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Meteoroid and Debris Impact Life of Spacecraft Optics

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Optical systems have been an integral part of space technology since Lunik 3 returned the first pictures from the far side of the moon in 1959. Meteoroids present an obvious hazard, and these natural projectiles have been joined by increasing numbers of man-made debris as space exploitation expands. Although the probability of catastrophic impact caused by the micrometeoroid and orbital debris environment is still extremely small for any given lens or mirror, degradation caused by roughening of the optical surfaces by microimpacts is almost certain, especially in lower orbits. A straightforward algorithm is presented for analyzing this degradation, along with an example analysis for a spacecraft in a Molniya orbit.

Nomenclature

A	=	projected surface area of optical component, m^2
D	=	crater diameter, cm
D/d	=	ratio of crater diameter to particle diameter
d	=	particle diameter, cm
d_d	=	debris particle diameter, cm
d_m	=	meteoroid particle diameter, cm
F	=	flux per square meter per year
F'	=	flux on optical surface per year
F_d	=	debris flux per square meter per year
F_m	=	meteoroid flux per square meter per year
$F_1(d)$	=	debris flux subfunction, $1.05 \times 10^{-5} d^{-2.5}$
$F_2(d)$	=	debris flux subfunction, $7.0 \times 10^{10}(d + 700)^{-6}$
G_e	=	tabulated gravitational defocusing factor (range: 1.0–0.57)
$g_1(t)$	=	debris growth function, $(1 + 2p)^{(t-1985)}$
$g_2(t)$	=	debris growth function, $(1 + p)^{(t-1985)}$
h	=	altitude, km (for debris $h < 2000$ km)
i	=	orbital inclination, deg
k	=	orientation factor, 1.0 for a randomly oriented or Earth-pointing optic
L	=	impact life, years
m	=	particle mass, g
N	=	number of particles of mass m or greater per square meter per second
p	=	historical annual growth rate of orbital mass, 0.05
R_E	=	radius of Earth, 6370 km
S	=	13-month smoothed solar flux F10.7 (range: 70–200)
t	=	calendar year A.D.
t_0	=	launch date A.D.
v	=	particle velocity, km/s
Δt	=	mission duration, years
ζ	=	body shielding factor (range: 0.6–1.0)
λ	=	wavelength, μ
ρ_p	=	particle density, g/cc
ρ_t	=	target (optic) density, g/cc
τ	=	orbital period, hr
τ_{LEO}	=	time to transit low-Earth-orbit region of space, hr
$\phi(h, S)$	=	debris flux subfunction, $\phi_1(h, S)/[\phi_1(h, S) + 1]$ (range: 0.005–1)
$\phi_1(h, S)$	=	debris flux subfunction, $10^{(h/200 - S/140 - 1.5)}$
$\psi(i)$	=	tabulated function of orbital inclination (range: 0.90–1.78)

Introduction

OPTICAL components on spacecraft are exposed to several degradation mechanisms. These range from catastrophic impact damage and complete loss of function to uniform reduction of reflectance or transmittance caused by outgassed volatile condensation, ultraviolet, cosmic ray, and Van Allen radiation.

On spacecraft designed to carry optical systems, volatile condensation is minimized through selection of low-outgassing materials of construction. Properly selected and coated mirror and lens materials are not sensitive to degradation by moderate levels of radiation. Catastrophic impacts still have a low probability, even in increasingly debris-cluttered near-Earth space; however, that optics will encounter submillimeter-sized particles that produce craters is absolutely certain (see Fig. 1).

Hypervelocity impact is more complex than simple penetration. It involves such phenomena as 1) thermally induced melting and cratering at the point of impact, out to a diameter up to 20 times the diameter of the impacting particle; 2) fracture of surrounding material with propagation of cracks up to 100 times the diameter of the impacting particle; and 3) shock-wave induced spalling of material from the back of the target to produce secondary projectiles.

