MASTER 99 AND IN-SITU SPACECRAFT MEASUREMENTS: TEST COMPARISONS IN LEO AND GEO

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ABSTRACT/RESUME

Master 99 offers a comprehensive tool [1] for the characterisation of the particulate impact environment from GEO to LEO. We first compare the particle diameter distributions with those of NASA ORDEM 2000 for a circular LEO orbit and find good agreement. The models are not immediately applicable to spacecraft measurements, however, unless folded with the sensor orbit vector, the detection sensitivity function and information on the angular sensitivity of the detector. We have developed software to use the Master 99 Analyst output which generates the particle parameter distributions incident on to any type of detector with arbitrary pointing direction and orbital exposure parameters. The detector response chosen for the comparison presented here is the penetration of aluminium plate and results are compared to the debris fluxes deduced for LDEF (mean altitude 465 km) from examination of the excess flux of impact craters and penetrations above those of the meteoroid background; comparison is also made with residue analyses on LDEF and those from the retrieved Solar Array on the Hubble Space Telescope (altitude 650km). Predictions are also made for the GEO environment, applicable to Geostationary satellites and potentially to results anticipated from the GORID plasma detector aboard EXPRESS II. It is found that MASTER 99 provides good general agreement between debris flux predictions and the those derived from LDEF; results are supported by the limited but critically important residue analyses. MASTER offers, additionally, a rich source of information from LEO to GEO, namely the interplay of different types of debris anticipated at different dimensions and the angular dependencies of different populations. The model shows that the meteoroid population is dominant for a penetration thickness ranging from 20 microns to 1mm of Aluminium; exposure configurations are identified which are essentially inaccessible to space debris and might, therefore, be used for meteoroid studies.

1. INTRODUCTION

Modelling is vital for both design and for understanding: in the prediction of spacecraft reliability, degradation or destruction; the development of experiments to detect space debris or meteoroids and for understanding the wider aspects of debris cosmogeny. A comprehensive model such as Master is invaluable in handling the complex quantities involved and essential for its application to the entire geospace environment. Data available within the model may come from a wide variety of sources; from in-situ experiments and from spacecraft surfaces; from remote observations and from vehicle launch statistics together combined with impact comminution models. There is a sense in which a model, derived from a number of such sources, is potentially better than any specific source data. Yet, there is also a sense that no model should conflict with the source data when applied back to each specific source configuration. Our approach to evaluating the performance of Master, therefore, leads to a test applied to one type of detection on the NASA Long Duration Experiment LDEF where an abundance of data is available [2].

The variety of source data, covering particle fluxes, or spatial densities and velocity vectors, can be integrated into one model only using a common parameter; this is usually particle diameter, perhaps with an assumed specific gravity or, for remote optical data, a reflection coefficient. The model is also, currently, geocentric to enable application to Earth orbital spacecraft and has to be folded with the spacecraft orbital parameters to yield intercepted fluxes. These fluxes if accompanied by particle size and impact angle may be converted back to a reaction at each impact such as the penetration, the impact plasma or flash generation or momentum. Models such as NASA 96 or ORDEM 2000, MASTER 97 and 99 represent comprehensive, and fairly similar, flux populations.

We explore, first, a comparison of MASTER 99 and ORDEM 2000 in terms of flux or particle diameters varying from 1 micron to spacecraft dimensions. The flux incident on a sphere is calculated at the altitude and orbit of NASA's Long Duration Exposure Facility (taken as mean altitude 465km and inclination 28.5°). Following this baseline comparison, MASTER is examined in more detail in application to LDEF which represents a unique source of international data on both meteoroids and space debris fluxes [2]. LDEF's gravity gradient stabilisation provided, critically, exposure in

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differing directions – up to 14 were available. Thin foils provided high sensitivity for 5 orthogonal directions e.g. [3]; the anisotropy provided opportunity for discrimination between meteoroids and space debris; complemented by cratering experiments and space vehicle post-flight examinations, to extend both reliability and range, a set of face-dependent flux distributions was established [4]. The modelling of space debris and meteoroids yielded self-consistent results supporting the Grun analysis flux [5] as the basis for meteoroid fluxes at 1 AU and deriving a set of debris fluxes for the cardinal faces [6].

