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AN INTRODUCTION TO THE ESA REFERENCE MODEL FOR SPACE DEBRIS AND METEOROIDS

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ABSTRACT

The contamination of the near earth environment by Space debris has reached a level, where the threat of a collision among an intact spacecraft and a debris object becomes more and more important to spacecraft design and operational considerations. Models are needed to estimate the current and future risk represented by the debris environment. The recent improvements concerning Space debris data acquisition (LDEF, Haystack) have underscored the necessity of a model, which is open to interpret and implement new deterministic data. The paper presents an introduction to the development and structure of the ESA Reference Model of Space Debris and Meteoroids. It lines out, which data are offered to the user and how to get access to them. The concluding analysis of a modelled debris population and the resulting flux to a target satellite gives a first insight to the available information.

1. INTRODUCTION

The issue of a study with the goal to establish a Reference Model for Space Debris and Meteoroids is a reaction of the European Space Agency (ESA) to the rising importance of the Space Debris problem. The study is managed by the European Space Operation Centre (ESOC). It started in February 1991 and ends in April 1993. Contractors are the Battelle Institute e.V. in Frankfurt a.M. and the Institute of Spaceflight Technology and Reactor Technology (IfRR) in Braunschweig. IfRR is responsible for all items related to Space Debris and develops the model itself. Battelle contributes with the execution of explosion experiments (see 4.5) exclusively dedicated to the Space Debris problem. Figure 1 depicts a flow chart of the treated work packages.

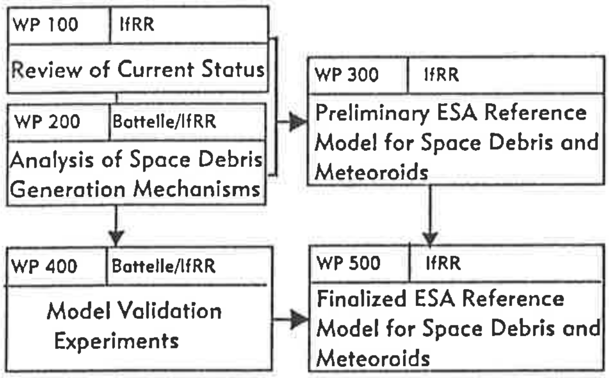

Figure 1 Work Package Flow Chart

2. THE NEED OF MODELLING

The problems related to Space Debris and hence the group of potential model users may be divided into two major parties:

(i) Spacecraft operators are mainly interested in short term effects. Models are used to estimate the untracked debris population and the resulting impact risk to an individual mission. This group expects a handy model output to allow an easy and quick risk analysis.

(ii) The consideration of long term effects addresses more scientific and political interests. Models allow the simulation of the highly dynamic characteristics of the debris environment, the analysis and explanation of impacts observed on space exposed hardware and projections of the environment to the future, which may lead to the proposal of mitigation measures. Here, the model output must be detailed enough to allow complex studies.

One major goal of the ESA Reference Model is the satisfaction of the requirements from both groups, that is to provide a handy model output as well as detailed information about debris sources and its dynamic properties.

3. EXISTING MODELS

Several models have been developed in the last two decades. Two general types dominate:

(i) Engineering models describe the debris environment by a set of straight forward formulas using a limited number of influencing parameters as their input.

These models are commonly derived from ground based measurement data and the evaluation of space returned hardware. They do not render detailed source or object information of the debris population. Their mode of operation bases on a generalization of the respected measurements. The simple structure makes them applicable to a broad circle of users. Widely in use is the NASA engineering model /1/.

(ii) More complex, quasi-deterministic computer based models report the history of individual debris objects.

These models concentrate on a detailed characterization of single population members or sub groups. They generate a debris population by the application of empirical fragmentation models to historically known fragmentations. Those models suffer from a high degree of uncertainty due an insufficient number of consolidating ground tests. They offer a large quantity of information describing the evolving

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parameters of the space debris environment. From a long list of models of this class the following computer codes should be mentioned:

- EVOLVE /2/ (NASA JSC)
- DEBRIS /3/ (Aerospace Corporation)
- FAST (Kaman Sciences)
- CRASH /4/ (IfRR)

Though each of the models allowed new and valuable insights to the nature of the debris environment, the problem is still far from being completely interpreted. The understanding of *cause and effect* of the debris environment, reaching from the description of initial breakup cloud conditions over the its evolutionary behaviour up to the description of flux directionality properties to a target object demands for the availability and understanding of a maximum of information. The ESA Reference Model for Space Debris and Meteoroids is planned to provide progresses into this direction.