Flight measurements to date indicate that these smaller impacts have negligible effect on optical reflectance and transmittance. Unfortunately, direct data for the effects on scatter are limited. Because low scatter is essential to the proper performance of imaging optics, the remaining analysis will focus on these phenomenon.

Optical Requirements

Analysis begins with determination of the relevant optical performance parameters. These consist of the wavelength λ of system operation and the level of scattering to which the system may be allowed to degrade before functionality is impaired. The second item can be specified in terms of bidirectional reflectance distribution function (BRDF); total integrated scatter (TIS), sometimes called total hemispherical scatter; or contamination level per MIL-STD-1246.[1]

In all cases it follows that the end-of-life (EOL) value specified must be larger than the beginning-of-life (BOL) value, usually by an order of magnitude. Any particle distributions in place on the optic at launch will therefore be "swallowed" by subsequent distributions involving larger particles in greater numbers. Consequently, for reasonable fabrication and specification practices the EOL contamination level should be independent of the BOL level.

The various functionality limit specifications are related as follows. TIS is found from BRDF as[2]

$$\text{TIS} = 0.022(\text{BRDF}) \tag{1}$$

and TIS is related to contamination level by[2]

$$\text{Level} = \left[\frac{(\text{TIS})\lambda^2}{5.5 \times 10^{-15}}\right]^{\frac{1}{5}} \tag{2}$$

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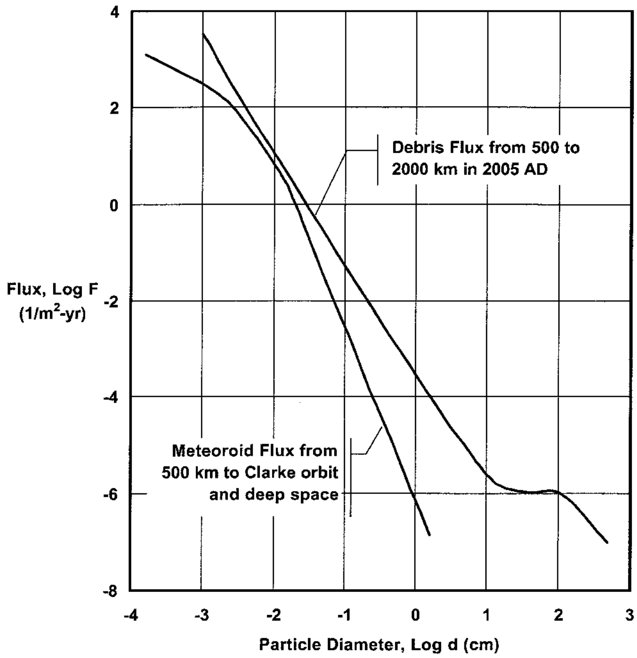

Fig. 1 Particle fluxes for both natural meteoroids and man-made debris. The natural meteoroid flux is constant, while the debris flux is moving upward with time.

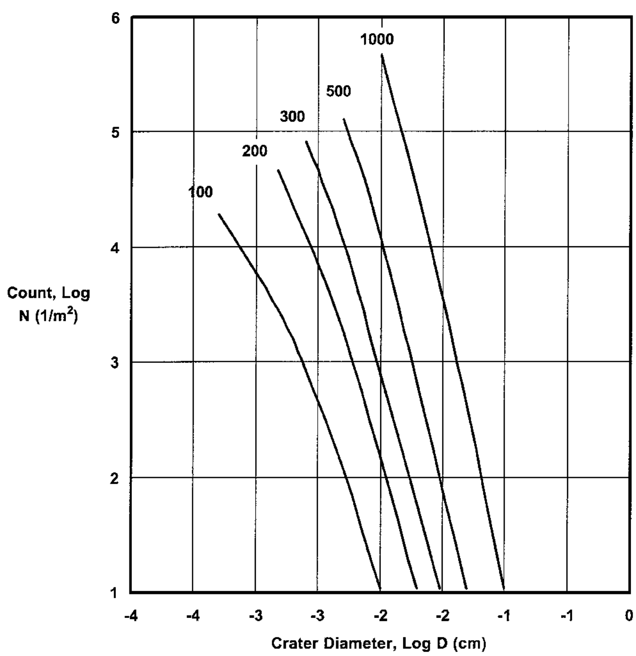

Fig. 2 MIL-STD-1246 cleanliness level vs crater diameter.

