PILOT SERVICE FOR IMPROVING SATELLITE RE-ENTRY PREDICTIONS AND ORBITAL DECAY MODELING

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ABSTRACT/RESUME

This paper briefly describes the content of the proposal submitted by ISTI, an Institute of the Italian National Research Council (CNR), in response to the ESA/ESTEC AO/1-4246/02/NL/LvH on Pilot Project for Space Weather Applications.

The principal aim of the envisaged work is to study, test and evaluate a space weather service to improve the satellite orbital decay modeling and the accuracy of re-entry predictions. The limitations of the currently used atmospheric density models and solar flux proxies will be investigated in quantitative detail and compared with the potential advantages of using a new temperature equation in the Jacchia-Roberts 1971 model and the $E_{10.7}$ parameter, from the SOLAR2000 project, to represent the solar flux.

1. INTRODUCTION

The Istituto di Scienza e Tecnologie dell'Informazione "Alessandro Faedo" (ISTI) – formerly CNUCE – is an institute of the Italian National Research Council (CNR). Since 1979, its Space Flight Dynamics Laboratory has been in charge of the re-entry predictions of potentially dangerous space objects for the Italian civil defence authorities. Following the fiery re-entry of the American space station Skylab, in 1979, the institute has been involved in the re-entry campaigns of several potentially risky and/or interesting space objects. Consolidating the leading role played in the field, a Space Object Monitoring Service (SMOS) was activated at ISTI, in 1994, to provide the national agencies and the government with advice and support on space debris and re-entry technical topics. Moreover, on the Italian Space Agency (ASI) behalf, the ISTI Space Flight Dynamics Laboratory participated to the four re-entry test campaigns promoted, in between 1998 and 2002, by the Inter-Agency Space Debris Coordination Committee (IADC). It has been in the framework of all these activities that special techniques, software tools and operational procedures have been developed and are continually being upgraded.

SATRAP, the SATellite Reentry Analysis Program [1], 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) [2]; Termosphere Density model 1988 (TD-88) [3]; Mass Spectrometer Incoherent Scatter model 1986 (MSIS-86) [4] and Mass Spectrometer Incoherent Scatter Extended model 1990 (MSISE-90) [5] – along with the possibility of directly processing the US Space Command (USSPACECOM) Two-Line Elements (TLE) which, for uncontrolled re-entries, are often the only source of orbital information available.

The proposed work will be aimed at highlighting the discrepancies and weak points of the SATRAP density models so as to improve both the confidence levels of the re-entry predictions and the satellite orbital decay modeling. Moreover, it will investigate whether the use of the $E_{10.7}$ index [6, 7, 8, 9], instead of the traditional $F_{10.7}$ cm radio flux, reduces the uncertainties in the residual lifetime estimations, when applied in both "a posteriori" and predictive analyses. Therefore, the limitations of the most widely used density models JR-71 and MSIS-86/90 will be compared with the potential advantages of using a reformulated nighttime minimum exospheric temperature in the JR-71 model and the $E_{10.7}$ parameter to represent the solar flux.

2. THE ENVISAGED PARTNERSHIP

SATRAP's atmospheric density 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 present, the daily observed $F_{10.7}$ cm radio flux and the A_P (or K_P) geomagnetic index are used in SATRAP. Their past values are obtained from the NOAA National Geophysical Data Centre (NGDC), while their current and forecast values are acquired from the NOAA Space Environment Centre (SEC), both located in Boulder, Colorado (US). Since the solar EUV radiation is not available, the $F_{10.7}$ cm flux is used as a useful proxy by most thermospheric models, therefore introducing additional sources of uncertainty due to a solar flux index not directly correlated to the solar ultraviolet irradiance.

