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Recent near Earth satellite flux data: contributions in the definition of the interplanetary flux at 1 AU heliocentric distance.

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Abstract. Recently analysed hypervelocity impact data from retrieved satellites are summarised. Analyses of perforation data show that mean densities are low (around 1.5–2 g/cm^3), impact velocities are consistent with radar meteor observations and that high aspect ratio particles are not found. Mean data, for $F_{max} > 30\,\mu m$ agrees well with the Grün et al. Interplanetary flux model, though there is evidence of a strong bias towards the Earth apex of motion direction. For $F_{max} < 30\,\mu m$ the data at LDEF's altitude is dominated by space debris.

1. Measurements available.

The interplanetary flux model derived by Grün et al. (1985) relied upon lunar rock impact data for its "shape", with absolute calibration provided by impacts on the Pegasus and Heos II satellites. More recently, impact flux measurements from LDEF and the EuReCa satellite provide additional data. LDEF was in an orbit of mean altitude 475 km and inclination of 28.5 degrees: EuReCa had a very similar orbit but with a mean altitude of 500 km. The main differences between the two satellites are thus pointing history and epoch.

We examine how this new data, supported by improved knowledge of penetration mechanics, leads to a better definition of the 1 A.U. micrometeoroid environment.

2. Recent progress in modelling and calibration.

2.1. Flux modelling

Zook (1990) suggested that the ratio of impacts on the east and west (apex and ant-apex of motion) faces of LDEF could be combined with modelling the satellite as it moved through an isotropic distribution of interplanetary dust to discriminate between three published meteoroid velocity distributions. Sullivan and McDonnell (1992) used a similar approach, applied to the space and west faces to determine a *single* or *characteristic* meteoroid particle velocity that represented the data. Deshpande (1994) continued this work and obtained a geocentric particle velocity of $23.3 \pm 5\,km/s$. This value agrees well with the impact-weighted mean obtained by Taylor (1995) following a re-appraisal of the radar meteor data of Southworth and Sekanina (1973). It should be noted that whilst the single

LDEF face	Equal particle mass		Equal penetration limit	
	V_{normal}	K	V_{normal}	K
East	16.8	2.11	21.4	2.77
West	9.6	0.32	15.3	0.23
North	13.1	1.13	17.3	1.20
South	12.0	0.88	16.3	0.81
Space	12.0	1.02	16.0	1.03
Earth	3.7	0.94	5.0	0.92

Table 1. Results of the modelling, using the Grün IP model, applied to LDEF's 6 main faces. The *equal particle mass* column gives the mean normal component of velocity of the equal mass particles hitting a particular face. The *equal penetration limit* column gives the mean normal component of velocity of particles giving an equal penetration limit F_{max} (using the penetration equation from McDonnell and Sullivan 1992). The K factors are the ratio of flux obtained (at either equal mass or equal penetration limit) compared to that obtained if LDEF were forced to be 'stationary' (i.e., if there was no orbital motion). It can also be noted that the mean gravitational enhancement at the LDEF altitude is 2.0 and the mean Earth shielding factor is 0.65.

velocity can be said to represent the impact data, it cannot then be assumed that all particles actually have this velocity and any flux transformations which have a velocity dependence (such as gravitational enhancement (Öpik 1951) or Earth shielding) should be applied to the entire distribution.

Table 1 shows the results of numerical modelling of impact fluxes on LDEF. The model calculates the exposure of the main faces of LDEF to the 'Grün flux', incorporating the spacecraft's full orbital geometry, the gravitational enhancement of flux and meteoroid velocity and Earth shielding (all of which are velocity dependent). The Sekanina and Southworth (1975) meteoroid velocity distribution, reappraised by Taylor (1995) was used, recalculated here for the altitude of LDEF.

2.2. Calibration

The micro-metre scale hypervelocity impact laboratory calibration data of McDonnell (1970), which extends to 16 km/s, has been used by McDonnell and Sullivan (1992) to define a perforation limit (F_{max}) equation. More recently, Gardner et al. (1995) used the full data set to obtain an equation for obtaining the diameter of particle (d_p) required to create a given perforation diameter (D_h) in a foil.