The contamination level is defined so that the numerical value equals the size, in microns (10^{-6} m), of the largest particle. There will be one particle of this size in one square foot, or 10.8 particles of this size per square meter, with a distribution of smaller particles.[3]

With respect to optical scattering, there is no difference between spherical particles resting on top of a surface and hemispherical cavities (craters). Thus, a given contamination level corresponds directly to the largest crater size of interest for scattering analysis (Fig. 2). This crater size D may be related to particle diameter d through the following relation[2]:

$$D/d = (\rho_p/\rho_t)^{\frac{1}{3}} v^{\frac{2}{3}} \tag{3}$$

The particle diameter is obtained as

$$d = D/(D/d) \tag{4}$$

Table 1 Correction factor values

h, km	G_e
0	1.00
2,000	0.900
20,184	0.670
35,786	0.632
40,180	0.627

and the particle mass can be found as

$$m = (\pi d^3/6)\rho_p \tag{5}$$

Meteoroids

The natural meteoroid flux consists of particles, mostly of cometary origin, with an average density of 0.5 g/cc moving at an average omnidirectional velocity of 20 km/s near Earth.[4] The basic flux is given by

$$\log_{10} N = \begin{cases} -14.37 - 1.213\log_{10} m & : \quad m > 10^{-6} \\ -14.34 - 1.584\log_{10} m - 0.063(\log_{10} m)^2 & : \quad m < 10^{-6} \end{cases} \tag{6}$$

Two correction factors can be applied to the basic flux: gravitational defocusing and body shielding. The gravitational defocusing factor accounts for the decrease in meteoroid flux density with increasing altitude, as fewer meteoroids are "focused" toward the center of Earth's gravitational field. This is presented as a chart in Ref. 4; a few key values of this factor are given in Table 1 for convenience.

The body shielding factor accounts for the directional decrease in meteoroid flux density with decreasing altitude, as the disk of the Earth fills more and more of the spacecraft field of view. The Earth thus acts as a shield to the spacecraft. This factor is defined by

$$\zeta = \tfrac{1}{2}(1 + \cos\{\arcsin[R_E/(R_E + h)]\}) \tag{7}$$

Mathematically, these two factors tend to cancel one another at any given altitude so that the net effect on total exposure is almost nil. They are included here for completeness. In practice, the flux on Earth-facing surfaces in low orbits is nearly zero, an important consideration for optics that point downward throughout most of their mission. Noting that there are $10^{7.50}$ s per year, the net yearly flux of meteoroids is then

$$\log_{10} F_m = \log_{10} N + \log_{10} G_e + \log_{10} \zeta + 7.50 \tag{8}$$

Debris

If the spacecraft orbit takes it below an altitude of about 2000 km, it will also be exposed to significant amounts of man-made debris (Fig. 1). This ranges from microscopic particles of solid propellant ash and paint flecks to derelict upper stages and dormant satellites. The relative velocity of these objects ranges from zero, for objects in the same orbit as the optical system, to about 11 km/s, for objects in retrograde orbits. This gives a working average impact velocity of 5.5 km/s, which is in excellent agreement with data from the Long Duration Exposure Facility (LDEF). The average density was once uniformly taken as 2.8 g/cc, but this has been modified by analysis of LDEF data and other sources as follows[3]:

$$\rho_d = \begin{cases} 2.8/d^{0.74} & : \quad d > 0.62\,\text{cm} \\ 4.0 & : \quad d < 0.62\,\text{cm} \end{cases} \tag{9}$$

