Shielding Distribution for Anisotropic Radiation in Low Earth Orbit

Mark W. Henley*
General Dynamics Space Systems Division, San Diego, California

The highly directional nature of radiation encountered in low Earth orbit (LEO) can be a basis for distributing mass for spacecraft radiation shielding. Trapped (Van Allen) radiation at low altitudes is concentrated within a plane perpendicular to the local geometric field lines. Trapped high-energy protons (which penetrate the relatively thin shielding required for electrons) have a pronounced east-west asymmetry at low altitudes, with the flux from the west much higher than that from the east. By distributing radiation shielding mass in response to these anisotropies, spacecraft mass can be reduced, the altitude limits of LEO extended, and the exposure of men and sensitive materials decreased. Geophysical behavior of trapped radiation is reviewed with particular emphasis on the factors responsible for radiation anisotropy. Shielding distribution in response to anisotropic radiation is then explored for consistently oriented spherical and cylindrical spacecraft. The 28.5-deg orbital inclination is considered in detail, with a brief extension of the concepts to other inclinations. These radiation shielding concepts may find near-term application in Space Station design.

Nomenclature

H = atmospheric scale height
I = magnetic dip
Je = flux from the east
Jw = flux from the west
R = magnetic dipole radius
Rc = radius of gyration
σ = standard deviation

Introduction

THE radiation flux encountered by a spacecraft in low Earth orbit (LEO) is anisotropic. Geomagnetically trapped charged particles are concentrated in a plane perpendicular to local geomagnetic field lines. Proton flux is asymmetric within this plane; more protons are incident from the west than from the east. Galactic radiation also exhibits an east-west asymmetry. Trapped radiation exposure at orbital inclinations between about 25 and 60 deg is related to spacecraft location with respect to geographic features, being greatest when the spacecraft is in the South Atlantic Anomaly (SAA).

We can maximize the effectiveness of a given mass of radiation shielding by distributing it in response to these anisotropies. Spacecraft shielding should be placed in locations that block incident radiation most effectively, i.e., in the plane of radiation and, predominantly, at the west-facing end. The mass required for trapped proton and galactic radiation shielding is prohibitive unless these anisotropies are considered. Radiation can also be combated through spacecraft orientation—the inherent mass distribution of a spacecraft can be oriented to minimize internal exposure.

These radiation shielding measures can benefit man in LEO. An "upper limit" to LEO altitude is created by trapped radiation; this limit can be extended. Radio biological effects of long-term LEO inhabitation can be reduced. Short-term biological and psychological effects (visual light flashes, corneal clouding, nausea, anxiety about future cancer or sterility, etc.) can also be moderated. The mass distributions discussed here are not limited to the protection of man, but they may also shield such sensitive materials as photographic film, electronic components, or perfect crystals grown in zero-*g*.

A nonuniform shielding distribution can also provide protection from hazards other than trapped radiation. Galactic radiation is more prevalent from the west than the east, thus a thick, west-facing shield for trapped protons may afford some additional reduction of galactic flux. The dosage from anomalously large solar flares may be reduced by orienting a nonuniformly shielded spacecraft so that its thickest shielding faces the direction of the most intense radiation. The spacecraft might also re-orient to point its thick (external) radiation shield toward meteoroid showers and orbital debris. The most heavily shielded end of a spacecraft could similarly be an appropriate place to dock explosive or radioactive satellites.

Prior literature has considered trapped radiation anisotropy with limited application to spacecraft shielding distribution. The east-west asymmetry in trapped protons due to the interaction of a planar radiation distribution was predicted by Lencheck and Singer[1] in response to the suggestion by Haerendel[2] that trapped proton fluxes in planar distributions at low altitudes are influenced by interaction with the atmosphere. Heckman and Nakano[3-5] were the first to confirm this prediction through experimental observations.

The planar nature of trapped radiation at low altitudes was first applied to radiation shielding considerations by Mar[6] and Fortney and Duckworth,[7] with subsequent comments on the importance of this anisotropy by Schneider and Janni,[8] Forthey,[9] Radke,[10] and Watts and Wright.[11] The present discussion extends the scope of previous shielding considerations for the planar nature of trapped radiation and applies the east-west asymmetry in trapped protons to spacecraft shielding.

