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COMPARISON OF THERMOSPHERIC DENSITY MODELS BY SATELLITE ORBITAL DECAY ANALYSIS

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ABSTRACT

Some of the most widely used thermospheric density models (JR-71, MSIS-86, MSISE-90, TD-88) were compared, by analyzing the decay histories of nine satellites. The satellite sample and the time interval examined encompassed a broad range of altitudes (200-1500 km) and solar activity levels (1987-1999).

The MSIS models, practically identical above 200 km, resulted to be the best ones to compute air density below 400 km, in low solar activity conditions. JR-71 seemed to be more accurate at greater altitudes and/or solar fluxes. TD-88 gave quite mixed performances, but generally closer to the JR-71 results. The intrinsic accuracy of JR-71, MSIS-86 and MSISE-90 was generally better than 20%, and sometimes close to 10%. This picture resulted progressively degraded at altitudes greater than 400 km.

INTRODUCTION

The SATellite Reentry Analysis Program (SATRAP)[1], developed at CNUCE to forecast the orbital decay of uncontrolled low earth satellites, includes a selection of semi-empirical atmospheric density models: Jacchia-Roberts 1971 [JR-71][2], Thermosphere 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].

The aim of the semi-empirical models is to represent a large quantity of data collected by various techniques and to describe thermosphere parameter variations. Those of Jacchia were mainly based on total density data derived from satellite orbital decay observations. The Mass Spectrometer Incoherent Scatter models were derived by combining satellite in-situ composition measurements and thermosphere temperatures inferred from ground-based incoherent scatter radars. A common feature of all these models is the use of relatively simplified physical concepts to describe the atmospheric density variations as a function of altitude, solar and geomagnetic activity, latitude, longitude, local time and day of the year. However, significant differences between the models remain, because they are based on distinct data sets, covering different time periods and geographic areas. Another intrinsic limitation of each model includes the use of the solar flux at 10.7 cm ($F_{10.7}$) and the geomagnetic planetary indices (K_P, A_P) as proxy indicators to represent the solar and geophysical influences on the atmosphere[6].

Reducing the semi-empirical model errors has proven to be very difficult, but the accuracy of each model can be evaluated through the orbital decay analysis of satellites of known shape, size, mass, attitude and orbital state evolution. Following this approach, an extensive calibration of the semi-empirical air density models included in SATRAP was carried out. The analysis was based on the decay histories of nine spherical satellites, of known orbital state evolution and physical characteristics (size and mass). The satellite sample and the time interval examined encompassed a broad range of altitudes and solar activity levels.

DRAG COEFFICIENT

At low altitude, where the residual air molecular flow is hyper-thermal and the atmosphere is rich in atomic oxygen, the drag coefficient for a spherical satellite should be 2.07 – 2.40[7-9]. At greater heights, the drag coefficient increases, due to a change in atmospheric composition, with the progressive prevalence of helium and hydrogen atoms, and to the violation of the hyper-thermal flow assumption[8].

At about 500 km there is a clear transition, whose magnitude is a function of the solar activity level, which affects the average composition and temperature of the high atmosphere[10]. At low solar activity levels, the drag coefficient of a sphere assumes a value close to 2.8 – 2.9 at 800 km and 3.0 – 3.1 at 1000 km, while the corresponding values during high solar activity conditions are about 2.4 – 2.5 and 2.7 – 2.8, respectively[10]. At an altitude of 1500 km the same values may apply, just increased by a further small amount. In any case, uncertainties of the order of 15% are to be taken into account.

ORBITAL DECAY DATA ANALYSIS

In order to test the atmospheric density models included in SATRAP, the historical record of the NORAD two-line elements for nine spherical satellites was obtained from the NASA/GSFC Orbital Information Group. The data were processed, using the appropriate NORAD models[11], to obtain the observed time evolution of the mean semimajor axis.

For each satellite, environmental condition (i.e. solar activity level), orbital regime and atmospheric model adopted, a drag coefficient was obtained by fitting with SATRAP the observed evolution of the mean semimajor axis resulting from the historical two-line elements record. The trajectory propagations included all the principal orbital perturbations (i.e. earth gravity harmonics, luni-solar attraction, solar radiation pressure and, of course, aerodynamic drag), and the observed daily values of the geomagnetic index A_P and the solar flux at 10.7 cm.

