Consideration of Solar Activity in Models of the Current and Future Particulate Environment of the Earth

H. Sdunnus[1], H. Stokes[2], R. Walker[2], J. Bendisch[3], H. Klinkrad[4]

[1] *eta_max space, Technologiepark Braunschweig, Rebenring 33, 38106 Braunschweig, Germany*
[2] *Space Debris Group, Space Department, DERA, Farnborough, Hampshire,GU14 0LX, UK, United Kingdom*
[3] *Institute for Flight Mechanics and Spaceflight Technology, Hans Sommer Str. 5, 38106 Braunschweig, Germany*
[4] *ESA/ESOC, Robert Bosch Str.5, 64293 Darmstadt, Germany*

1 ABSTRACT

Modelling the particulate environment of the earth and the resulting impact risk to space missions has become an important part of mission planning. Though in most small-size particle regimes the number of natural particles, i.e. meteoroids exceeds the number of man made debris particles by far, the risk of a meteoroid impact seriously damaging a spacecraft is small when compared to the debris particles. The hazard posed by the current population of man-made debris particles from on-orbit fragmentations, solid rocket motor firings, and other sources to both, manned and unmanned spacecraft is no longer negligible.
In view of these facts the reliable prediction of future impact risks is at least as important as the definition of today's risk. A proper consideration of environmental influences from the solar activity is crucial to achieve this task.

This paper gives a short survey of existing space debris and meteoroid models. The consideration of solar activity in these models is reviewed. The variation of collision risk in terms of the debris particle flux encountered by a target satellite will be presented and discussed with respect to time and different altitudes.

2 INTRODUCTION

The protection against the hazards posed by debris particles is costly and difficult. Reliable models to estimate the current and future characteristics of the impact risk are needed and various models have been developed. NASA's ***ORDEM 96*** derives the impact risk from measurements. The variation of flux wrt. time and orbit altitude time is implemented by simple weighting functions that mainly depend on altitude and solar activity. Other, semi-deterministic models such as ESA's Meteoroid and Space Debris Terrestrial Environment Reference Model (***MASTER***) or the Integrated Debris Evolution Suite (***IDES***) developed by DERA consider the evolution of the on-orbit population wrt. time by applying classic orbit propagation methods to single particles, generated according to source term models. Since orbit propagation tools are applied, historic solar activity data is a main input factor to generate a reference population at a given epoch. For extrapolation into the future, various approaches are applied by these models.

3 REVIEW OF MODELS

Current space debris flux models may be divided into so-called analytical (or empirical) models, based on the fit of measurement data, and so-called semi-deterministic models, based on the simulation of source terms (e.g. launches, explosions, solid rocket motor firings) with respect to time. The following models will be subject to closer evaluation within this paper :

- ***ORDEM96 (analytical)***
  ORDEM96 /1/ introduced in early 1996 is restricted to circular target orbits for altitudes up to 2000 km. The model offers directional flux information and is valid for particle diameters down to 1 micron. It discriminates by particle source terms as e.g. intact satellites, larger fragments, small fragments, paint flakes, AL_2O_3 particles and also considers the recently discovered NaK particles. It takes into account elliptical debris orbits. The model is calibrated by measurement values derived from space returned hardware and ground-based radar. The variation of flux under the influence of solar activity is implemented by means of analytical formulas.

- ***MASTER (semi deterministic)***
  ESA's MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) model /2/, /3/ is based on quasi-deterministic principles, using orbit propagation theories and volume discretisation techniques to derive spatial

densities and velocity distributions for particles larger than 0.1 mm in a 3D spherical control volume ranging from LEO to GEO. Space debris are generated for historic fragmentation events, and orbit states are propagated to a reference epoch, before they are merged with data of tracked objects. Collision flux from debris and meteoroids can be recovered for any (also highly eccentric) target orbits between LEO and GEO altitudes. The only source term considered by the current version of the MASTER model are breakup fragments. Update activities aiming for a consideration of other source terms including very small fragments down to 1 micron, paint flakes, AL_2O_3 particles and NaK droplets are currently going on.