Fortunately, reliable studies and researches have been carried out in the last few years to produce a solar flux proxy based on a full spectrum model of EUV solar emissions. The new parameter, $E_{10.7}$, has the same units as the commonly used $F_{10.7}$ index and can be used in the existing atmospheric density models in place of the $F_{10.7}$ flux. The $E_{10.7}$ daily index has been developed by the Space Environment Technologies (SET) SpaceWx Division in Los Angeles, California, and is supplied to NOAA/SEC through a Cooperative Research and Development Agreement (CRADA). By legal agreement, NOAA/SEC does not provide forecast or high time resolution solar irradiances data and has given that task to SET. On the other hand, SET needs a support contract to provide the users with the current and forecast data products such as $E_{10.7}$.

For the highlighted reasons, ISTI envisaged a cooperation agreement with the SET SpaceWx Division. On the basis of this cooperation, ISTI would become the user of the services provided by SET in the form of daily historical, nowcast and forecast values of the parameter $E_{10.7}$. SET would also provide consultancy and assistance with using the reformulated exospheric temperature equation in the JR-71 model.

2.1 Background SET Experience

Space Environment Technologies' SpaceWx Division was spun-off in 2001 from a similar-named division in Northrop Grumman/Logicon. SpaceWx developed the world's first commercial operational solar irradiance specification system that provides historical, nowcast, and forecast solar irradiances from the SOLAR2000 model. This model has been developed as a scientifically collaborative project [9] for accurately characterizing solar irradiance variability across the spectrum. The overarching scientific goal of SOLAR2000 is to understand how the sun varies spectrally and through time from X-ray to infrared wavelengths.

Two major customers of the SOLAR2000 irradiance product include the NOAA Space Environment Center, where SET contractually provides an operational solar irradiance specification system, and the USAF ISC2/HASDM project administered by Lockheed Martin, where SET provides nowcast/forecast solar proxies and geomagnetic indices.

2.2 SET Roles and Services

SET will be acting as a service provider to ISTI supplying:

- data services, in the form of daily historical, nowcast and forecast values of the parameter $E_{10.7}$ from the SOLAR2000 model;
- consultancies and assistance in revising the nighttime minimum exospheric temperature formulation, for use in the JR-71 model, and in comparing the new and traditional temperature formulations in an "a posteriori" analysis.

3. $E_{10.7}$ AVAILABILITY AND APPLICATIONS

$E_{10.7}$ is the integrated solar EUV energy flux at the top of the atmosphere and is reported in units of the $F_{10.7}$ cm solar radio flux. $E_{10.7}$ is designed to substitute for $F_{10.7}$ in all models that use the latter proxy, but it offers significant improvement as an index of the energy input to the thermosphere and ionosphere. Recent studies have demonstrated that $E_{10.7}$ improves the solar component of the atmospheric heating when compared with $F_{10.7}$ [8].

The $E_{10.7}$ historical values are available from February 14th, 1947, to a few weeks prior to current epoch. Fig. 1 shows an example of the historical daily values of $E_{10.7}$ over five solar cycles.

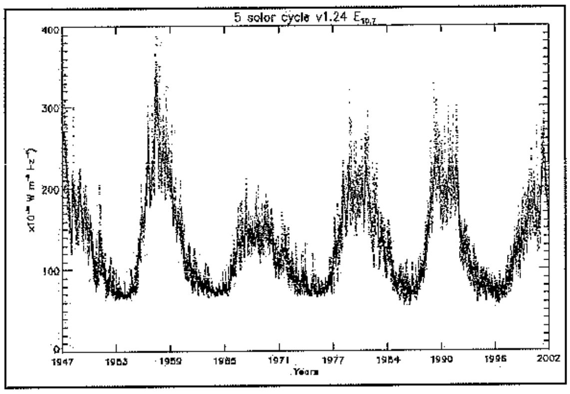

Fig. 1. $E_{10.7}$ over the five past solar cycles

An "a posteriori" analysis of the orbital decay of a set of spacecraft will be accomplished by using the historical $E_{10.7}$ indices. Therefore, the results of this analysis will be first compared with the results obtained using the $F_{10.7}$ historical daily values and, subsequently, with the observed orbital decay. In this way the solar flux proxy more accurately describing the sun-atmosphere interaction will be identified.