The debris flux for any given year is found from[5]

$$F_d = k\,\phi(h, S)\,\psi(i)\,[F_1(d)\,g_1(t) + F_2(d)\,g_2(t)] \tag{10}$$

This model tends to overpredict fluxes for small particles (below 100-μm diam); in fact, the current consensus among researchers in this field is that the debris curve should taper off at small sizes, analogous to the observed flattening of the Cour-Palais curve for meteoroids. This phenomenon is caused by the likelihood that the very smallest particles (< 1 μm), with their low mass-to-area ratios, are blown right out of Earth orbit, if not out of the solar system, by light pressure from the sun.

The orientation factor k theoretically ranges from zero to four. In practice, k will approach zero on the wake surface of a spacecraft (opposite the spacecraft velocity vector) and a value of 3.5 on the ram surface. For surfaces at right angles to the spacecraft velocity, or for randomly oriented surfaces, $k = 1.0$.

The solar extreme ultraviolet flux S, as measured by proxy using 10.7-cm wavelength radio emissions, heats the thermosphere. Variations in this heating over the 11-year solar cycle cause the upper atmosphere to expand and contract. When it expands, satellites and debris particles alike at any given orbital altitude are exposed to more atmospheric drag. Periods of high solar heating, therefore, tend to show lower debris density.

The orbital inclination function $\psi(i)$ reflects the fact that debris is presently concentrated in two off-equatorial planes. Without specific knowledge of the proposed spacecraft inclination, a value of 1.5 is appropriate.

The value of t to use in Eq. (10) can be estimated from the launch date t_0 and the proposed mission duration Δt as

$$t = t_0 + \tfrac{2}{3}\Delta t \tag{11}$$

Impact Life

Given the flux of maximum size particles generating the crater size of interest for both meteoroids and debris, the total occurrence of critical impacts per unit area per year is given by

$$F = K_x[F_m + (\tau_{\mathrm{LEO}}/\tau)F_d] \tag{12}$$

This value is independent of optical component size because we are defining a particle distribution per unit area analogous to that in MIL-STD-1246.

The factor K_x in Eq. (12) accounts for shielding by the telescope shroud, sunshade, or contamination shield, if present. Using the spherical geometry presented in cross section in Fig. 3, the reduction of flux caused by increasing shroud length is found to be a simple function of exclusion angle:

$$K_x = 1 - \sin\alpha \tag{13}$$

Finally, having determined the number of craters of maximum allowable diameter produced on the optical surface each year, an "impact life" can be defined for the component as

$$L = 10.8/F \tag{14}$$

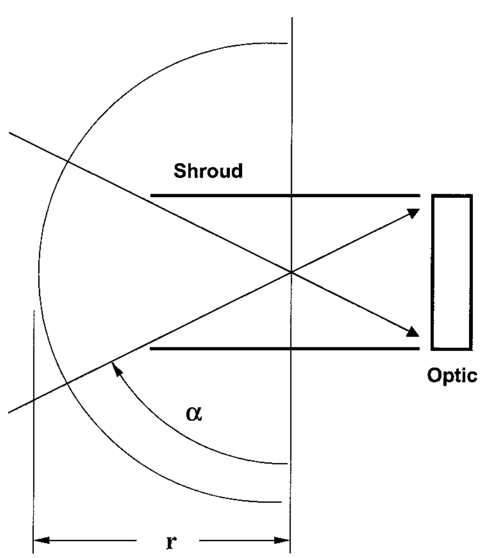

Fig. 3 Reduction of optic field of regard, and particle flux, as a result of the presence of shroud with exclusion angle α.

which indicates how long the optical component will meet its functional specification on orbit.