The semi-deterministic approach used here implies the propagation of individual particles by means of 'classic' orbit propagation tools. Solar activity here is considered in terms of measured or projected cycles.

- ***IDES (semi deterministic)***
  The Integrated Debris Evolution Suite (IDES) /4/ depicts objects larger than 10 microns in the debris environment. IDES is used primarily to predict directional collision flux to a satellite orbit for debris sizes larger than 1 mm over the next 50 years by simulating the long-term evolution of the debris environment. The only source term considered by the current version of the IDES model are breakup fragments. Update activities aiming for a better representation of other source terms, e.g. paint flakes and NaK droplets, are currently going on.
  As the MASTER model, IDES uses classic orbit propagation models applied to individual particles larger than 10 cm, and to classes of particles having comparable orbital elements at sizes between 10 microns and 10 cm.

3.1 ORDEM96

The solar activity here is represented by expressions modulating the number of objects in circular and elliptical orbits. In a first step, the model gives a set of functional forms, describing the number of objects within a 1 km bin centered about the altitude h and the number of particles in elliptical orbits, whose perigees are centred within a 1 km bin at altitude q. In this case the apogee altitude of all particles is assumed to be at 20.000 km. These formulas are given for 6 different inclination ranges and six source terms. To give an impression about the structure of these equations, the influence of solar activity to the inclination band at 28° shall be briefly described:

$$\phi_i(h,s) = \frac{\phi_{i,L}\phi_{i,U}}{\phi_{i,L} + g(t)\phi_{i,U}} \qquad \text{Equ. 1}$$

$$\phi_{i,L} = 0.14(1+10^{1.88-s/110}) \times 10^{(h-600)/200+0.6} \qquad \text{Equ. 2}$$

$$\phi_{i,U} = 10^{[1370(1/h-1/600)+0.6]} \qquad \text{Equ. 3}$$

Figure 1 depicts the resulting curves as a function of altitude and h solar activity s. The considered solar activity range reaches from s = 50 to s = 250 in intervals of Δs=25. All curves are related to a reference value at h = 500 km and s = 150, where Φ_i = 4,9 ($\Phi_{i,L}$ = 0,75, $\Phi_{i,U}$ = 11,39). It is assumed that the population growth is 0, i.e. g(t) = 1 (epoch = 1995.00 status).

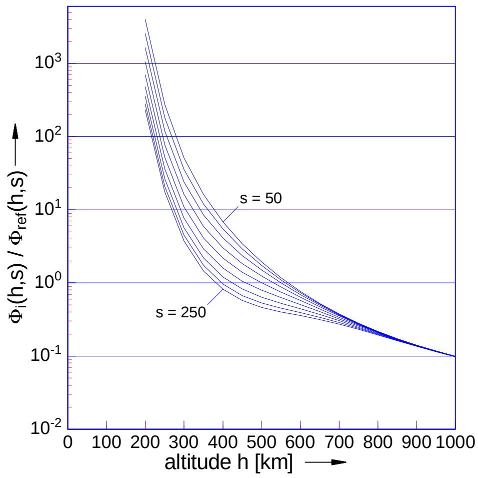

Figure 1 $\Phi_i/\Phi_{i,ref}$ (h = 500km, s = 150) as a function of altitude and solar activity.
Inclination = 28°, Intact objects

3.2 MASTER

MASTER consists of two branches. The developer's branch of MASTER is used to establish a population of particles at a given reference epoch, which is further processed to act as the database for the MASTER user's branch. The user's branch is distributed to the model users on a CD ROM (see /3/). Up to the reference epoch, classic and proven orbit propagation methods including the forces induced by the solar cycle are used for orbit propagation. ESA/ESOC's FOCUS orbit propagation routine is applied for this task (see /5/). FOCUS combines the analytical integration method according to King-Hele with a quick access density model based on the MSIS-77 atmosphere. A rotating and oblate atmosphere, the density scale height variation with respect to altitude, and the diurnal bulge are considered by FOCUS. Historic solar activity values and future projections are obtained from /6/.