2. METHODOLOGY

2.1. Model comparison ODEM 2000 & MASTER 99

For the flux through a sphere, the approach is very simple, because neither azimuth, elevation nor velocity need be considered. Results of Master and ORDEM for a $1m^2$ sphere moving at LDEF's altitude are shown in Figure 1 for particle sizes of 1 um to 1 m. The comparison might well hide, in principal, significant differences of directionality and velocity or differences in the populations needed to represent the Earth environment currently. The populations entered in the two agency models are essentially similar, however, regarding the population types and orbital parameters, the distributions following Kessler [7], incorporated at first in NASA 96; differences are unlikely to be apparent in a LEO circular orbit and in the comparison of different model ouputs, differences may result more from technical factors inherent to the model. The degree of agreement, shown in Fig. 2 was, nevertheless, unexpectedly close considering the different model approaches. We see differences are less than a factor of two and little overal bias if a comparison were averaged over the size range. If just the flux to a sphere were to be measured this is where the comparison of models and experiment might end but no experiment, exposure configuration or real measurement can ever experience this flux to a sphere. All measurements involve a bias or detection above a limiting sensitivity; which will be particle parameter dependent. Hence the extensive multiparameter arrays of this model flux must be acquired and processed in relation to response function.

2.2. Application of impact response functions

Penetration relationships and cratering formulae have been explored since the early days of space launches and prior to the build up of space debris were concerned with meteoroid impacts. Studies reported typically from centimetre scale light gas guns e.g. [8,9] and from electrostatic accelerators [10,11] for microparticles. Based on analysis of microscale data combining the foil measurements reported from 1 to 16 km sec^{-1} [10] which also incorporates dimensional scaling parameters to agree with centimetre scale cratering, we have a tested relationship very appropriate to fold with all particles and velocities encountered in MASTER 99; meteoroids and debris. This (McDonnell Sullivan) formula [12] provides well characterised behaviour for the penetration of metallic targets ranging from micron to centimetre scale in thickness. The relationship is:

$$\frac{f_{\max}}{d_p} = 1.272 d_p^{0.056} \left(\frac{\rho_p \rho_{Al}}{\rho_{Fe} \rho_t} \right)^{0.476} \left(\frac{\sigma_{Al}}{\sigma_t} \right)^{0.134} V^{0.806} \quad (1)$$

For thick target data, the crater depth T_c is taken as 1.5 times f_{max} and T_c/D_c is typically 0.5 to 0.6 for space impacts. The penetration formula is, importantly, compatible with the formulae, which were used to derive the model flux diameters from the source cratering and penetration data from space analyses.

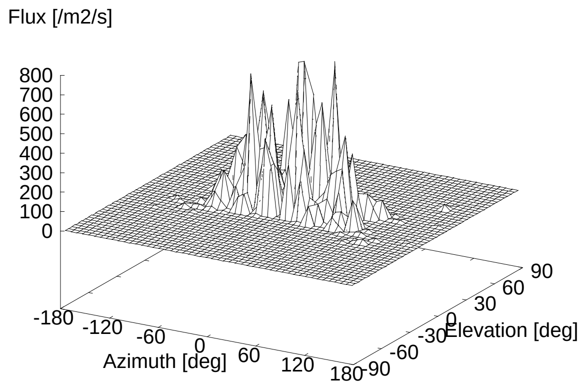

Fig. 1. Azimuth and elevation distributions for Long Duration Exposure Facility orbit at all sizes above 1 micron diameter size for the flux passing through a sphere. Concentration in the "debris plane" (some +/- 5 degrees in elevation but +/-60 in azimuth permits an approximation to consider all elevation directions to have zero value. Azimuth distributions and associated velocity distributions are calculated explicitly.

2.3. Model Parameter Handling

MASTER 99 does not currently output an independent azimuth, elevation and velocity distribution for any specific particle size; only two of these three are specified for access in the standard issue. Hence its application to a moving ("detector") surface is not explicit unless assumptions are made on one of these three parameter sets. This is quite reasonable in the case of LEO orbits for space debris where interception occurs within a "debris plane". This is not the case for meteoroids, however, but for debris on a LEO satellite examination of the azimuth – elevation distribution reveals (shown in Fig. 1) a ready solution. Even for eccentric particles the most particles are within a few degrees of the local plane perpendicular to the nadir. The average elevation is taken as zero, therefore, but the azimuth and velocity distributions used explicitly to calculate the local detector approach vector relative to the detector pointing at growth velocity; the detector need not be pointing in the forward direction and the actual impact angle is calculated so that the sensor response is determined. For impact penetration, the angle relative to the surface normal of the sensor surface is used to find the velocity component at angle θ relative to the surface, reducing the effective velocity entered in the penetration formulae as $\upsilon \cos \theta$. The velocity for each impact is calculated as the azimuth and elevation arrays are scanned for each particle size. An array of penetration bins is created, using 3 per factor of 10 in mass; the binning of f_{max} values for each particle size ($d_{p)}$ is then incremented is performed for all detector hits. The resulting f_{max} from all sizes yields therefore the integrated effect of all particles within the model. MASTER 99 is limited to particles above 1 micron and we generally see, in the data, a roll off at values of penetration below f_{max} = 5 microns, corresponding to a value of d_p = 1 micron when integrated over all debris velocities.