The nowcast values of $E_{10.7}$ are generally provided 24-hours ago to current time, while the index forecast values are given from the current epoch to five solar cycles in the future. Fig. 2 shows an example of recent and forecast $E_{10.7}$ values compared to those of $F_{10.7}$.

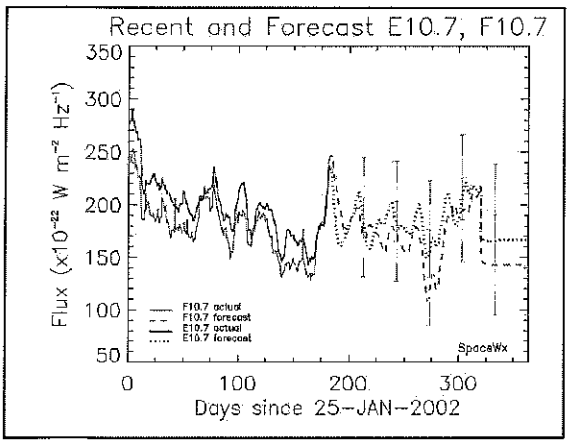

Fig. 2. $E_{10.7}$ recent and forecast values

The nowcast and forecast values of $E_{10.7}$ (and $F_{10.7}$) will be used in predicting the orbital decay of a set of space objects. Even in this case, the results obtained, using both $E_{10.7}$ and $F_{10.7}$, will be compared and examined to identify the more accurate solar flux proxy.

4. LOGIC OF THE WORK

The aim of the work proposed will be to study, test and evaluate a space weather service in order to improve:

- the satellite orbital decay modeling and, consequently, the orbit determination and propagation accuracy;
- the accuracy of the re-entry predictions of risky space objects.

Such an activity, whose logic is summarized in the flow chart of Fig. 3, will be described in the following sections.

4.1 Comparison and Accuracy Assessment of Atmospheric Density Models

The limitations of the atmospheric density models (JR-71, MSIS-86/90) and solar flux proxies ($E_{10.7}$, $F_{10.7}$) will be investigated through an "a posteriori" analysis of the orbital decay of a sample of space objects, the orbital state evolution of which is known. The sample of space objects will encompass a broad range of orbital altitudes and inclinations, while the time interval examined will cover different solar activity conditions. Such an analysis will also allow to check the performances of the daily historical values of the new $E_{10.7}$ parameter.

4.2 Improvement of the Atmospheric Density Specification

A reformulated nighttime minimum exospheric temperature (T_c) will be incorporated in the JR-71 model. Two new T_c formulations will be tested and compared among them and with the current traditional formulation. The new temperature equations will be those from Bowman, that use $E_{10.7}$ and $F_{10.7}$ in the 2nd degree polynomial fits to the exospheric temperature from the US HASDM (High Accuracy Satellite Drag Model) project [10, 11].

The comparison between the new and traditional T_c formulations for JR-71 in "a posteriori" analysis will occur:

i. first through $F_{10.7}$ and $E_{10.7}$ comparison with measured solar EUV energy flux for AE-E, SNOE, and TIMED/SEE satellite data sets, to provide a knowledge base of how the solar EUV energy is behaving for a variety of solar activity conditions; and

ii. second through $F_{10.7}$ and $E_{10.7}$ placed in the T_c equation to provide densities for comparison with an ensemble of known reference densities from low-latitude, well-characterized ballistic coefficient spacecraft.

4.3 Assessing the Confidence Levels of Re-entry Predictions

A sample of spacecraft that have still not re-entered the Earth atmosphere, but are approaching the re-entry conditions in the course of this work, will be identified to predict their re-entry time. For each of these objects, atmospheric density model and solar flux proxy, the re-entry predictions will be computed at certain times (i.e. one month, one week, one day, etc.) before the final orbital decay.