The MASTER model is not intended to render long term (> 10 years) flux predictions. To compute impact fluxes at epochs different from the MASTER reference epoch, the model does not perform the complex and time consuming orbit propagation process. Instead, an approach proposed in the former NASA engineering model /7/ is applied to extrapolate reference results with respect to time. The approach determines a factor Φ as a function of altitude h and solar activity s.

$$\Phi(h,s) = \frac{\Phi_1(h,s)}{\Phi_1(h,s)+1} \qquad \text{Equ. 4}$$

$$\Phi_1(h,s) = 10^{(h/200 - s/140 - 1.5)}$$

Figure 2 shows Φ as a function of altitude up to 1000 km. The considered solar activity indexes range from s = 50 to s = 250, the stepsize between the single curves is 25. It is obvious that the influence increases with increasing solar activity indices and is most effective at lower altitudes. The factor approaches 1 (= no influence) at altitudes close to 1000 km. The approach is assumed to be independent from size, which is - as far as orbital mechanics are concerned - definitely a simplification.

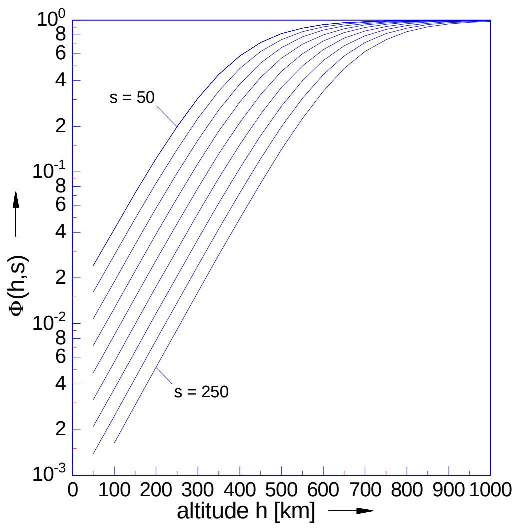

Figure 2 Φ as a function of altitude.
note : stepsize between the single curves is Δs = 25.

Figure 3 shows the result of equ. 4 when applied to the values (partly predictions) of the current solar cycle between 1995 and 2006 (depicted in the upper part of the figure). The curves are related to a reference value at T = 1995.00, which is close to the reference epoch of the MASTER model. Altitudes between 200 km and 1000 km are investigated. The solar activity shift factor depicted in the lower part of the figure is given for epochs between 1995 and 2006 when assuming that the population growth is zero. [1] The profiles thus show the percentages of flux (relative to T = 1995.00) to be expected for a target at the given altitude and time.

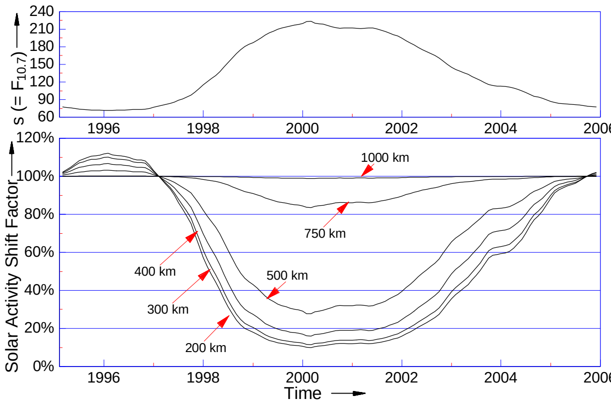

Figure 3 upper part : current solar cycle
lower part : values derived from equ. 4 when applied to the current solar cycle for different altitudes. All values are related to a reference value at T = 1995.00

3.3 IDES

As MASTER, IDES is based on semi-deterministic modelling and orbit propagation techniques. IDES propagates the orbits of individual large objects with respect to atmospheric drag, geopotential, luni-solar and solar-radiation pressure perturbations. Small objects are binned by their values of relevant orbital parameters and propagated sample-wise. For each sample object representing a certain number of real objects propagation is performed over a period Δt and results are applied to all objects represented by the sample. Historic solar activity values are obtained from /6/ and used for future projections.