3. MASTER AND ORDEM

The particle flux passing through a sphere for LDEF's orbit was modelled using MASTER 99 Analyst and NASA ORDEM 2000. Fig. 2 shows a comparison between the outputs of these two models. The agreement between them is very good. This could be expected, as the source data used for each is the same, however, the approaches used are different. The differences in populations and directionality effects are masked in this plot. MASTER's diameter range includes particles down to 1 micron while ORDEM 2000 only includes those down to 10 microns.

4. RESULTS OF MASTER FOR LEO

4.1. Master Velocity Distribution for LDEF

The velocity distribution for the debris populations and meteoroids passing through a sphere for LDEF orbit is shown in Fig. 3. SRM dust dominates the other populations and meteoroids, although at smaller dimensions. The higher velocity of meteoroids, however, gives higher weight to the penetration effects.

The processed MASTER output in Fig. 4 to Fig. 6 show the penetration distributions for LDEF's East, West and North faces. The relative importance of each population can be seen as a function of increasing penetration value. For the East face (Fig. 4) SRM dust dominates up to 30 microns but meteoroids then dominate from f_{max} =30 to 30 cm. At f_{max} =100 microns paint flakes comprise a few percent of meteoroids; above 1 mm a similar percentage of debris is expected, but by fragments from collisions and explosions.

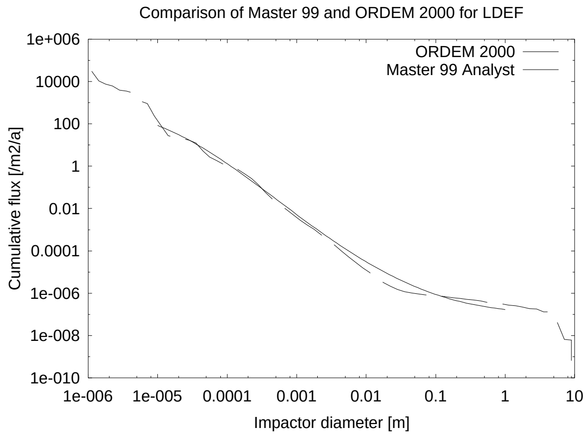

Fig. 2. Comparison of Master 99 and NASA ORDEM 2000, plotted cumulatively, for particle fluxes passing through a sphere (LDEF orbit). The two models show very good agreement, which, although expected because of the use of the same source data, take a quite different approach. Possible differences in the relative numbers of different populations and directionality effects are masked in this plot. Master includes particles to 1 micron and ORDEM 2000 down to 10 microns.

For the West face Fig. 4 Solid rocket motor dust is exceeded by meteoroids, but by a factor of only 3. The only significant debris is from high eccentricity slag generated from apogee burns of GEO insertion manoeuvres, which approaches 10 percent of the total penetrations in the centimetre region. Fragments are insignificant over the whole range.

For the North face Fig. 5 Solid rocket motor dust is exceeded by meteoroids, but by a factor of only 3. The only significant debris is from high eccentricity slag generated from apogee burns of GEO insertion manoeuvres, which approaches 10 percent of the total penetrations in the centimetre region. Fragments are insignificant over the whole range.

4.2. Comparison with Meteoroid and Space Debris data from LDEF

Fig. 11 shows processed MASTER output for LDEF's East and West faces with results derived from comprehensive measurements of the space exposed surfaces on LDEF [3]. The agreement between the data and modelling for East face is especially good; at small sizes Master's cut off is caused by the 1 micron size limit. LDEF's West face debris expected from Master results is lower than the measured flux by one to two orders of magnitudes; this deserves consideration because of strong evidence from chemical data from residue analyses [12]

5. RESULTS OF MASTER FOR GEO

5.1. Master Velocity and flux distributions for GORID orbit

The velocity distribution for the debris populations and meteoroids passing through a sphere for GORID's orbit is shown in Fig. 7. At low velocities SRM dust exceeds meteoroids by many magnitudes. The processed MASTER output for the Ram, Wake and GORID sensor are shown in Fig. 8 to Fig. 10.

The penetration distributions for GEO orbit in the Ram direction are shown in Fig. 8. There is some dominance by meteoroids except at micron scale where SRM dust may be 10 times the meteoroid population but this is exaggerated by the artificial cut-off of meteoroids below 1 micron in the Master model.

The penetration distributions for GEO orbit in the trailing (wake) direction are shown in Fig. 9. A surprisingly natural impact environment is seen, with the meteoroid population exceeding any debris by 8 orders of magnitude. An ideal exposure for experiments detecting meteoroids and shower studies would be afforded by this exposure direction.

The penetration distributions for the GORID sensor [13] aboard the Geostationary satellite Express II are shown in Fig. 10. SRM dust exceeds meteoroids below 10 microns (several microns particle diameter) but no other populations are significant in the measurement range.