McDonnell and Baron (1993) have applied the McDonnell and Sullivan penetration equation (Equation 1) to a variety of spacecraft detector materials to permit cross comparison. They have thus shown that there is little evidence for growth in the space debris population at micro-metre scales; the flux determined in 1986 for the Solar Max Mission (Laurance and Brownlee 1986) is quite accurately confirmed on LDEF (1984-90) and for EuReCa (1993) at $F_{max} = 10\,\mu m$.

$$\frac{F_{max}}{d} = 1.272 d^{0.056} \left(\frac{\rho_p}{\rho_{Fe}} \frac{\rho_{Al}}{\rho_t}\right)^{0.476} \left(\frac{\sigma_{Al}}{\sigma_t}\right)^{0.134} v^{0.806} \tag{1}$$

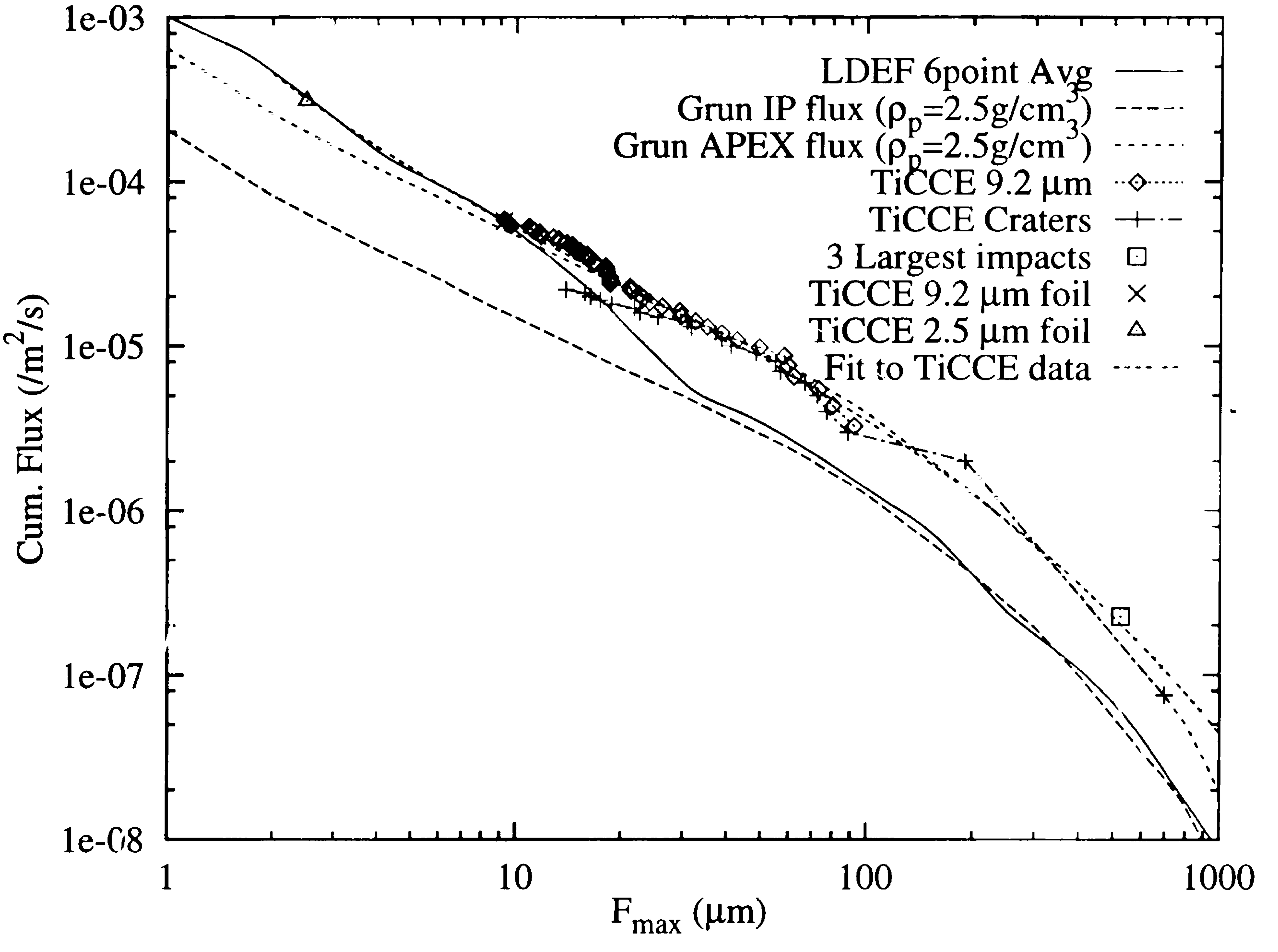

Figure 1. The near Earth space penetration environment. Ballistic limit (F_{max}) cumulative flux distributions from the LDEF and EuReCa satellites, compared to the interplanetary flux model of Grün et al. Model data has been numerically integrated using Taylor's velocity distribution (converted to LDEF's altitude) and the penetration equation of McDonnell and Sullivan; Earth shielding and gravitational enhancement have been accounted for. Whilst the LDEF average flux at $F_{max} > 30\ \mu m$ agrees well with the Grün interplanetary flux, the EuReCa data (pointing towards the Sun-Apex direction) exceeds the LDEF average by a factor of ~3.