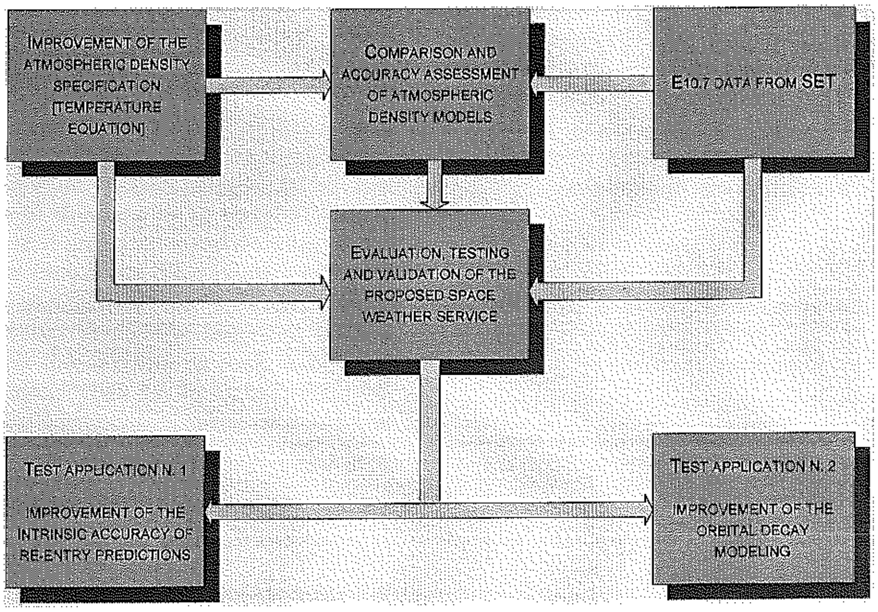

Fig. 3. Logic of the envisaged work

The estimated re-entry times will then be compared with the observed re-entry date, usually provided by the NASA/GSFC Orbital Information Group in its "Decay Prediction Report". The differences between estimated and observed re-entry times will be correlated to the air density model uncertainties and/or to the use of specific solar flux proxies – $E_{10.7}$ or $F_{10.7}$ – to represent the solar influences on the Earth's atmosphere.

As a part of this study, the accuracy of the nowcast and short-term forecast values of the $E_{10.7}$ index will be tested.

4.4 Test Applications

The results of the previous analyses will be applied to evaluate, test and validate a space weather service aimed at more realistically describing the atmospheric density, along with the solar-terrestrial interactions affecting its structure and composition.

Using the results obtained, two test applications are foreseen: the first one to improve the intrinsic accuracy of the re-entry predictions, the second to more accurately model the satellite orbital decay due to air drag. While the results of the first application might helpfully provide the scientific community with information and instructions to reduce the overall uncertainty of the re-entry prediction process, the outcomes of the second activity might be advantageous both for orbit determination (improvement of the solution; reduction of residuals) and trajectory prediction (improvement of the accuracy).

5. TECHNICAL DESCRIPTION OF THE WORK

A lengthy comparison and assessment of the accuracy of the semi-empirical air density models JR-71 and MSIS-86/90 will be carried out by analyzing the orbital decay of a sample of space objects encompassing a broad range of orbital altitudes (150 – 1500 km) and inclinations. The examined time interval will cover at least a full solar activity cycle, while two solar flux proxies ($E_{10.7}$ and $F_{10.7}$) will be used to describe the solar interaction with the earth's atmosphere. All the activities have already been discussed in section 4. So, only the mathematical approach, used to solve some technical problems, will be highlighted in this section. In particular, some information about the achievement, processing and propagation of orbital data will be given.

5.1 Sources of Orbital Data

For each spacecraft considered, the historical record of the US Space Command (USSPACECOM) two-line elements (TLE) will be acquired from the NASA/GSFC Orbital Information Group (OIG). The observed time evolution of the mean semi-major axis will be computed by converting these elements to an osculating position and velocity with the appropriate models [12].