6. CHEMICAL EVIDENCE FROM SPACE ANALYSES

We have compared in section 4 the Master modelling to flux data derived entirely from physical modelling. The approach uses LDEF's high directional sensitivity to meteoroids and space debris to separate out the two additive components, examined in terms of penetration or cratering. Crucial factors, in broad terms, are that space debris cannot access the space or Earth facing surfaces and hence the meteoroid fluxes in the modelling (based on the Grun 1985 model [5] can be verified to high precision. Given this, the model can predict the meteoroid flux on any other face, which will, in general, also be accessible to space de\bris. The additional flux is considered, to limits of error applicable, the space debris flux. Data is derived from foil measurements providing high sensitivity and additionally the meteoroid shape factors [14, 15] and from a much wider body of data provided for the meteoroid and debris special investigator group (NASA M D SIG) [16] including surveys of the entire structure.

The chemical data, available from less extensive studies, is often biased by selective effects of detection limits. Extensive energy dispersive X ray studies of the LDEF Chemistry of Meteoroids Experiment are reported by Bernhard [17] and, despite the unresolved impactor cases (some 70 percent), the evidence is very convincing and even gives strong clues to the type of debris; overall debris levels of some 15 percent of the meteoroid flux are shown. Bias is considered to arise from natural causes because meteoroids have higher velocities and less opportunity for retention of residues. Further work was performed on Eureca, exposed at altitudes of 500 km shows the extent of space debris at smaller dimensions well supporting the modelling output now provided by Master. More recent, and more sensitive measurements, have been performed by Graham and Kearsley [12] on the Hubble Space Telescope (HST) solar array cells recovered [4, TN 7]. Both micrometeoroids and debris have been sub-classified as shown in Table 1 from Graham et al HVIS 2000 [12]. Beyond the prime discrimination between debris and meteoroids, further differentiation between sub-classes of meteoroids and debris is presented.

At higher altitudes than LDEF the data may not be fully comparable quantitatively and, because both EuReCa and HST attitudes are solar pointing they average the unique directionality offered by LDEF. However, the relative numbers of debris and meteoroids in the data, if compared to the average of LDEF (namely to mimic the averaging effect of HST or EuReCa orbits) certainly underscore the Master 99 results and space derived flux based modelling results [18]. Evidence from the residue analyses of a millimetre space debris flux is also very clear, however, and yet these are not shown in the results of trailing surfaces of LDEF modelled by Master 99. Further scrutiny is needed.

7. CONCLUSIONS

Master 99 Analyst offers a comprehensive approach to characterising debris from LEO to GEO and is readily applicable to differing spacecraft orbits. It compares well to NASA ORDEM in calculations of flux through a sphere. Considering the calculated effects of penetration from the Master 99 output, the populations and their relative importance yield realistic fluxes, velocities and directionality. When compared to space data on LDEF agreement is good for the ram and wake directions, although these directions have very different signatures. The flux of debris on the wake direction is lower that anticipated and indicated by both the derived flux from modelling and from residue studies. The element of possible temporal flux changes between LDEF's exposure (1984 to 1990) and Master in 1999 has not been examined.

8. FIGURES

Table 1. Criteria for the identification of residue form Graham et al [12].

Micrometeoroids		**Space Debris**	
Mg, Si, Fe	(mafic sulphates)	Ti, C, N, O, Zn	(paint)
Fe, S	(iron sulphides)	Fe, Cr, Mn, Ni	(steel)
Fe, Ni, S	(iron-nickel metal)	Al, O	(SRM debris)
Fe, Ni	(silicon carbide)	Sn, Cu	(PCB debris)
Si, C	(hydrous silicates)	Al, Mn, Fe, Cr	(alloy)
Ca, C, O	(calcite)		

Table 2. Micrometeoroid and space debris components identified from Hubble Space Telescope Solar array residue analyses [4,12]. Residues from natural particulates are clearly associated with known meteorite types; the non-natural residues may now, with the benefit of Master, be associated with the differing populations. A significant advance compared to the LDEF CME data [17] is the lower fraction of undetermined identifications of projectiles (some 20% compared to 70%).