The drag coefficients obtained were then compared among them and with the theoretical predictions appropriate for the altitude and solar activity conditions encountered by the satellites. The deviations observed were therefore directly correlated to the model discrepancies and uncertainties in the estimation of the atmospheric density. The nine spherical satellites used are listed in Table 1.

Table 1. Spherical satellites used for the orbital decay analysis

SATELLITE NAME	SATELLITE MASS [kg]	CROSS SECTION [m^2]
GRIDSPHERE	37	0.8703
AJISAI	685	3.6305
STELLA	48	0.0452
ODERACS A	1.48	0.0081
ODERACS B	1.48	0.0081
ODERACS E	5.00	0.0182
ODERACS 2A	5.00	0.0182
GFZ 1	20	0.0363
STARSHINE	39	0.1810

Table 2 shows the orbital parameters corresponding to the first NORAD two-line elements set available. In addition to semimajor axis (SMA) and inclination (INC), the perigee (PH) and apogee (AH) heights are given as well. Six satellites were below 400 km, two in between 750 and 900 km and one close to 1500 km.

Table 2. Initial orbital parameters

SATELLITE NAME	SMA [km]	INC [deg]	PH [km]	AH [km]
GRIDSPHERE	7204.1	87.6	762.5	889.5
AJISAI	7866.9	50.0	1478.5	1499.1
STELLA	7176.7	98.7	794.7	802.5
ODERACS A	6723.4	56.9	339.8	350.6
ODERACS B	6724.7	56.9	342.3	350.7
ODERACS E	6726.4	56.9	347.1	349.4
ODERACS 2A	6718.9	51.6	331.6	349.9
GFZ 1	6767.8	51.6	378.9	400.3
STARSHINE	6766.8	51.6	381.7	395.7

The orbital decay of the satellites was investigated at high, medium and low solar activity levels, during a full solar cycle, above 750 km. Below 400 km, the analysis was only possible at medium and low solar activity conditions.

RESULTS

Above 700 km, the atmosphere density models compared were JR-71, MSIS-86 and MSISE-90. Below 700 km, it was also possible to include in the analysis TD-88, defined only at low altitudes[3].

Two types of comparison were carried out: between the models themselves, and with respect to the theoretical drag coefficient estimations. Around 1500 km of altitude (Figure 1), and in low solar activity conditions, comparable results were obtained with JR-71 and the MSIS family of models. However, assuming that the theoretical estimations of the drag coefficient were realistic, both models underestimated the local air density by 30-50%. In high solar activity conditions, the MSIS models predicted an air density lower by 20-25% with respect to JR-71; on the other hand, JR-71 seems to underestimate the actual atmospheric density, at most, by 10-15%.

Around 800 km the situation looks better (Figure 2). Again, in low and medium solar activity conditions, MSIS and JR-71 gave similar results, with discrepancies lower than 10%. The agreement with the environment density was probably affected by an uncertainty of the same amount. In conditions of high solar activity, JR-71 resulted closer to the theoretical estimates of the drag coefficient, while the MSIS models predicted an air density lower by 15-20%.

Below 400 km (Figure 3) six satellites were analyzed. At low solar activity, all the models seem to overestimate the local air density. The drag coefficient obtained with the MSIS models resulted closer to the theoretical estimations, even though lower by 10-20%. Both JR-71 and TD-88 gave, typically, even smaller values. At moderate solar activity, the drag coefficients obtained with JR-71 and TD-88 were closer to the values inferred from the theoretical estimates. However, an intrinsic uncertainty of the order of 10-15% remained.

Below 300 km, the atmospheric models displayed closer predictions. At low solar activity, typical discrepancies lower than 15% were observed, with JR-71 and MSIS very close. These models probably describe the real environment with an accuracy of 15%. At moderate solar activity, the resulting picture was practically the same for JR-71 and MSIS, while TD-88 provided significantly diverging results below 250 km.