The following discussion of non-uniform radiation shield distribution for spacecraft in LEO considers the factors responsible for the observed anisotropy of trapped radiation, and the shielding distributions for spherical and cylindrical spacecraft in 28.5-deg inclination orbits. The discussion is

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*Preliminary Design Engineer, Advanced Space Systems. Member AIAA.

briefly extended to include other inclinations and methods of controlling spacecraft orientation.

Geomagnetically Trapped Radiation

A basic understanding of the motion of charged particles within the Earth's magnetic field is essential in evaluating trapped radiation near the Earth. The motion of geomagnetically trapped particles is shown schematically in Fig. 1, which is modeled after a description by Hess.[12] A charged particle moving in a uniform magnetic field will follow a helical path centered on a magnetic field line. The distance between a particle and the field line that it orbits is known as its radius of gyration. Protons have larger radii of gyration than electrons, due to the greater mass and energy of the proton.

Convergence of geomagnetic field lines alters this simple helical motion. Field lines converge as a particle moves helically toward either magnetic pole, causing the pitch angle (the angle between the particle's velocity vector and the magnetic field) to increase. When the pitch angle reaches 90 deg, the particle stops its movement toward the pole and begins to return toward the equator. This endpoint in the particle's path along the field line is known as its mirror point; the plane within which the particle is confined is called the mirror plane.

Planar Radiation Distribution

Particles that are not moving normal to the magnetic field at the spacecraft's altitude are mirrored at lower altitudes and are lost from the Van Allen belts through interaction with the atmosphere. The pitch angle distribution about the mirror plane is, therefore, nearly planar at LEO altitudes. This distribution is approximately Gaussian,[3-4] with a standard deviation (σ) given by:

$$\sigma = [(3H/4R)(2+\cos^2 I)]^{1/2} \tag{1}$$

The standard deviation for low orbits at 28.5-deg inclination is roughly 10 deg.

East-West Asymmetry

The eastward flux of positively charged particles is greater than the westward flux. Protons moving westward are more likely to be filtered out by the atmosphere due to their lower mirror point altitudes (Fig. 2; modified from Ref. 4). The east-west symmetry is most pronounced for protons of higher energies because of their larger radii of gyration. The ratio of eastward to westward flux can be approximated by the expression:[12]

$$\frac{Je}{Jw} = \exp\{2Rc \cos I/H\} \tag{2}$$

where Rc is the radius of gyration.

South Atlantic Anomaly

Trapped radiation fluxes persist to low altitudes in one relatively small area, the South Atlantic Anomaly (SAA). The geomagnetic field is approximately a dipole offset by about 11 deg from the Earth's axis of rotation and displaced about 400 km toward the Western Pacific, causing an anomalous region over the South Atlantic where the Van Allen belts reach lower altitudes. The SAA is responsible for nearly all the trapped radiation flux received in low orbits with inclinations between 25 and about 60 deg. The location of the most intense proton radiation, as described by Stassinopoulos,[13] is illustrated in Fig. 3. (Proton flux shown is not current; the SAA location remains relatively accurate.)

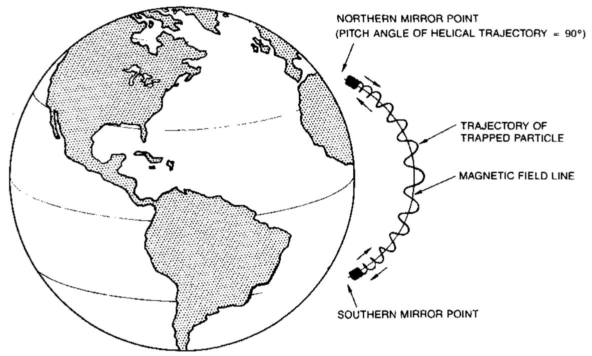

Fig. 1 Motion of a charged particle in a dipole field.

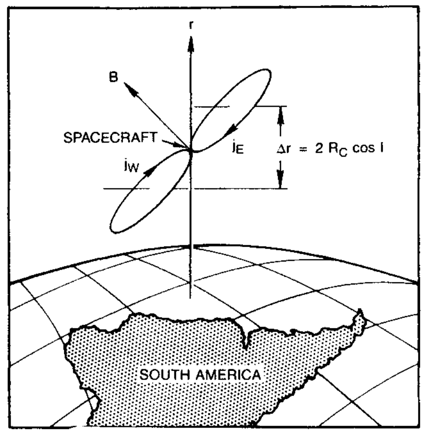

Fig. 2 East-west asymmetry in proton flux (after Ref. 3).