Example Analysis

Consider a silicon corrector plate on an Earth-observing spacecraft in a Molniya orbit. The operating wavelength is 4 μm. The optical performance limit is given in terms of TIS as 0.0022 sr^{-1}. The equivalent contamination level is

$$\text{Level} = \left[\frac{(0.0022)(4)^2}{5.5\times10^{-15}}\right]^{\frac{1}{5}} = 364$$

and so the crater size of interest is 364 μm. For silicon with a density of 2.5 g/cc, the crater/particle diameter ratio for the average velocity meteoroid is

$$(D/d)_m = (0.5/2.5)^{\frac{1}{3}}(20)^{\frac{2}{3}} = 4.3$$

The maximum meteoroid size is then

$$d_m = 364/4.3 = 84.7\ \mu m = 0.00847\,\text{cm}$$

The mass of a meteoroid with such a diameter is

$$m = (0.5\ \text{g/cc})[\pi(0.00847\,\text{cm})^3/6] = 1.59\times10^{-7}\ \text{g}$$

The basic flux of such particles and larger is found from Eq. (6) as

$$\log N = -14.34 - 1.584\log(1.59\times10^{-7}) - 0.063[\log(1.59\times10^{-7})]^2 = -6.48$$

The gravitational defocusing factor and body shielding factors are found using the mean altitude for a Molniya orbit or 20,090 km. From Fig. 8 in Ref. 4, $G_e = 0.67$.

$$\zeta = \frac{1}{2}\left[1+\cos\left(\arcsin\frac{6370}{6370+20,090}\right)\right] = 0.985$$

and so the yearly flux of meteoroids of diameter d_m or larger per square meter is

$$\log F_m = -6.48 + \log(0.67) + \log(0.985) + 7.50 = 0.840$$

$$F_m = 6.91\ \text{m}^{-2}\cdot\text{yr}^{-1}$$

For debris the crater/particle diameter ratio for the average velocity debris particle is

$$D/d = (4.0/2.5)^{\frac{1}{3}}(5.5)^{\frac{2}{3}} = 3.64$$

so the defining debris particle diameter is

$$d_d = 364/3.64 = 100\ \mu\text{m} = 0.0100\ \text{cm}$$

Calculating the basic debris flux automatically, using $k = 1.0$ for the Earth-pointing optic, $\phi(h, S) = 1.0$ on average, $\psi(i) = 1.5$, and a reference date of 2005 for a nominal duration of 10 years, $F_d = 10.6\,\text{m}^{-2}\cdot\text{yr}^{-1}$.

From Eq. (13), the flux reduction factor caused by the presence of a typical shroud with a 60-deg exclusion angle is $K_x = 0.134$. Using the astrodynamic relations presented in Ref. 6, the ratio of τ_{LEO} to τ is found as ~0.083. The total flux on the same temporal basis is then

$$F = (0.134)\,[6.91 + (0.083)(10.6)] = 1.04\ \text{m}^{-2}\cdot\text{yr}^{-1}$$

The impact life of the optical component is therefore

$$L = \frac{10.8\ \text{craters/m}^2}{1.04\ \text{craters/m}^2 \cdot \text{yr}} = 10.3\ \text{yr}$$

Conclusions

The foregoing analysis defines a simple, direct algorithm for estimating the useful life of spaceborne optics, based on scatter increases caused by impact craters, as specified by a contamination level. Cracks are not evaluated because previous investigations have shown them to be very small contributors to scatter. Also, the potential for secondary impacts on interior optics caused by spalling is ignored because the probability of impact by particles large enough to generate secondary projectiles is extremely small: about 10^{-5} for typical optic surface areas and mission durations. Finally, the differences between the distributions of smaller particles predicted by MIL-STD-1246 and those resulting from micrometeoroid and orbital debris impacts are also ignored, as it is the largest particles in each distribution that control the level of scatter.

This algorithm allows the analyst to rapidly assess changes in impact life with variations in the orbital time frame, altitude, inclination and eccentricity; the orientation of the optic relative to the Earth and the spacecraft velocity vector; and the configuration of any shrouds or adjacent spacecraft structures that may be present.

Acknowledgment

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