3. Flux comparisons.

Comparison (shown in Figure 1) between the average of LDEF's 6 faces (Neish 1995) and the results from the EuReCa TiCCE experiment (Gardner et al. 1996, Gardner 1995) which points towards the Earth apex/solar direction, shows a factor of ~3 difference between the two satellites. This strongly suggest that the impact flux in the size range corresponding to values of F_{max} from 20 to 700μm is dominated by a component from the Earth's apex of motion (and hence clearly of natural origin). Below $10\,\mu m$ F_{max}, an Earth apex bias is *not* observed and thus it is postulated that the flux in this size range is primarily due to orbital particles, such as space debris and aerocaptured meteoroids (Ratcliff et al. 1993), which become randomised for EuReCa's pointing history and hence coincides well with the LDEF average.

The striking difference between the TiCCE and LDEF fluxes gives an *upper limit* to any debris component (which could be therefore seen as isotropic on TiCCE). This is found to be about 10% of the TiCCE flux or 30% of the LDEF average in the range of F_{max} between 30 to $100\,\mu m$.

Figure 1 also shows the interplanetary flux model of Grün et al. (1985) which has been numerically integrated using Taylor's velocity distribution and the penetration equation of McDonnell and Sullivan. The effects of earth shielding and gravitational enhancement were included in the integration. Particle densities of $2.5\,g/cm^3$ were assumed, to correspond with the value selected by Grün et al., using instead a a density of $1.5 g/cm^3$ the flux was ~10% lower. The satellite data incorporated in Grün et al.'s model had, in the size range of interest, a significant enhancement towards the Earth's apex of motion; in making use of this enhanced flux, they reduced it by a factor of π to obtain a flux as might be observed on a tumbling surface. For comparisons with the TiCCE experiment which (due to spacecraft pointing constraints) was always within 55° of the apex direction (Collier 1995), the integrated flux has been multiplied by π to produce the line marked "Grün APEX", in order to indicate a reasonable upper limit that might be expected due to the apex asymmetry.

As may be clearly seen from the figure, the spacecraft data is entirely consistent with a meteoroid dominated flux in the size range $F_{max} = 30–1000\,\mu m$ for LDEF and $10–1000\,\mu m$ for TiCCE. This is also supported by the data fits shown in Figure 2. For $F_{max} < 30\,\mu m$, the north, south and east (and hence the mean) show significant departure from the 'Grün flux' modelling, although the space and west faces (which are *not* expected to receive significant debris contributions) show no such departure.

4. Properties of the meteoroid flux.

Analysis of perforations in the EuReCa TiCCE experiment (McDonnell and Gardner 1995) provides direct evidence of the shape of meteoroids. The records (Figure 3) show that, whilst perfectly spherical particles are very uncommon, most of the impacts are not far from this shape, with the aspect ratio (length/width) rarely exceeding 2. Thus the space impactors in this range are neither extreme in shape or friability. Their impact penetration power can thus be characterised by existing penetration equations, as used here.

Gardner (1995) uses a minor modification of the GMC equation (Gardner et al. 1996) to analyse impact flux data from the LDEF satellite. His method of comparing fluxes on foils and thick targets gives a 'characteristic' impactor density of $1\ g/cm^3$ and suggests the need for further analyses to determine the relationship between this value and the *true* mean particle density when velocity and density distributions are used. McDonnell and Gardner (1996) show that, as with the 'characteristic' impact velocities discussed earlier, this density is indeed *not* the true mean; their analyses demonstrate that although a small component of low density particles ($<1\,g/cm^3$) is required, the characteristic value is consistent with a mean particle density of 1.5–2.0 g/cm^3.