	Debris	**Meteoroids**	**Unknown / unclassified**
Survey I (100 to 35oo micron craters	10%	69%	21%
Survey II (1 to 100 micron craters)	56.3%	25.9%	20.3%

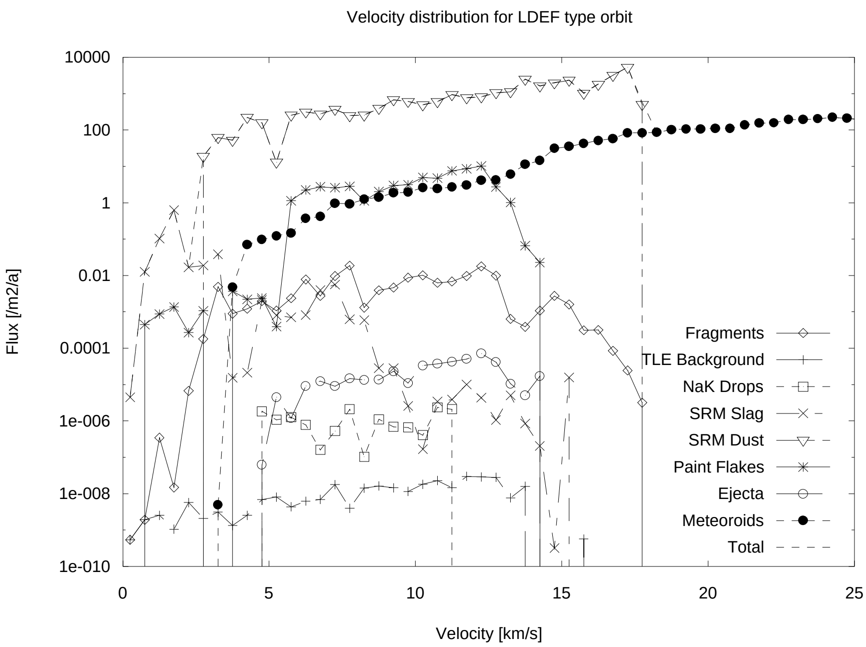

Fig. 3. Velocity distributions for the debris populations and meteoroids passing through a sphere for LDEF orbit, all sizes. SRM dust dominates the other debris and meteoroid populations, though at small dimensions but the higher velocity of meteoroids gives higher weight to the penetration effects. Directional effects are shown, in terms of the penetration effect, in figures 4 through to 6.

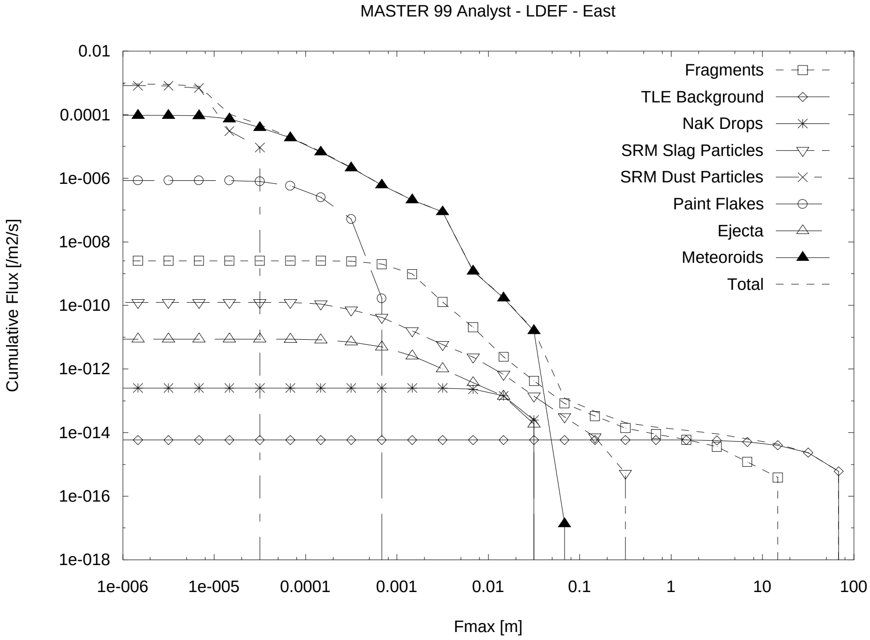

Fig. 4. Penetration distributions for plate thickness above 1 micron for LDEF East (8 degrees South of true Ram) direction. As a function of increasing penetration value, we see the relative importance of differing debris populations. Solid rocket motor dust dominates up to 30 microns but meteoroids then dominate from f_{max} =30 to 30 cm. At f_{max} =100 microns paint flakes comprise a few percent of meteoroids; above 1 mm a similar percentage of debris is expected, but by fragments from collisions and explosions.