4. THE ESA REFERENCE MODEL

4.1 Basic Requirements

A number of basic requirements establish the demanded model capabilities of the ESA Reference Model:

a) consideration of all important man-made debris sources
b) consideration of the natural sources (meteoroids)
c) modelling of the evolutionary behaviour of the space debris environment
d) description of the impact flux of Space Debris and of meteoroids to a target object in terms impact probability, impact velocity and direction
e) diameter threshold : $d > 0.1$ mm
f) altitude threshold : $h < 2000$ km

4.2 Performance Requirements

Independent from the basic model requirements a number of user oriented performance requirements have been defined. They were (with rising importance)

a) minimization of computing time
b) minimization of storage need
c) maximization of model flexibility
d) optimization of model handling
e) maximization of information content
f) maximization of model accuracy

4.3 Selecting the Modelling Approach

The trade off between several modelling strategies with respect to the above listed requirements led to a decision for a deterministic modelling approach. Especially the points 4.2 c-f are strengths of this approach and influenced the competition decisively. Information content and model accuracy were judged as requirements, which should be fulfilled to the highest possible level. The rapid development of the computer hardware sector decreased the importance of criteria like computing time or storage need. On the other hand, model flexibility and inclusion of new data have been emphasized due to ongoing advances on the field of data acquisition. The development of a measurement based model comparable to /1/ was depraved, because own data sources are currently not available.

4.4 The Model Structure

The model is splitted into 4 modules related to basically different tasks (figure 2). The interface between model operator (ESOC) and user is foreseen at stage 3. Stages 1 and 2 will be managed by the model operator. Depending on the preferred way of access (see 4.6), the user is free to choose between an analytical engineering model and a small sized software module (COLMOD) to perform level 3. The alternatives on level 4 are an analytical meteoroid model (see 4.4.4) or a derived numerical method. The function, input, output and interfaces of the four stages have been defined as follows:

Stage 1: S/W POEM
Function: Generation of a debris population
Input: Definition of source and sink terms by the S/W operator.
Output: A debris population known by individual object sources, orbits and object describing parameters.

Stage 2: S/W DISMOD (contributed by ESOC)
Function: Generation of a three dimensional spatial density distribution
Input: debris population (stage 1), 3D - segmentation
Output: A spatial density [$1/km^3$] distribution as a function of radius, right ascension and declination.

Stage 3 (a) S/W COLMOD (contributed by ESOC)
Function: Determination of debris flux to a user defined target
Input: Spatial density distribution (stage 2), target orbit
Output: Debris flux [$impacts/m^2/yr$] to a spherical target in terms of impact probability, velocity and angle. Impactor source and 3D-resolution is retained.

Stage 3 (b) Analytical Space Debris Engineering Model
Function: Determination of debris flux to a target
Input: Target orbit
Output: Debris flux [$impacts/m^2/yr$] in terms of impact probability, velocity and angle.

Stage 4 (a) S/W METMOD
Function: Determination of meteoroid flux to a user defined target
Input: Characterisation of the meteoroid environment.
Output: Meteoroid flux to a target orbit as a function of impact probability, angle and velocity.

Stage 4 (b) Analytical Meteoroid Model
Function: Determination of meteoroid flux to a user defined target
Input: Characterisation of the meteoroid environment.
Output: Meteoroid flux to a target orbit as a function of impact probability and velocity.

4.4.1 Generation of a Debris Population

The following man-made source terms are modelled :

-launches -explosions -collisions

Other sources as paint flakes, residuals from solid rocket motor firings or fragments from erosional effects are neglected. The relevant literature gave no evidence to the suspicion that these objects could decisively contribute to the considered size range above 0.1 mm. The model is however still open to respect them if necessary.