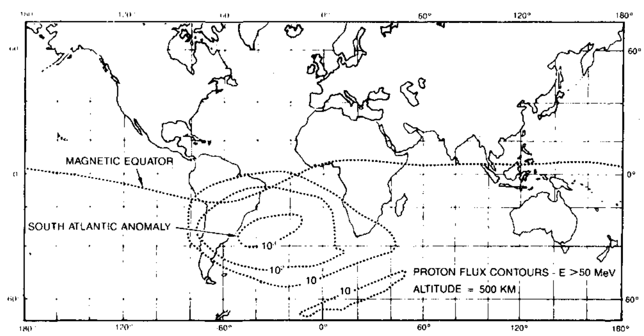

Fig. 3 The South Atlantic Anomaly contributes most of the dose in LEO (from Ref. 6); flux is given in terms of protons/cm^2 s. (For qualitative illustration only.)

Dependence Upon Altitude and Latitude

The flux of charged particles received from the Van Allen belts is strongly dependent upon altitude and latitude. The atmosphere filters out most trapped radiation with mirror points at low altitudes. A proton mirroring at the fringes of the atmosphere may or may not be absorbed, depending on the radius of gyration of its motion within the mirror plane around the mirror point. Protons of high energies (with very large radii of gyration) are thus removed preferentially by the atmosphere. Spacecraft in high-inclination orbits pass through the outer Van Allen belt and are exposed to increased electron fluxes. Orbits with inclinations between 25 and 60 deg spend more time within the SAA and receive larger fluxes of trapped protons.

Solar Effects

Solar activity influences trapped radiation. At solar maximum, the density of the upper atmosphere increases, resulting in more collisions of trapped particles and the neutral atmosphere at any given altitude, and reducing fluxes of trapped protons. Thus, spacecraft altitude may be increased at solar maximum to compensate for increased atmospheric drag while maintaining a relatively constant dose rate.

Solar activity also influences the anisotropy of trapped protons. The angular distribution of trapped protons is a function of the scale height of the atmosphere which, in turn, depends upon solar activity. Figure 4 illustrates the approximate extent of east-west asymmetry expected at solar maximum and minimum for various altitudes and proton energies.

Nonuniform Shielding Designs

The optimum shielding distribution for consistently oriented spacecraft in an anisotropic environment is nonuniform. In a planar flux, shielding should intercept the plane in a ring surrounding the volume to be shielded. In a unidirectional flux, shielding should be placed in the single direction of incident radiation.

High-energy protons normally contribute most of the dose received within a spacecraft in LEO. Electrons with energies typical of Van Allen belts can be stopped by relatively modest shielding thicknesses,[14] while much thicker shielding is required to stop trapped protons.[15] When one considers the relatively unidirectional flux of high-energy protons in LEO, such shielding becomes more practical. We might provide this shielding without increasing spacecraft mass by placing incidental materials (e.g., fuel, food, water, or refuse) in the proper locations to intercept the western section of the mirror plane.

Galactic radiation is a secondary factor in LEO, with relatively low total energy deposition but higher relative biological effectiveness (RBE).[16] Galactic radiation also exhibits an east-west asymmetry similar to that observed in trapped protons. The high-energy particles exhibited in the spectrum of galactic radiation require extremely thick shielding materials. In cases where great thicknesses of propellant or water stores (on the order of meters thick) are available, some moderation of galactic radiation may be achieved, again with benefits maximized by locating shielding masses toward the west. Effective application of the east-west asymmetry in galactic radiation to spacecraft shielding is limited to situations wherein very large shield masses are available, whereas trapped proton shielding in LEO can be realized with much more moderate shield thicknesses.

The 28.5-deg orbit is used extensively and deserves thorough consideration. The following discussion focuses on the 28.5-deg orbit, with a brief extension to other orbital inclinations.