Fig. 1. Comparison of Atmospheric Models at 1500 km

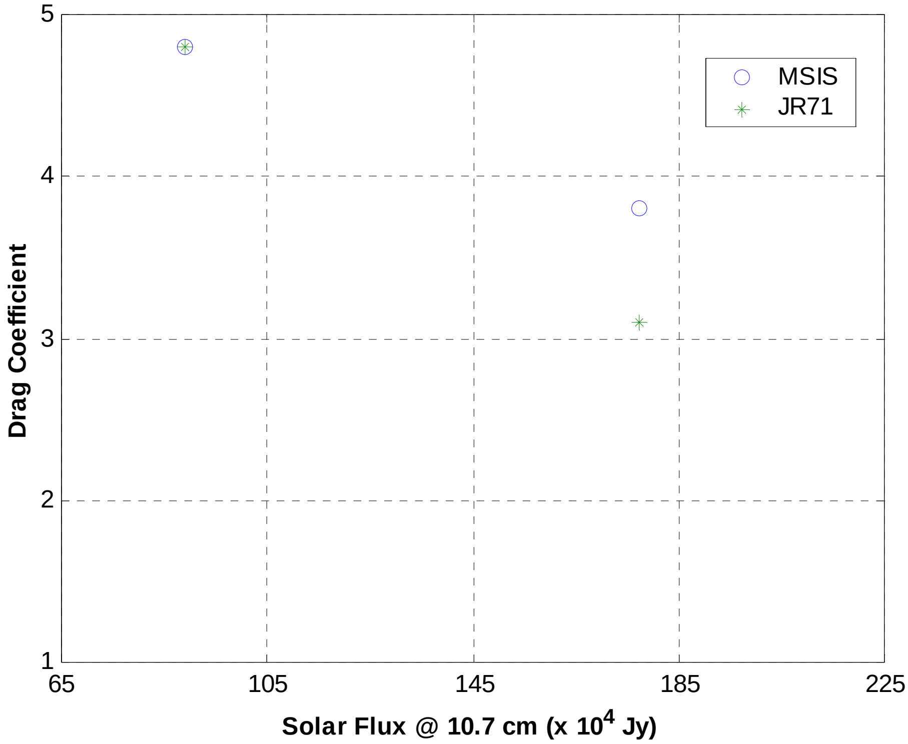


Fig. 2. Comparison of Atmospheric Models at 800 km

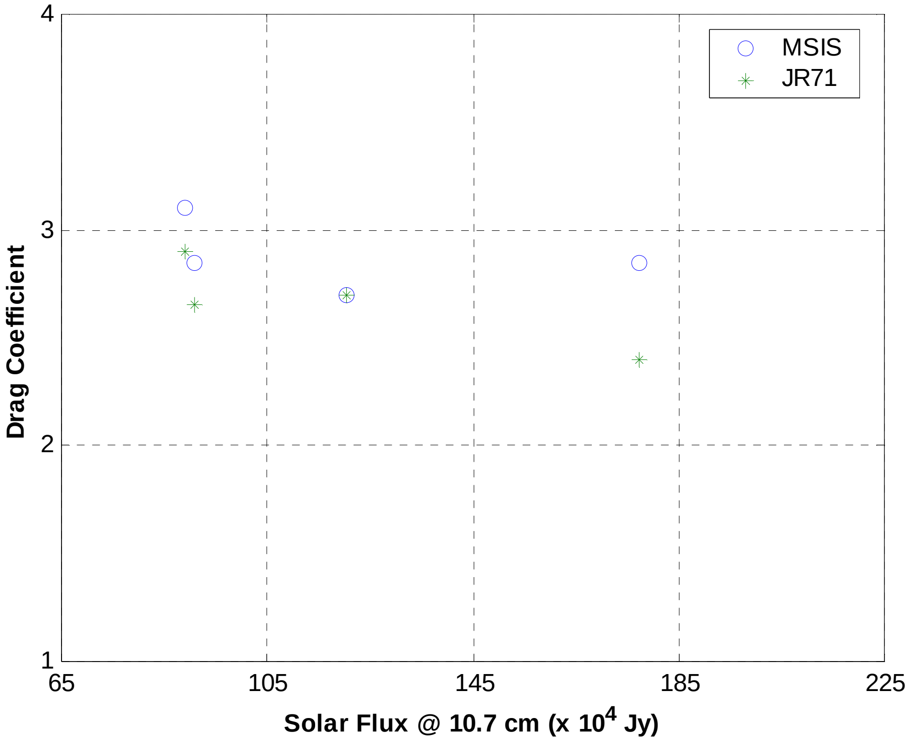
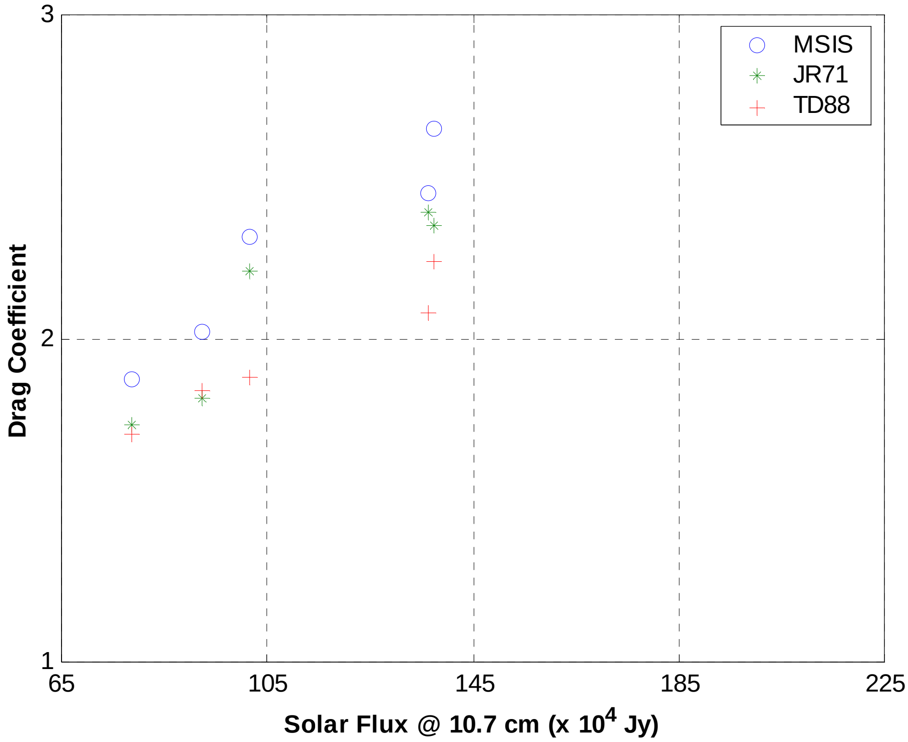


Fig. 3. Comparison of Atmospheric Models below 400 km



CONCLUSIONS

An extensive calibration of semi-empirical atmosphere density models was carried out, by analyzing the orbital decay of nine spherical satellites in the 200-1500 km altitude range. The orbital decay data used spanned a full solar activity cycle (1987-1999).

If the drag coefficients estimated on the basis of theoretical analysis are assumed, the conclusion is that no model, between those considered in this study, is currently able to correctly compute the atmospheric density at every altitude and solar activity condition. While MSIS-86 and MSISE-90 give practically the same results above 200 km, and may be considered the best models to compute the air density below 400 km and in low solar activity conditions, JR-71 seems to be more accurate at greater altitudes and/or solar fluxes. TD-88, defined only below 700 km, gave quite mixed performances, but generally closer to the JR-71 results. These conclusions confirm the outcomes of earlier studies[12].

The intrinsic accuracy of JR-71, MISIS-86 and MSISE-90 is generally better than 20%, often better than 15% and, in certain instances, close to 10%. But this picture, valid below 400 km, seems to progressively degrade at greater altitudes, up to 1500 km, the upper limit of this analysis. Moreover, the modeling of air drag on simple shape satellites may be affected by complex and not fully understood phenomena.

An improvement of the theory aimed at estimating the drag coefficients of simple shape objects, as a function of orbital altitude and environmental conditions, together with dedicated laboratory measurements, are necessary and recommended to more accurately investigate the deficiencies of the actual atmospheric density models. This progress is desirable to improve the knowledge of the physical circumterrestrial environment and, consequently, to augment the reliability of satellite lifetime and reentry predictions.

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