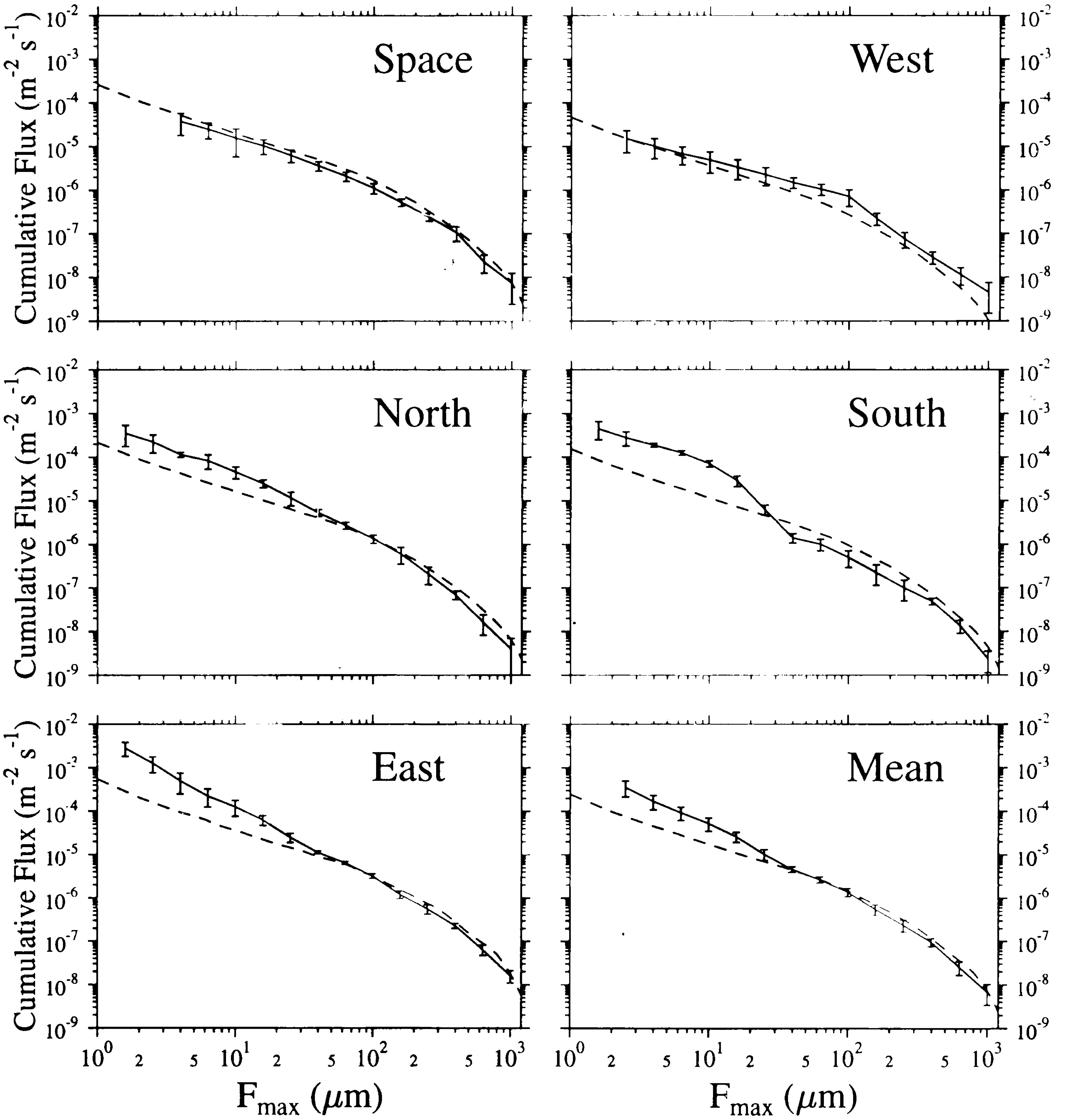

Figure 2. Fluxes on the different faces of the LDEF satellite, compared with the results of modelling using the Grün flux. The excess flux on LDEF's north, south and east faces is attributed to an orbital component. At values of $F_{max} > 30\,\mu m$ LDEF's impacts are dominated by meteoroids.