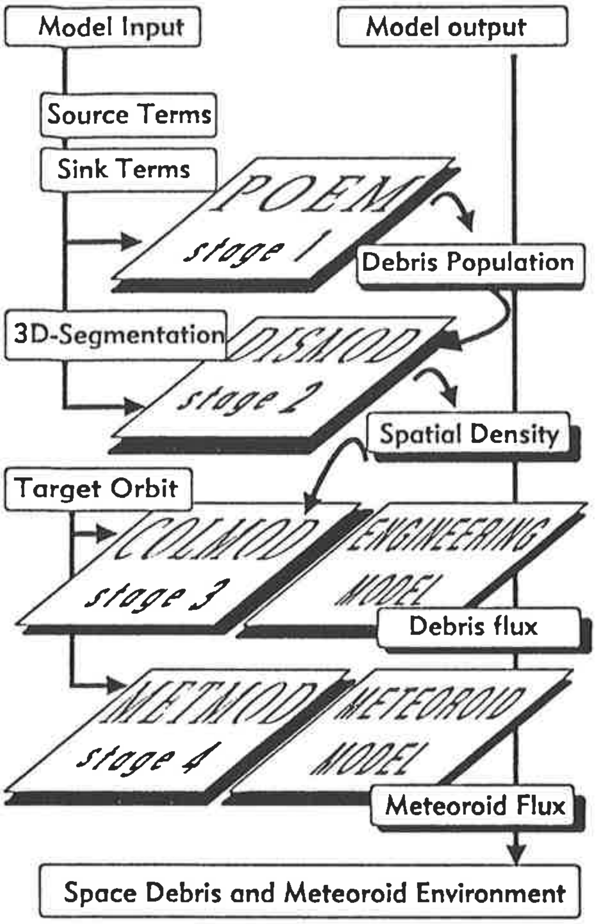

Figure 2 Global Model Structure

All source terms are modelled under the best possible consideration of deterministic data. Measurements of USSPACECOM (Two Line Elements) are implemented as the trackable population. The application of a fragmentation model to 106 (cut off date : 04/92) historic breakups known by date, parent object mass, breakup position and the number of catalogued fragments /5/ renders the untrackable debris population. In order to allow an adequate application of the fragmentation model, a rough classification of fragmentation causes has been done with respect to either Low Intensity Explosion (LI), High Intensity Explosion (HI) or Collision (CO). In case of mid or long term future simulations the model operator (ESOC) may define a traffic rate describing the future number of launches and changing space flight policies.. The population of untrackable objects then is obtained from the random generation of future breakups under consideration of the defined traffic scenario.

The implemented fragmentation model has been established under the condition that all components are supported by experiments and published in literature. More than 20 alternatives have been analyzed to settle the following model:

Mass distribution

- Low Intensity Explosion (LI):

$$N(>m) = N_0 \cdot e^{-\left(\frac{B \cdot K \cdot \sqrt{m}}{K+\sqrt{m}}\right)}$$

N_0	total number of objects	
$N(>m)$	number of objects of mass > m	
m	fragment mass	[kg]
B	explosion intensity	$[kg^{-0.5}]$
K	calibration parameter (=2)	$[kg^{0.5}]$

(source : /4/)

- Collision (CO):

$$N(>m) = A \cdot \left(\frac{m}{m_{ej}}\right)^{-B} \qquad (2)$$

m_{ej}	ejected mass = $m_p \cdot v_p^2 \cdot [s^2/km^2]$	[kg]
m_p	projectile mass	[kg]
v_p	projectile velocity	[km/s]
B	slope parameter	[-]
A	mass consistence parameter	[-]

(source : /6/)

- High Intensity Explosion (HI):

  90% of the parent object mass fragments following the LI approach (equ. 1)

  10% of the parent object mass fragments following the CO approach (equ. 2 , $m_{ej} = 0.1 \cdot M_{SAT}$,A = 0.439, B = 0.75).

The approaches fulfil the demand of mass consistence. The model parameters are calibrated to a given number of objects above a given tracking threshold (catalogued objects).