Atmospheric drag perturbations on the particle orbits are predicted by employing the complex, analytical expressions developed by King-Hele. Look-up tables are used to obtain atmospheric density/density scale

[1] Note : The currently available version of MASTER uses predictions, which are lower than the ones presented here.

height according to the CIRA72 reference atmosphere and the exospheric temperature modulated by the solar flux level.

IDES is designed to perform also long term analysis. During a long simulation run over many years it is, however, computationally too intensive to consider all short term variations of all orbital paths. Therefore, IDES uses fast, analytical, one step orbit propagators to determine the long term variations in the orbital elements.

4 SOLAR CYCLE DATA

Figure 4 shows the solar cycles as used or recommended by the before mentioned debris models. For historic cycles, it is evident that IDES uses monthly values, while MASTER uses 13-months mean observations (centred on month 7). ORDEM uses 13-month smoothed F10.7 values of the solar activity of the year *previous* to the current epoch. Due to this fact the cycle recommended to be used for the ORDEM model shows a shift in time, when compared to the others.

For future predictions, the curves show slight differences, both in phase and amplitude of the cycles. Though the models (i.e. ORDEM and MASTER) use the same source for future predictions (see /6/) differences occur most probably due to different dates of model issue and thus prediction update status. For MASTER the predicted values start in August 1997.

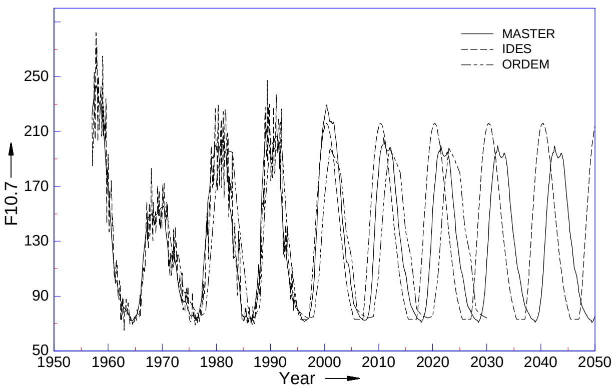

Figure 4 Historic and future solar cycles as used or recommended by the IDES,MASTER and ORDEM debris models.

5 EVOLUTION WITH RESPECT TO TIME

Atmospheric drag is the main sink term of the man-made debris population and the solar activity is the driving force for the variation of this perturbation. To give an impression on how the MASTER and the IDES debris models behave under the influence of the above presented solar cycle predictions, the following example shall be given. It is assumed that the spaceflight activities in the future will proceed as in the past. Historic launch rates are applied for the next decades and explosions may continue with the same rate as today. No mitigation measures are present. This scenario is commonly known as the 'business as usual' *(BAU)* scenario. In IDES this scenario is reflected by a particular future launch and explosion rate, in MASTER by a global population growth rate, which has been set to 2% in this case - a value which is commonly adopted for the growth of fragments, but still rather conservative. Before discussing the results in figure 5, it should again be stressed that MASTER is not meant to be a tool for long term predictions, while IDES is.

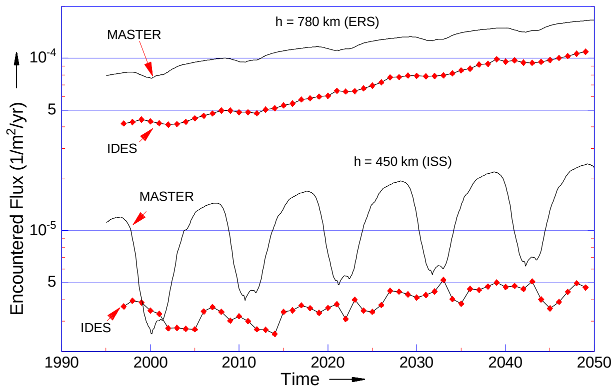

Figure 5 Comparison of IDES and MASTER in terms of flux > 1cm vs. time for ERS-1 like orbit (h = 780 km) and an International Space Station (ISS) like orbit (h = 450 km).
'*business as usual scenario'*