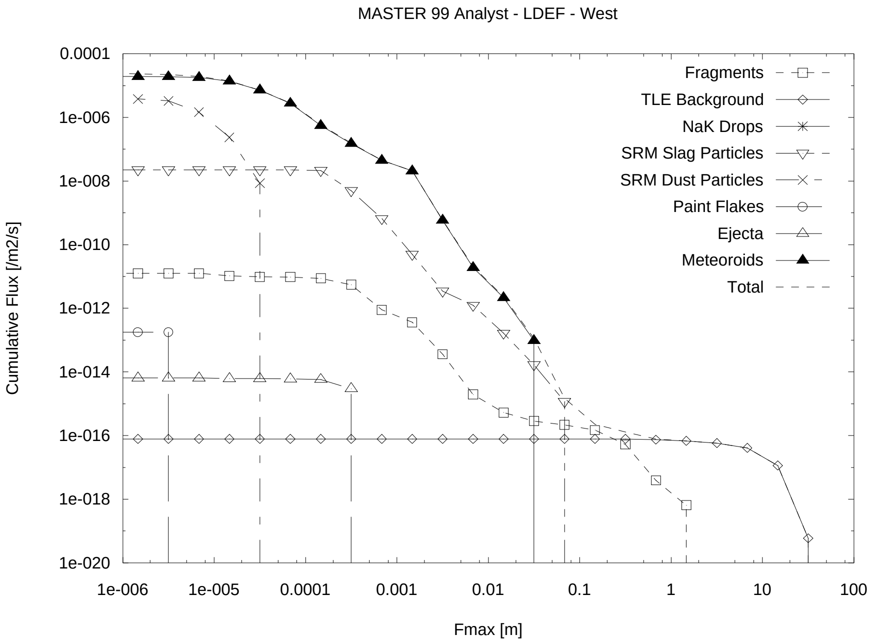

Fig. 5. Penetration distributions for LDEF as Fig. 4 but for the West (trailing) face. Solid rocket motor dust is exceeded by meteoroids, but by a factor of only 3. The only significant debris is from high eccentricity slag generated from apogee burns of GEO insertion manoeuvres, which approaches 10 percent of the total penetrations in the centimetre region. Fragments are insignificant over the whole range.

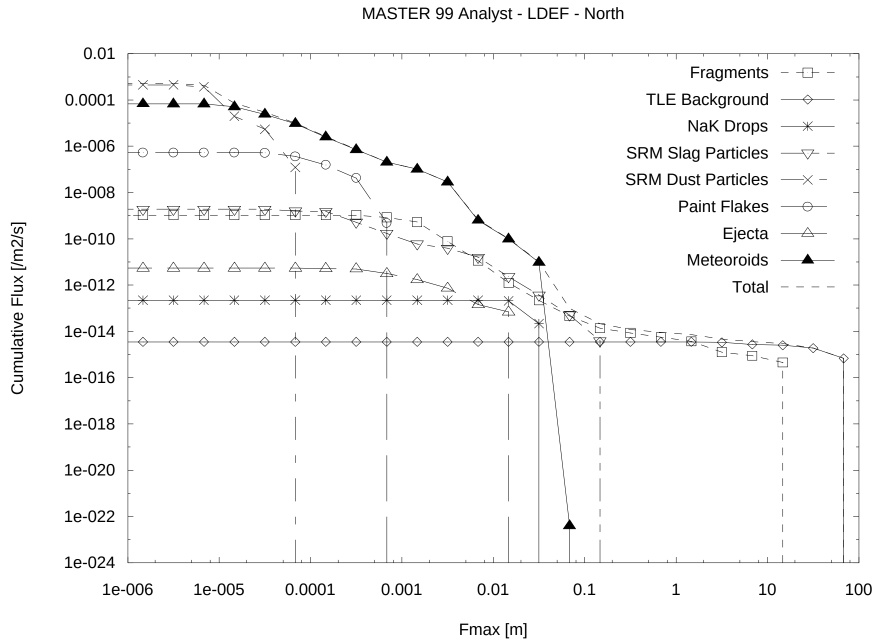

Fig. 6. Penetration distributions for LDEF as Fig. 4 but for the North face, approximately at right angles to the velocity vector. The situation is, unsurprisingly, midway between Ram and Trailing regarding the differing debris populations and meteoroids.