Additional velocity distribution

$$\log(\Delta v) = \begin{cases} 0.875 - 0.0676 \cdot \left(\log \dfrac{d}{d_m}\right)^2 & , d > d_m \\ 0.875 & , d \le d_m \end{cases}$$

$$d_m = \frac{\sqrt[3]{E_p}}{c} \quad ; \quad E_p = \frac{1}{2} \cdot m_p \cdot v_p^2 \qquad (3)$$

Δv	most probable additional velocity	[km/s]
d	fragment diameter	[m]
m_p	projectile mass	[kg]
v_p	projectile velocity	[m/s]
c	$8 \cdot 10^8$	

(source: /2/)

Size distribution:

$$m(l) = \rho(l) \cdot V(l) = \rho(l) \cdot \frac{\pi}{6} \cdot l^3 \qquad (4)$$

$\rho(l) = 2.8 \cdot l^{-0.74}$ for l > 0.62 cm
$\rho(l) = 4.0$ for l ≤ 0.62 cm

m	object mass	[g]
ρ	object density	$[g/cm^3]$
l	effective diameter	[cm]

(source: /1/)

The spreading of additional velocities and mass-to-area values for objects with same mass is considered by superposing spreading functions.

The modular structure of the level 1 software (POEM) allows an easy update of single model components by eventually improved data. The implemented model will be reviewed with respect to results from fragmentation tests carried out during this study.

Sink terms are respected by orbit propagation routines. The implemented FOCUS propagator /7/ covers all major perturbation forces demanded by the variety of debris orbits and shapes. Orbit propagation is the most CPU time-critical module (> 90% of CPU_{total}) and must be utilized with special care. In case that aerodynamic drag dominates, a second propagation routine including simple analytic formulas is applied.

4.4.2 Generation of a Three Dimensional Spatial Density Distribution

Spatial density is obtained by dividing a spherical control volume surrounding the earth into discrete volume bins (fig. 3) equidistant in radius, right ascension and declination (Δr, $\Delta\alpha$, $\Delta\delta$ = const.) /8/. The bins at position i_r, j_δ, k_α are characterized by their central cell position vector $\vec{r}_{ijk}$ in an inertial equatorial system and their particular volume V_{ijk} ($\neq$ const.).

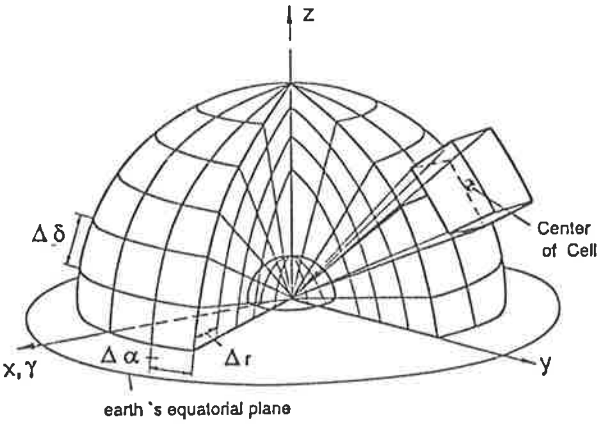

Figure 3 Division of the Control Volume

Each bin passage of a population member is registered with respect to its residential time and its central cell velocity amount and direction. Object source information is retained. Spatial density related to the n-th object passing a single bin is calculated by

$$D_{n(ijk)} = \frac{T_{n(ijk)}}{T_{REV,\,n} \cdot V_{ijk}} \tag{5}$$

$D_{n(ijk)}$	spatial density of n-th object	[1/km³]
$T_{n(ijk)}$	residential time of n-th object	[s]
$T_{REV,n}$	orbital period of n-th object	[s]
V_{ijk}	bin volume	[km]³

The consideration of all population members and all bins renders a three dimensional resolution of spatial density. The described operations (level 2) are carried out by the model operator (ESOC). The data offered to the user comprise a condensed description of all bin passages by the considered population.