Spherical Spacecraft

Our understanding of the anisotropy of trapped radiation in LEO is applied to the shielding of a spherical spacecraft in Fig. 5, demonstrating optimal shielding of a central point. While there are few, if any, spherical spacecraft at present, and the main concern here is with shielding a region rather than a point, the sphere is useful as an illustrative example. Radiation shielding of the sphere is distributed predominantly in the ring that intercepts the mirror plane. This annular distribution is skewed to the west in response to the east-west asymmetry in trapped protons.

Cylindrical Spacecraft

The flux received within a cylindrical spacecraft depends upon its orientation. Radiation dose reduction through cylinder orientation has been consdered previously.[6] The optimum orientation within a narrow pitch angle distribution is parallel to the mirror plane approximated by that distribution.

To minimize drag, an orientation that aligns the cylinder's axis of rotational symmetry with the direction of orbital motion is desirable. In this orientation, a cylindrical spacecraft in a 28.5-deg inclination is roughly parallel to the mirror planes of the South Atlantic Anomaly. The cylinder's axis will be tangent to the orbital path and therefore not always parallel to lines of geographical latitude. Lines of magnetic latitude (and mirror planes) are also not quite parallel to lines of geographic latitude. The actual angle between the mirror plane and the cylinder's axis thus varies between 0 and about 25 deg, depending upon the orbital path through the SAA.

As in the case of spherical spacecraft, addition of shielding for the consistently oriented cylindrical spacecraft will be most effective in certain locations (Fig. 6). Additional shielding would be wasteful in sections of the cylinder's surface that are perpendicular to the Earth's magnetic field during SAA transits (parallel to the mirror plane); it is most effective in sections perpendicular to the mirror plane. The east-west asymmetry again influences this distribution, as thickest shielding is placed at the west end of the spacecraft. Protons incident upon the cylinder's sides at oblique angles will encounter a greater thickness since they traverse materials in approximately straight-line paths. The optimum of shielding on the sides of the cylinder will taper from west to east.

This shielding distribution minimizes total radiation influx but will not shield all of the cylinder's volume equally. The central regions of the west end will have the lowest dosages, and it may be desirable to retreat to these regions during SAA transit or to design the spacecraft so that the most time-consuming activities (sleeping, etc.) are performed at the west end. While this shielding distribution does not pro-

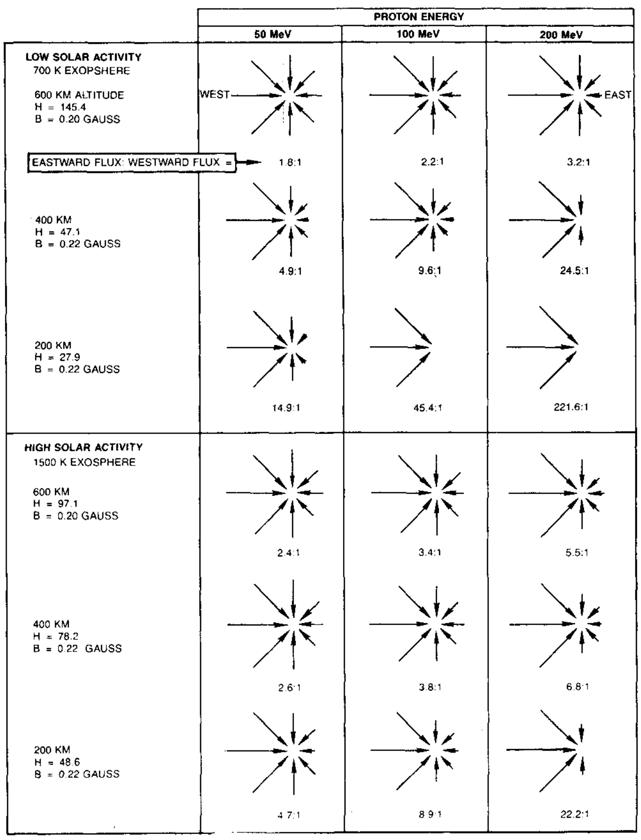

Fig. 4 Approximate east-west asymmetry in South Atlantic Anomaly; vector length indicates relative proton flux density.