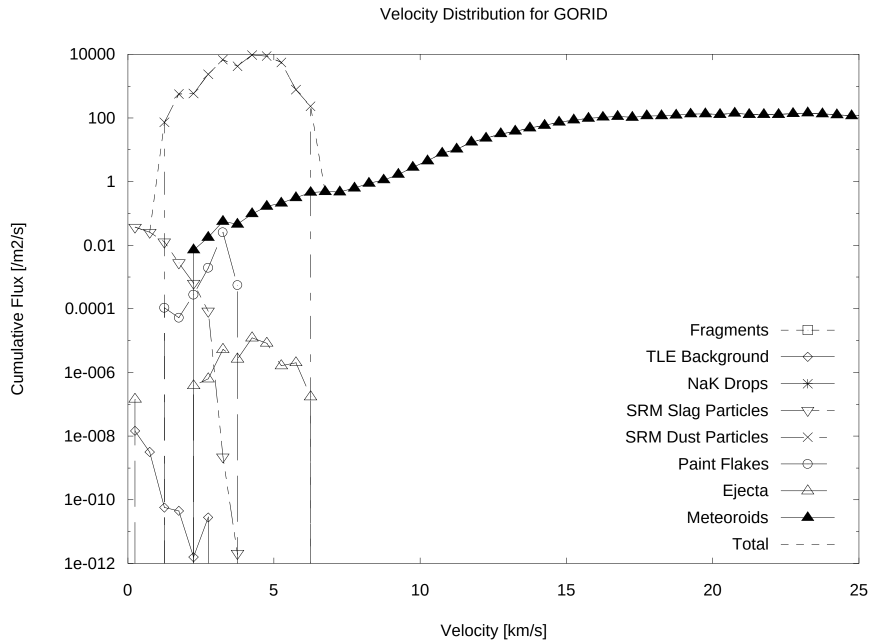

Fig. 7. Velocity distributions for GEO orbit, showing the flux through a sphere for all sizes above 1 micron. At low velocities SRM dust exceeds meteoroids by many magnitudes. Directional effects are shown for penetration effects in figures 8 through to 10.

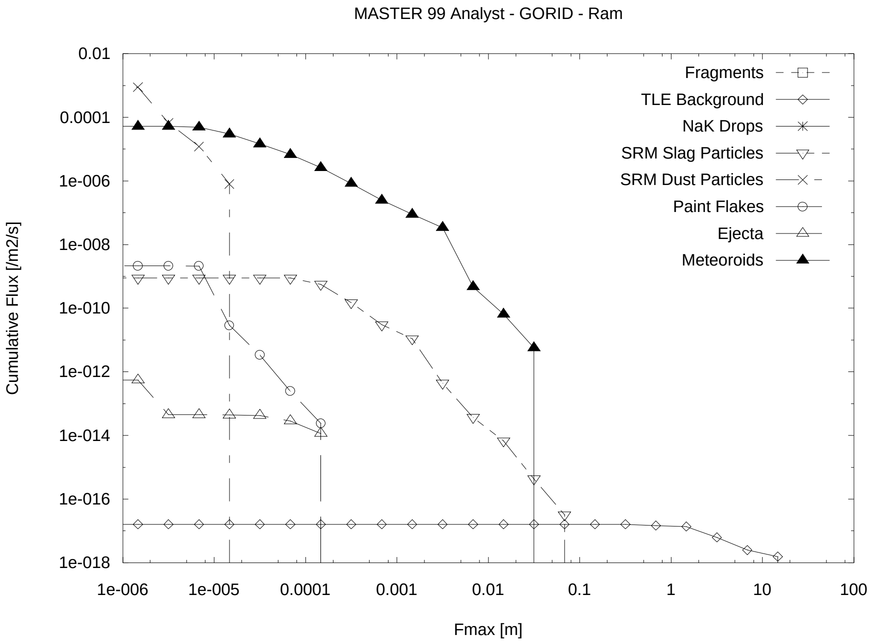

Fig. 8. Penetration distributions for GEO orbit in the Ram direction, showing dominance by meteoroids except at micron scale where SRM dust may be 10 times the meteoroid population but this is exaggerated by the artificial cut off of meteoroids below 1 micron in the Master model.

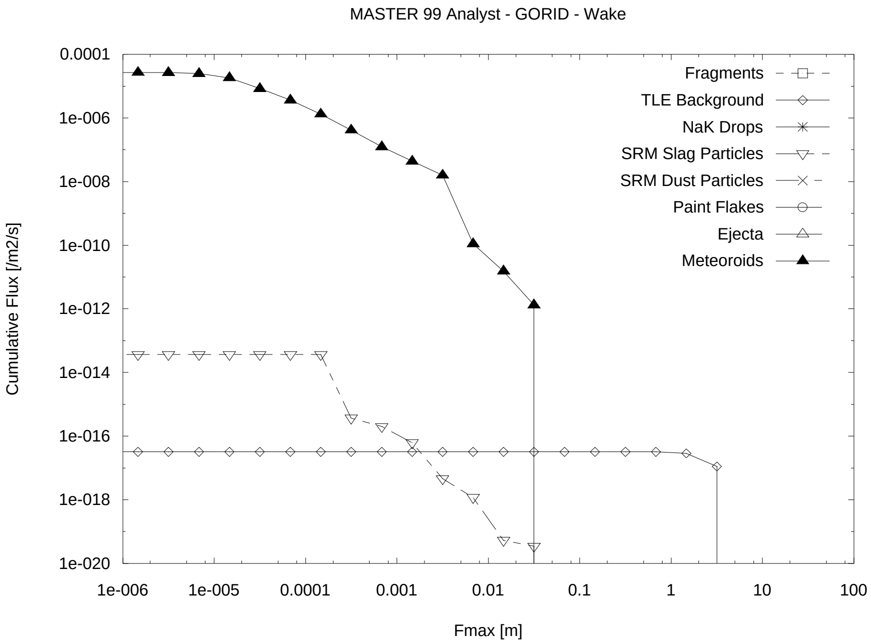

Fig. 9. Penetration distributions for GEO orbit in the trailing (wake) direction. Contrasting with the Geo ram distributions, a surprisingly natural impact environment is seen, with the meteoroid population exceeding any debris by 8 orders of magnitude. An ideal exposure for experiments detecting meteoroids and shower studies would be afforded by his exposure direction.