4.4.3 Determination of Debris Flux

A user defined target object, idealized as a sphere of unit cross section, is confronted to the debris density distribution. Assuming the spatial density D_{ijk} to be constant within the single bin, the risk P_{ijk} of a collision between the target and all N_{ijk} population members passing the bin is

$$P_{ijk} = \sum_{n=1}^{n=N_{ijk}} D_{n,\,ijk} \cdot v_{n,\,ijk} \cdot T_{n,\,ijk} \cdot A_{n,\,Tar} \tag{6}$$

$v_{n(ijk)}$	relative velocity between target and n-th object	[m/s]
$A_{n,Tar}$	collision cross sectional area	[m²]

The collision cross sectional area $A_{n,Tar}$ is a function of the target cross sectional area A_{Tar} and the impactor cross sectional area A_n. The particular characteristics of the Space Debris environment allow the assumption that A_{Tar} is decisively larger than the area A_n of the potential impactors ($A_{Tar} > A_n \rightarrow A_{n,Tar} \approx A_{Tar}$). This postulate allows the simplified calculation of flux per cell F_{ijk} to the target in terms of impacts per unit time and target area :

$$F_{ijk} = \sum_{n=1}^{n=N_{ijk}} D_{n,\,ijk} \cdot v_{n,\,ijk} \tag{7}$$

The relative velocity vector between the target and the potential impactors determine the flux directionality distribution within the bin, i.e. the flux dependence on azimuth and elevation angle with respect to the local horizontal plane. The successive consideration of bin passages along the target orbit in discrete steps of the revolution angle *u* renders a flux distribution, which is resolved with respect to the position of the target on its orbit. Neither former models nor space returned hardware are able to render this quality of resolution.

One should note that equ. (7) is restricted to the before specified assumptions. In particular the method is not qualified to evaluate the interactive collision risk between all members of a debris population.

4.4.4 Determination of Meteoroid Flux

An analytical meteoroid model /9/ describing the interplanetary meteoroid flux at 1 A.U. distance from the earth was adopted for this study:

$$\begin{aligned} F_{Met}^{\,ip}(m) = c_0 \cdot \big(&(c_1 m^{0.306} + c_2)^{-4.38} + \\ &c_3(m + c_4 m^2 + c_5 m^4)^{-0.36} + \\ &c_6(m + c_7 m^2)^{-0.85} \big) \end{aligned} \tag{8}$$

$c_0 = 3.147 \cdot 10^{7}$ $c_1 = 2.2 \cdot 10^{3}$ $c_2 = 15$
$c_3 = 1.3 \cdot 10^{-9}$ $c_4 = 1.0 \cdot 10^{11}$ $c_5 = 1.0 \cdot 10^{27}$
$c_6 = 1.3 \cdot 10^{-16}$ $c_7 = 1.0 \cdot 10^{6}$

F_{Met}^{ip}	meteoroid flux	[impacts/m²/yr]
m	meteoroid mass	[g]

The meteoroid flux change due to the vicinity of shielding bodies (earth) is described by

$$\zeta = \frac{1 + \cos \Theta}{2} \qquad \sin \Theta = \frac{R}{R + H} \qquad (9)$$

ζ	shielding factor
Θ	half shielding angle
R	radius of shielding body
H	atmosphere altitude (100 km)

The flux increase by the attracting force of the earth gravitational field is described by :

$$G_E = 1 + \frac{R_E}{r} \qquad (10)$$

G_E	focusing factor
R_E	radius of the earth
r	orbit radius

A meteoroid velocity distribution as proposed by /1/ has been adopted. Discrete seasonal meteoroid streams and flux directionality effects introduced by the meteoroid velocity distribution and the satellite motion are respected by the fourth stage of the developed software (METMOD). This tool should however be reserved to scientific oriented applications.

4.5 Fragmentation Experiments

The greatest disadvantage of empirical fragmentation models is their large degree of uncertainty due to an insufficient number of available test data. Mass and velocity distribution models as implemented in the ESA Reference Model partially are derived from a narrow data base. Therefore, three fragmentation tests were carried out by the Battelle Institute in connection with this study /10/ to enlarge the limited data base. An unique characteristic of these tests is their exclusive dedication to a major debris source - the propulsion related fragmentation of rocket upper stages. Though at least 30% of the observed fragmentations and 45% of the tracked fragment population result from this source only poor efforts have been done to enlarge the understanding of this generation process. The analysis of Battelle experimental data is still in progress, but does already give rise to the hope that fragmentation models will get a broader support.