5.2 Ballistic Parameter Estimation

For each space object, environmental condition (i.e. solar activity level), orbital regime, atmospheric model and solar flux proxy adopted, a ballistic parameter, defined according to the relationship

$$B = \frac{C_D A}{M} \quad (1)$$

(where A, M and C_D are, respectively, the space object average cross-section, mass and drag coefficient) will be estimated by backward fitting, in a least squares sense, the semi-major axis decay described by the historical two-line elements.

5.3 Semi-major Axis Residuals

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

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

where a_{i_obs} and a_{i_com} are, respectively, the observed and computed semi-major axis at the same epoch and N is the number of observations available, i.e. the number of TLE used in the fitting.

5.4 Orbit Propagation

SATRAP [1] will be used to predict the orbital state evolution of each space object considered. SATRAP is a numerical orbital predictor that uses the Cowell's method to solve the equations of motion and a single step 8^{th} order Runge-Kutta method for their numerical integration.

The main orbital perturbations can be modeled: zonal and tesseral harmonics – up to the 40^{th} degree and order – third body attraction of the moon and the sun, solar radiation pressure (with eclipses), and aerodynamic drag.

For each spacecraft, atmospheric density model and corresponding computed ballistic parameter, the TLE relative to a pre-selected initial epoch will be propagated with SATRAP to compute the satellite orbital evolution.

5.5 Assessing the Intrinsic Accuracy of Air Density Models

Spherical satellites will be used to assess the accuracy of the examined air density models. In fact, being they characterized by a constant mass-to-area ratio, their drag coefficients can be computed according to Eq. 1 whenever this ratio is known. Therefore, for each spherical satellite, orbital regime and environmental conditions, the drag coefficients obtained by fitting the observed semi-major axis decay with the various atmospheric models will be compared with each other and with a theoretical estimation of the drag coefficients. The deviations observed will be directly correlated to model discrepancies and uncertainties in the computation of the atmospheric density.

6. TECHNICAL GOALS

The aim of the proposed activity is to demonstrate the advantage of using the modified JR-71 model (including a new formulation of the exospheric temperature) and the new solar flux proxy $E_{10.7}$ to potential astrodynamics users in the field of orbit determination and prediction.

The results of this activity might be also very useful for scientists and engineers involved in the difficult task of predicting the re-entry time of potentially dangerous space objects.

7. STRATEGY FOR FURTHER DEVELOPMENTS

Further developments in the field of air density modeling have recently led to the formulation of the new empirical atmospheric model NRLMSISE-00 [13]. The database underlying the NRLMSISE-00 model incorporates data on total mass density, based on orbital drag and satellite accelerometers, new incoherent scatter radar observations covering more than a solar cycle and data from the Solar Maximum Mission (SMM). When compared to the respective types of data on which the MSIS-86/90 and JR-71 models are based, the model incorporates the strengths of each data set. We are planning in the future to implement this model in SATRAP with the $E_{10.7}$ parameter to represent the solar flux. We also intend to include the Russian GOST [14, 15] model in our software. This model is constructed empirically from observations of the orbital motion of Russian Cosmos satellites and can be envisaged as an independent source of information on the structure and properties of the upper atmosphere.

However, to really improve the global models used in astrodynamics computations, in a wide range of altitudes and environmental conditions, a lot of work has still to be done. Studies like the one proposed might be useful to highlight the discrepancies and weak points of the current air density models and parameters adopted to model the solar-terrestrial interactions. As a matter of fact, analyses of this type could be very helpful to identify and/or formulate the best models and assumptions and, of course, to improve the results whenever their conclusions are applied. Nevertheless, they generally require a lot of time to be spent in lengthy and massive comparisons and assessments, as well as in estimating appropriate environmental indices, like the solar flux proxy $E_{10.7}$. These are the main reasons why activities like those described in our proposal demand adequate funding to be taken on.

Our draft proposal was well received by the European Space Agency. However, the final proposal was not included among those to be funded by the Space Weather Applications Pilot Project. We look forward to carry out all the envisaged work in the future, while continuing to improve, in the meantime, our knowledge and experience in these important fields of astrodynamics and space weather applications.

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