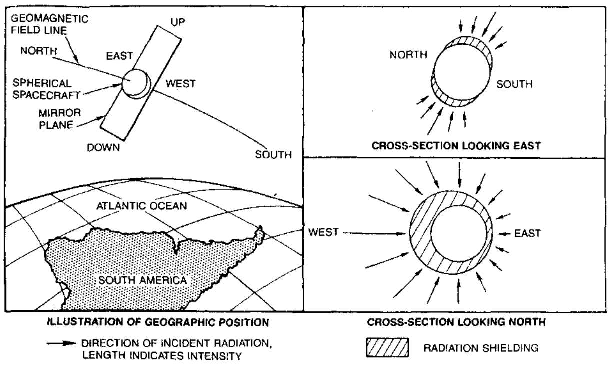

Fig. 5 Shielding distribution for a spherical spacecraft consistently oriented during transits of the South Atlantic Anomaly.

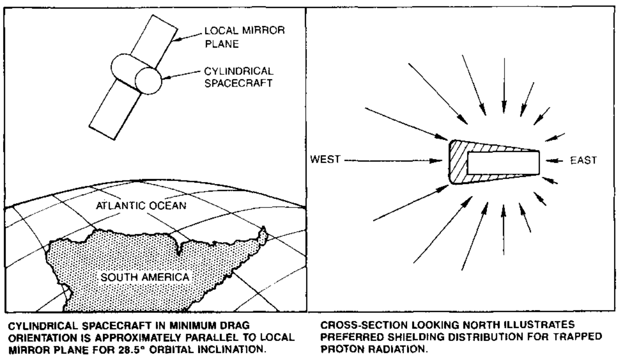

Fig. 6 Shielding distribution for a cylindrical spacecraft in minimum-drag orientation over South Atlantic Anomaly.

tect all portions of the internal volume equally, the dose in any portion of the spacecraft will be reduced significantly.

Orbital Inclinations Other Than 28.5 Deg

Orbital inclination has a strong effect on trapped radiation flux. Low-inclination orbits have a greater altitude range allowed by trapped radiation but this ceiling might be increased further by using the methods discussed here since these orbits apparently also have narrow pitch angle distributions.[17] High-inclination orbits are exposed to solar flare radiation and increased galactic fluxes, although a significant part of the total radiation flux is still from the SAA and outer Van Allen belts. Shielding for the east-west asymmetry becomes difficult for high inclinations because the west end of an Earth-oriented (or an inertially oriented) spacecraft on northward passes through the SAA becomes the east end on southward passes.

Orbits of intermediate inclination receive the greatest fluxes from the SAA. While 28.5-deg orbits do not cross the SAA's region of peak intensity, orbits with inclinations greater than about 45 deg transit this region on both northward and southward passes. Because magnetic latitude does not parallel geographic latitude, northward transits of the SAA place the minimum-drag-oriented cylinder roughly parallel to the mirror planes, while the cylinder is at significant angles during southward passes. Thus, the means of shielding large volumes of a cylinder discussed previously will apply well during northward passes, while retreat to a shielded region will be more advantageous during southward passes.

Control of Spacecraft Orientation

The shielding distributions and spacecraft orientations discussed here are gravitationally unstable: small controlling forces must be applied to counter the torque exerted upon the spacecraft by the gradient of the gravity field. Flywheel energy storage could allow temporary transfer of rotational energy to align the spacecraft parallel with the mirror plane with the same end presenting westward on all transits. Tether-gravity gradient techniques[18,19] for this purpose are also conceivable. Magnetic torques are another mass-conserving means of influencing attitude; their use could be worth the mass expenditure in special circumstances.

These are but a few of the potential means of affecting spacecraft orientation, which are discussed in detail elsewhere (e.g., Wertz[20]). It should be noted that gravitational instabilities may be inconsequential if the shielded volume is part of a larger system, e.g., a manned module on a Space Station.

Summary

Distribution of radiation shielding in response to the anisotropy of radiation in LEO can significantly increase the effectiveness of a given shield mass. The discussion here has been simple and brief, and might be expanded to include a quantitative optimum distribution for specific altitude, inclination, atmospheric conditions, and spacecraft geometry. In particular, shielding distribution for anisotropic radiation should be considered in the design of an Earth-oriented Space Station in a 28.5-deg inclination orbit. It is hoped that the concepts outlined here will assist mankind in LEO.

Acknowledgments

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