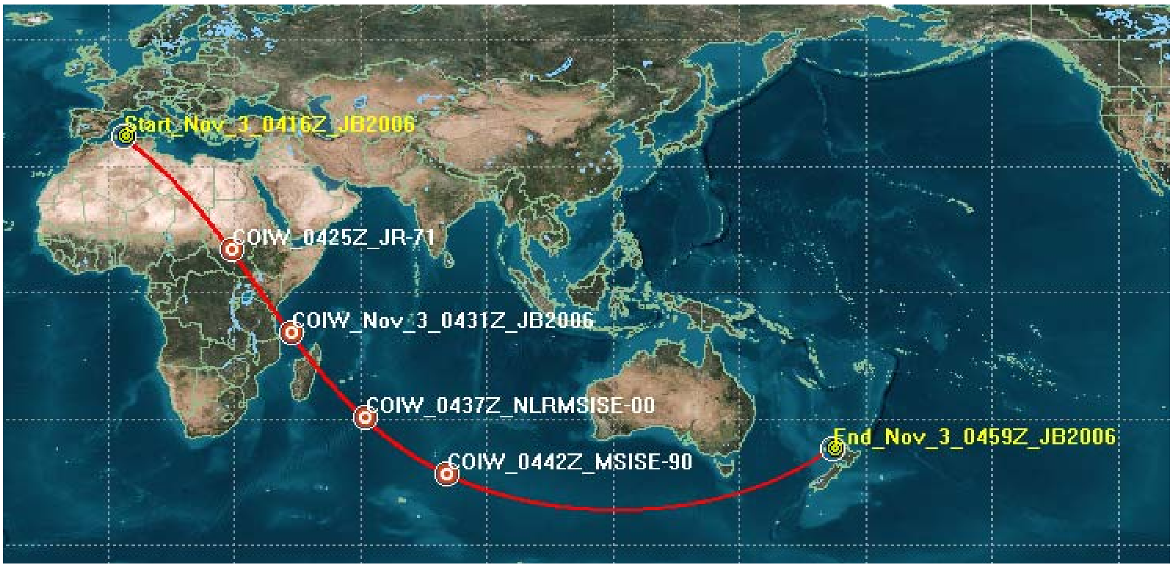

Fig. 14. Last EAS reentry prediction with the TLE of 3 November 2008, 02:14 UTC. The centers of the impact windows (COIW) obtained with the four atmospheric density models are shown, together with the uncertainty window associated to JB2006.

During the EAS campaign, the mean residual prediction error was observed to be generally lower with JB2006, used for the first time in such a context. This might suggest better performances of the JB2006 model in predicting the re-entry time of satellites at sunspot minimum, but further investigations are needed to confirm this result.

5. CONCLUSIONS

The Cosmos 1025 and EAS reentry test campaigns promoted by IADC offered a good occasion to assess the reentry prediction performances, in conditions of low solar activity, of various thermospheric density models used by the astrodynamics community. Some potentially interesting results were obtained, like the still competitive achievements, after nearly 40 years, of JR-71 and the generally lower mean residual prediction errors obtained with JB2006 during the EAS campaign. However, further work and analysis will be needed to confirm these preliminary indications, in particular concerning the lower prediction errors exhibited by JB2006.
Limiting the discussion to the subject of this paper, future research will try to extend the statistical base, to possibly include other models, as JB2008 [4] and the Russian Upper Atmosphere Density Model GOST-2004 [17], and to explore other domains of solar and geomagnetic activity, even far from the quiet conditions characterizing the Cosmos 1025 and EAS orbital decay.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] Anselmo L. and Pardini C., *Computational Methods for Reentry Trajectories and Risk Assessment*, ADVANCES IN SPACE RESEARCH, Vol. 35, 1343–1352, 2005.

[2] Pardini C, Tobiska W.K. and Anselmo L., *Analysis of the Orbital Decay of Spherical Satellites Using Different Solar Flux Proxies and Atmospheric Density Models*, ADVANCES IN SPACE RESEARCH, Vol. 37, 392–400, 2006.

[3] Bowman B.R., Tobiska W.K., Marcos F.A. and Valladares C., *The JB2006 Empirical Thermospheric Density Model*, JOURNAL OF ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS, Vol. 70, 774–793, 2008.

[4] Bowman B.R., Tobiska W.K., Marcos F.A., Huang C.Y., Lin C.S. and Burke W.J., *A New Empirical Thermospheric Density Model JB2008 Using New Solar and Geomagnetic Indices*, Paper AIAA 2008-6438, AIAA/AAS Astrodynamics Specialist Conference, Honolulu, Hawaii, 18-21 August 2008.

[5] Pardini C. and Anselmo L., *Re-entry Predictions for the Spacecraft Cosmos 1025*, Proceedings of the 25th Meeting of the Inter-Agency Space Debris Coordination Committee, Toulouse, France, 2-6 July 2007.

[6] Pardini C. and Anselmo L., *Re-entry Predictions for the Early Ammonia Servicer* (*EAS*), Proceedings of the 27th Meeting of the Inter-Agency Space Debris Coordination Committee, Darmstadt, Germany, 25-27 March 2009.

[7] Cappellari J.O., Velez C.E. and Fuchs A.J. (Eds.), *Mathematical Theory of the Goddard Trajectory Determination System*, NASA/GSFC Report, GSFC X-582-76-77, Greenbelt, MD, USA, 1976.

[8] Hedin A.E., *MSIS-86 Thermospheric Model*, JOURNAL OF GEOPHYSICAL RESEARCH, Vol. 92, 4649–4662, 1987.

[9] Hedin A.E., *Extension of the MSIS Thermosphere Model Into the Middle and Lower Atmosphere,* JOURNAL OF GEOPHYSICAL RESEARCH, Vol. 96, 1159–1172, 1991.

[10] Space Science Division of the Naval Research Laboratory, Upper Atmospheric Physics Branch, Upper Atmospheres Section, web site: uap-www.nrl.navy.mil/uap, 2009.

[11] Pardini C. and Anselmo L., *SATRAP*: *Satellite Reentry Analysis Program,* Internal Report C94-17, CNUCE Institute, CNR, Pisa, Italy, 30 August 1994.

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

[13] Tobiska W.K., Bower S.D. and Bowman B.R., *The Development of New Solar Indices for Use in Thermospheric Density Modeling*, JOURNAL OF ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS, Vol. 70, 803–819, 2008.

[14] Pardini C. and Anselmo L., *On the Accuracy of Satellite Reentry Predictions*, ADVANCES IN SPACE RESEARCH, Vol. 34, 1038–1043, 2004.

[15] Pardini C. and Anselmo L., *Impact of the Time Span Selected to Calibrate the Ballistic Parameter on Spacecraft Re-entry Predictions*, ADVANCES IN SPACE RESEARCH, Vol. 41, 1100–1114, 2008.

[16] *Terms of Reference for the Inter-Agency Space Debris Coordination Committee (IADC)*, Inter-Agency Space Debris Coordination Committee (IADC), web site: www.iadc-online.org, 4 October 2006.

[17] Volkov I.I., *Earth's Upper Atmosphere Density Model for Ballistic Support of the Flight of Artificial Earth Satellites*, GOST R 25645.166-2004, The Official Edition, National Standard of the Russian Federation, State Committee on Standardization and Metrology of Russian Federation, Moscow, Russia, 2004 (in Russian).