From comparisons elsewhere it is known that the predictions made by MASTER are higher than those made by IDES. Apart from this fact, both models show only small influences of the solar cycles in case of the ERS-1 like orbit, resulting in a steady growth of the predicted flux to the target. For the 450 km orbit, there are high fluctuations in encountered flux from centimetre-sized debris because at the ISS altitude, the atmosphere is much more dense than at 780 km altitude. This means that the air drag decay rates are larger and the dwell time of objects (including debris) are shorter. Consequently, the debris population at 450 km is smaller and is heavily influenced by changes in the atmospheric density due to solar activity in its 11-year solar cycle. The amplitude of the changes predicted by the approach in MASTER is, however, much higher than for IDES, though the tendency of the curves is again well comparable. Considerations including orbital mechanics may lead to the suggestion that the analytic approach used in MASTER exaggerates the fluctuations induced by solar cycles in low altitudes. The currently ongoing upgrade activities of the MASTER model may investigate this finding in further detail.

6 SUMMARY AND CONCLUSION

A survey of existing space debris and meteoroid models has been given. The approach to consider solar activity as an input to orbit propagation in these models was reviewed. It was pointed out that the general approaches are fairly different, reaching from pure analytical expressions (ORDEM) to a complete semi-deterministic propagation (IDES).

Historic and future solar cycles as used by the IDES, MASTER and ORDEM debris models have been presented. Minor differences were found here.

The variation of collision risk in terms of the debris particle flux encountered by a target satellite has been presented and discussed with respect to time and different altitudes. It turned out that the analytical approach taken from the former NASA Engineering model /7/ and applied in the user's branch of the MASTER model for short term predictions into the future (< 10 years) may have its weaknesses. The developer's branch and thus the quality of the reference population of the MASTER model is not affected by this fact.

7 REFERENCES

/1/ D.J. Kessler, J. Zhang, M. J. Matney, P. Eichler, R.C. Reynolds, P.D. Anz-Meador, and E.G. Stansbery, , *A Computer-Based Orbital Debris Environment Model for Spacecraft Design and Observations in Low-Earth Orbit,* NASA TM 104825, 1996

/2/ H. Klinkrad, J. Bendisch, H. Sdunnus, P. Wegener and R. Westerkamp, *An Introduction to the 1997 ESA MASTER Model*, Proc. of the 2nd European Conf. on Space Debris, pp. 217-224, ESA SP-393, May 1997.

/3/ H. Sdunnus, *Meteoroid and Space Debris Terrestrial Environment Reference Model,* Final report, ESA/ESOC contract 10453/93/D/CS, Darmstadt, July 1995

/4/ 'Walker, R., Hauptmann, S., Crowther, R., Stokes, H., Cant, A., *Introducing IDES: Characterising the Orbital Debris Environment in the Past, Present and Future,* AAS 96-113, Advances in the Astronautical Sciences, Space Flight Mechanics 1996, Vol. 93, Part I, pp. 201-220, 1996.'

/5/ E.Gonzalez, H.H.Klinkrad: *FOCUS1. Fast Orbit Computation Utility* SW; MAS.W.P. 305; Sep. 1989

/6/ National Oceanic and Atmospheric Administration, *Preliminary Report And Forecast Of Solar Geophysical Data,* NOAA-USAF Space Environment Services Center, SESC PRF 1053, 7 November 1995, published weekly

/7/ D. J. Kessler, R. C. Reynolds, P. D. Anz-Meador, *Orbital debris environment for spacecraft designed to operate in low Earth orbit*, NASA TM 100471, 1989