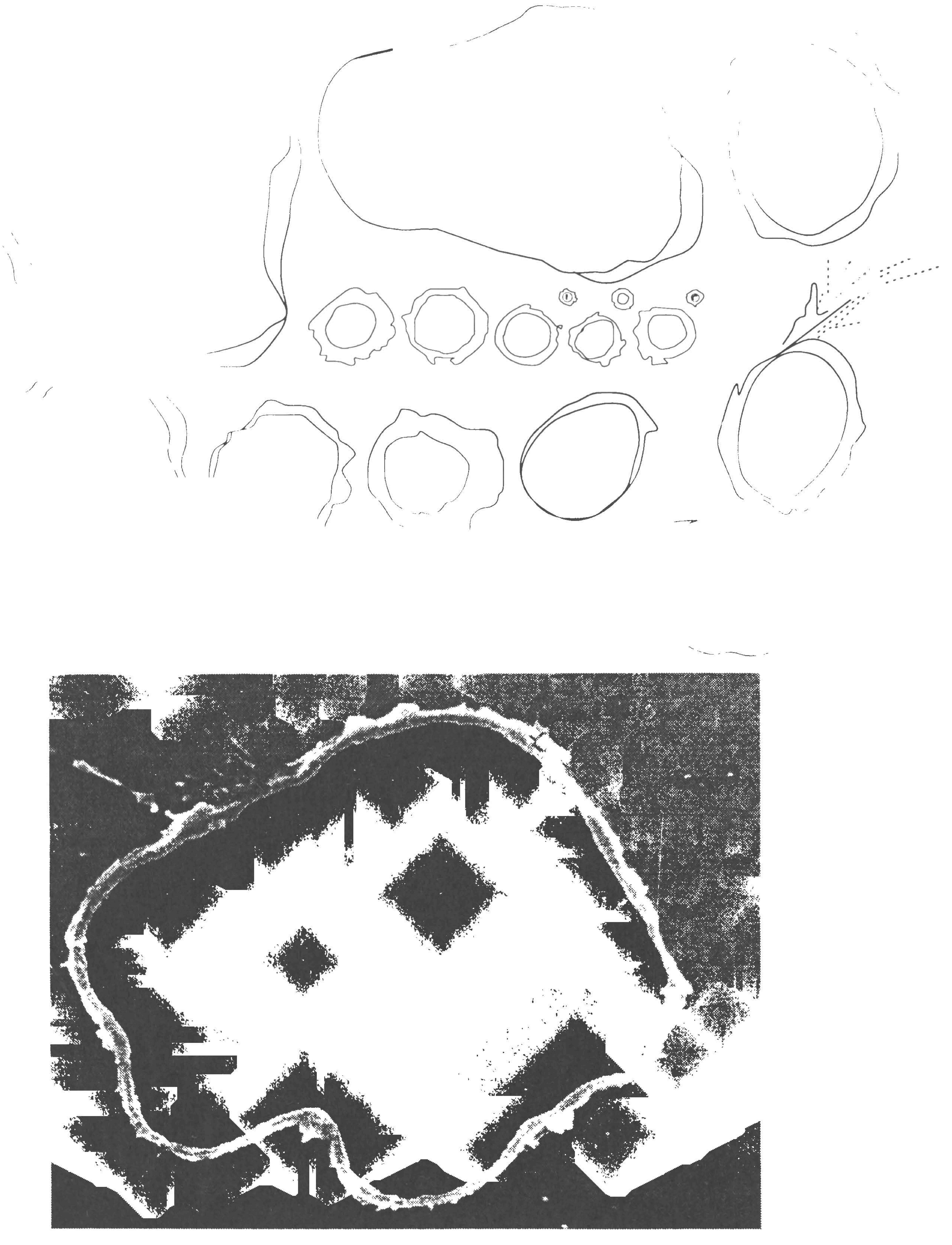

Figure 3. Typical perforations found on the EuReCa TiCCE experiment. Particle shape is not preserved for the smallest impacts, but large particles effectively "punch out" their geometrical cross section. The line drawings in the upper portion of the figure are all at the same (arbitrary) scale. It should be noted that some of the ellipticity in the foil perforations is due to non-normal impact trajectories.

5. Conclusions

1. The particle flux detected by LDEF agrees well with the mean interplanetary flux model of Grün et al. for $F_{max} > 30\,\mu m$. Below $30\,\mu m$ a significant enhancement is observed on the north south and east faces, which is attributed to space debris.

2. The flux detected by the Eureca Satellite is consistent with a significant bias in the meteoroid population towards the Earth's apex of motion.

3. Flux comparisons between thick and thin target data give a mean particle density of 1.5–2.0 g/cm^3 for particles in the range $5\,\mu m < F_{max} < 150\,\mu m$.

4. Concerning particle shape factors, the general agreement between the theoretical distribution of perforation shapes from spherical impactors and the distribution observed on the TiCCE satellite leaves little room for high aspect ratios for meteoroids, despite the low density determined from the penetration densities. An aspect ratio of up to 2:1 would be typical, and thus penetration comparable to a spherical impactor.

5. In the meteoroid region an upper limit of the space debris flux on LDEF of 30% is derived.

6. Acknowledgements

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