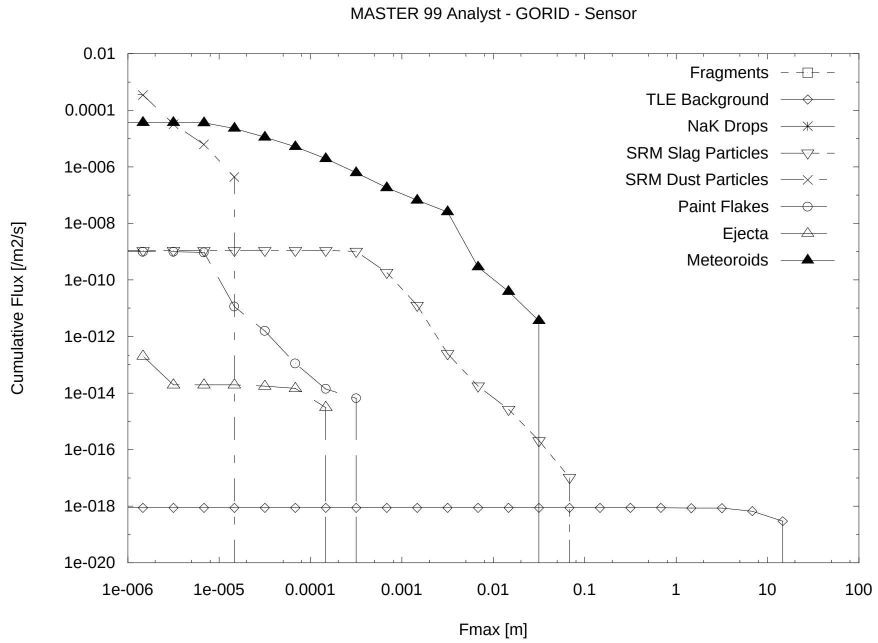

Fig. 10. Penetration distributions for GORID sensor [13] aboard the Geostationary satellite Express II. SRM dust exceeds meteoroids below 10 microns (several microns particle diameter) but no other populations are significant in the measurement range.

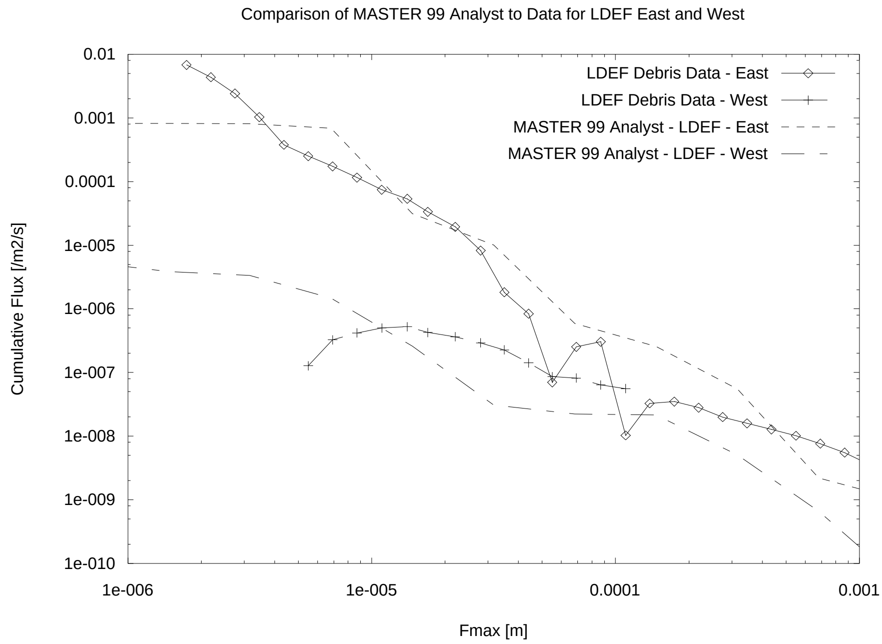

Fig. 11. Master model results compared to the debris populations in the East and West directions derived from comprehensive space exposure measurements on LDEF [6]. The agreement between the data and modelling for East face is especially good; at small sizes Master's cut off is caused by the 1 micron size limit. LDEF's West face debris expected from Master results is lower than the measured flux by one to two orders of magnitudes; this deserves consideration because of strong evidence from chemical data from residue analyses [12].

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