4.6 The User Interface

The complete description of the debris population distributed in a three dimensional bin environment (output from level 2, see 4.4.2) may reach an extent of data, which might not be wished by all users. Some are however interested in each available degree of information and do not agree to any compressing simplification of the model output. Those interests are contrary and caused ESOC and IfRR to offer a two-fold access to the user of the ESA Reference Model :

4.6.1 Access via the COLMOD Routine

The small sized COLMOD software and a data set describing the bin environment and the related information of passages by population members (source, spatial density, velocity) at a given epoch is delivered to the user via low cost direct access media such as CD-ROM or magnetic tape. Under assistance of the COLMOD routine the user is able to interpret the data and to compute flux to self defined targets. All source information and three dimensional resolution of spatial density and flux is maintained. Improved meteoroid flux data including seasonal streams could be provided in a similar manner. This type of access requires special hardware resources (see 4.6.4).

4.6.2 Access via Engineering Formulae

A fit of the results from the COLMOD routine (level 3) will be published in form of a purely analytic engineering model, which renders flux as a function of debris diameter, target altitude, target inclination and time. Compared to the NASA engineering model /1/ it offers an improved model accuracy for the debris part. However, most information about impactor sources, the distribution of debris orbital elements and the three dimensional resolution of density and flux are no longer accessible.

4.6.3 Getting Authorization

It is planned to provide all parts of the model in the summer of 1993. Maintanance and distribution will be performed by ESOC/MAS in Darmstadt (FRG). Detailled information about the distribution process may be delivered by ESOC/MAS.

4.6.4 Hardware Requirements

The model access via the COLMOD routine requires hardware resources concerning storage capability. An ASCII format data set containing the whole bin environment including all offered information requires up to 100 Megabyte hard disk storage. A decisive data reduction to less than 10 MB is possible by submitting selected segments of the bin environment (adopted to the missions to be evaluated) or by compressing data. It is recommended to implement the software on a work station or comparable hardware.

4.7 Results

The paper had to be limited to the presentation of only a small part of the data offered by the model. A survey of the information at the user's disposal has been given in /8/.
The temporal development of the number of objects within the considered control volume (h_p < 2000 km) (figure 4) shows a first sharp increase around 1965. It is caused by the high energetic fragmentation of two soviet spacecrafts (COSMOS 50, 57). A second increase around 1968 results from the first soviet anti-satellite experiment, where three spacecrafts were involved (COSMOS 248, 249, 250).

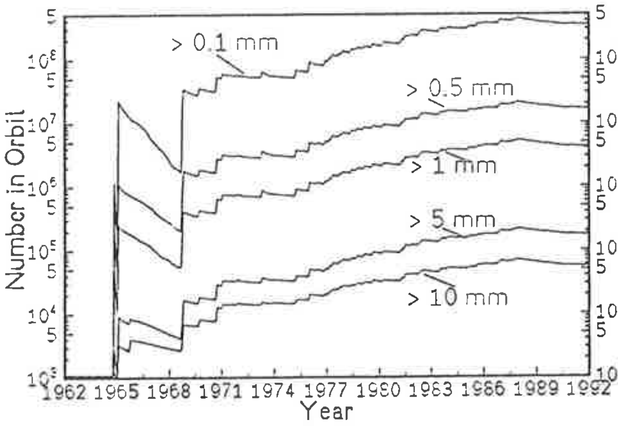

Figure 4 Number of Objects in Orbit vs. Time

The population steadily increases up to 1988 and shows a slight decrease thereafter. For the year 1992 the simulation renders a number of 58400 objects larger than 10 mm in diameter. The population of objects larger than 1 mm is predicted to be two, the 0.1 mm population 4 order of magnitude larger. The numbers already indicate a weakness of the implemented fragmentation models. The simulated results do not explain the flux observed on space returned hardware (LDEF, Solar Max). The reason is the evident underestimation of the number of generated fragments by the fragmentation model. The effect is size dependent and may reach from a factor of about 2 for the 10 mm population to more than one order of magnitude in the 0.1 mm size regime. The effect is under investigation and will be respected by the final version of the model and the derived engineering model.

Figure 5 depicts the spatial density of the 10 mm population in 1992.00 as a function of radius and declination.

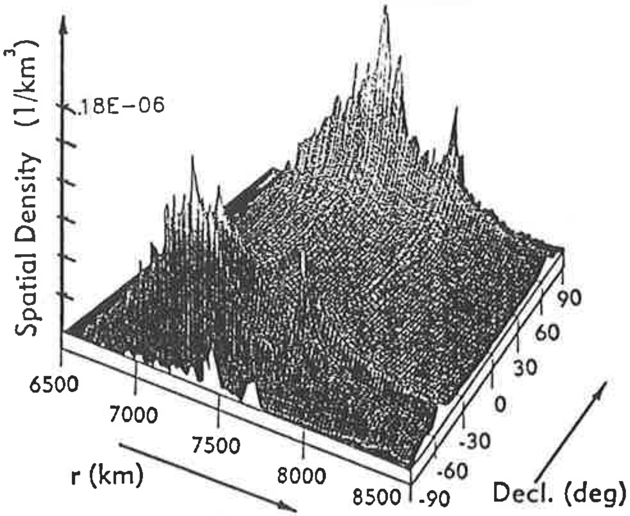

Figure 5 Spatial Density vs. Altitude and Declination, 58400 Objects > 10 mm

Due to cumulations of the debris population around inclinations of about 63°, 80° and 100° spatial density peaks occur at high latitudes. These peaks ($0.18 \cdot 10^{-6}$ 1/km^3) are up to a factor of 3 larger than the values averaged over all declinations. The resulting flux to a target object consequently depends on the latitude bands it crosses, thus on its revolution angle u and orbital inclination i. Figure 6 depicts an output of the COLMOD routine. The flux of objects larger than 10 mm along a ERS-1 type near circular target orbit (a = 7150 km, i = 98.5°, ω = 5°) shows increase of flux at about Δu = 20° before and after the point of highest declination (u = 90°). The effect is symmetric to u = 180° (equator crossing), where the local flux is predicted to be about a factor 4 smaller than near the poles. Those data are not offered by the engineering model.

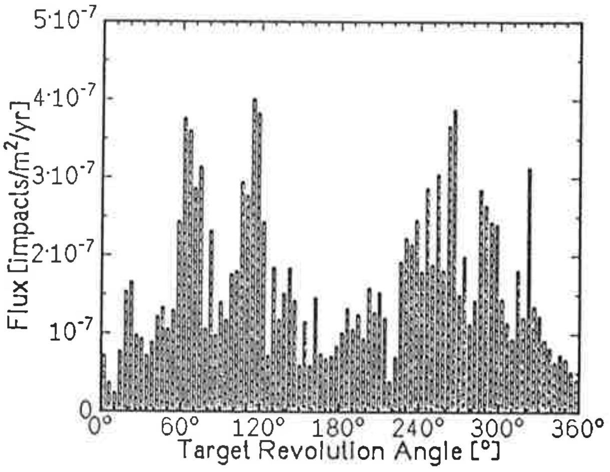

Figure 6 Flux vs. Target Revolution Angle

A variety of further data is offered to the user, but cannot be presented here. Flux distribution as a function of impact velocity and the angular flux distribution in the target horizontal plane are provided by the engineering model as well as by the deterministic access via the COLMOD routine.

5. SUMMARY AND CONCLUSIONS

The design of the ESA Reference Model for Space Debris and Meteoroids allows the provision of information with innovative quality and quantity. The twofold model access via an analytical engineering model or a deterministic software tool will satisfy the requirements of spacecraft operators as well as scientific oriented applicants. For the first time a three dimensional resolution of the debris spatial distribution and the derived flux characteristics to target orbits have been made accessible by a debris model. The application of empirical fragmentation models however brought up the problem of a debris size dependent discrepancy between simulation results and measurements. The future interpretation of the problem depends on the extent of the available data base and underlines the demand for further experiments.

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