EMPIRICAL MODEL FOR THE EARTH'S COSMIC RAY SHADOW AT 400 KM: PROHIBITED COSMIC RAY ACCESS

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ABSTRACT

It is possible to construct a unit sphere of access that describes the cosmic radiation allowed to an earth-orbiting spacecraft. In the upper hemisphere of the allowed portion of the cosmic ray sphere of access, the cosmic ray cutoffs can be ordered by application of Stormer theory in offset dipole coordinates. In the downward hemisphere, in westerly directions, the cosmic radiation is allowed at large zenith angles well below the spacecraft-earth horizon, with particles being able to reach satellites at 400 km altitude from large zenith angles of ~140° at azimuthal directions equatorward of west in both the northern and southern hemispheres. We have found it is possible to model the occluded portion of the cosmic ray sphere of access as a circular projection having a diameter bounded by the satellite-earth horizon. Maintaining tangency at the eastern edge of the spacecraft-earth horizon, this optically occluded area is projected downward (toward the earth) by an angle β which is a function of the magnetic field inclination and cosmic ray arrival direction. This projected plane, corresponding to the forbidden area of cosmic ray access, is bounded by the spacecraft-earth horizon in easterly directions, and is rotated around the vertical axis by an angle α from the eastern direction, where the angle α is a function of the offset dipole latitude of the spacecraft.

1. Introduction. It is of considerable interest to evaluate the primary cosmic ray flux which is able to reach a satellite in earth orbit from any specified direction of arrival. The evaluation requires a knowledge of the geomagnetic cutoffs for all four pi steradins of possible arrival directions at all points along the spacecraft orbit. In practice, in order to keep the computational problem within manageable (and economic) bounds, cutoffs are generally calculated for a selected set of directions at each of a chosen set of representative directions along the orbit (Humble et al., 1979). It is then necessary to interpolate cutoffs for directions intermediate to those for which explicit calculations have been performed for a specific location, and for locations intermediate to those for which calculations have been undertaken for particular directions of particle arrival. For the upper hemisphere of arrival directions Smart and Shea (1977) showed that the cutoffs are reasonably

well ordered, for some locations, by Stormer theory. Humble et al. (1979) pointed out that at least some of the exceptions were due to the intervention of the 'shadow cone'.

Recent interest has focussed on particles arriving at the spacecraft from the lower, earthward facing, hemisphere. We have previously reported finding that primary cosmic rays are able to reach a satellite orbiting at quite low altitudes from zenith angles considerably larger than that of the local earth horizon. For a spacecraft at 400 km these angles are at least 140° at all latitudes we have investigated, and reach 150° at one location (Humble et al., 1983; Humble, 1983). We report here results from some further calculations of this type, and then describe a possible method for modelling the bounds of that portion of the unit sphere of access to which primary particles of any energy are unable to gain access because of the presence of the solid earth.

2. Method. A trajectory tracing technique has been devised to search rigidity/zenith-angle space for accessible arrival directions (Humble et al., 1983). The search proceeds, for a given location and azimuth, in the directions of increasing zenith angle and decreasing rigidity, until no further accessible directions of arrival can be found. A number of searches has been performed using this technique. Each was started at a zenith angle of 100° which is above the local satellite-earth horizon at all altitudes considered (Humble, 1984). It was found that, for zenith angles greater than that of the satellite-earth horizon, primary particles are only able to reach the satellite from generally westerly directions. Such particles experience a $\underline{V} \times \underline{B}$ force having a positive radial component in the final stages of their approach to the satellite. Their trajectories consequently have positive upwards curvature, and the local zenith angle of arrival can be greater than that of the satellite-earth horizon. The range of accessible azimuths increases with altitude, as would be expected.

3. Results at 400 km. A considerable number of trajectories have been calculated for the 400 km altitude. In analyzing these results we have found that it is possible to construct a unit sphere of access which describes the access of primary cosmic ray particles to any given detector. In the relatively simple case of a ground-level location the upper half of this sphere is totally allowed and the lower hemisphere is totally forbidden, due to the presence of the earth. For a satellite in earth orbit the situation is more complicated. All of the upper hemisphere is allowed to cosmic rays of some energy, as is part of the downward hemisphere. The latter may be divided into two parts. One is essentially a continuation of the allowed upper hemisphere - an annulus of allowed directions at zenith angles z_e such that $90° \leq z_e < z_h$, where z_h is the zenith angle of the horizon seen by the spacecraft. The second region lies at $z_e > z_h$, opens to the west, and is due to the $\underline{V} \times \underline{B}$ effect discussed in the previous section. The remainder of the sphere of access represents forbidden directions of arrival. We have found that it is possible to model the forbidden, or occluded, portion of the unit sphere of access, in an empirical manner and to varying degrees of accuracy, by the following technique.

Consider the equatorial plane of the unit sphere surrounding the spacecraft. Project the sphere onto a plane calibrated as a polar plot in zenith (as radius) and azimuth. Rotate the disc corresponding to the equatorial plane of the sphere through an angle β about a magnetic north south axis, until its projection, now an ellipse, on the polar plot has a minor axis which matches the distance between the largest and smallest values of zenith indicated. The rotated plane is then relocated, and subsequently rotated about a vertical axis, such that it is tangent to the satellite-earth horizon at the inner surface of the unit sphere at an angle α from the easterly direction. In our present model α is equal to the offset dipole latitude of the spacecraft. Figure 1 shows examples of the fit between the model curve and the points calculated for particular directions of arrival. The rms difference is about 3°; however, the greatest differences occur at positions where there is the largest deviation between the invariant latitude and the offset dipole latitude contours.

4. Results for Higher Altitudes. In general, it has been found that the largest accessible zenith angle for a given latitude, longitude, and azimuth, would also increase with increasing altitude. More detailed results are given by Humble et al. (1983) and Humble (1983). We have not yet applied the empirical model described in this paper to altitudes of 1000 km and above. Preliminary calculations have, however, been made. As the altitude increases above 1250 km a range of large zenith angles in generally easterly directions begins to become accessible, while smaller (but still below-horizon) zenith angles in the same azimuthal directions remain inaccessible. The higher altitude permits particles approaching the general region of the satellite at low altitudes from the west to pass above the top of the atmosphere more than one gyro-radius beneath the satellite. Such particles will arrive at the satellite from easterly directions at large zenith angles. The following table summarizes the results which have been obtained.

Altitude km	Maximum Zenith Angle
400	150°
600	156°
800	166°
1000	172°
1250	180°

Note that a zenith of 180° for an altitude of 1250 km means that primary cosmic ray nuclei are able to reach a satellite at that altitude from the nadir direction, directly underneath it, for at least one location somewhere on the orbit. This does not, however, mean that all possible directions of arrival are accessible at such a location. Easterly arrival directions at below-horizon zeniths are still forbidden.

References.

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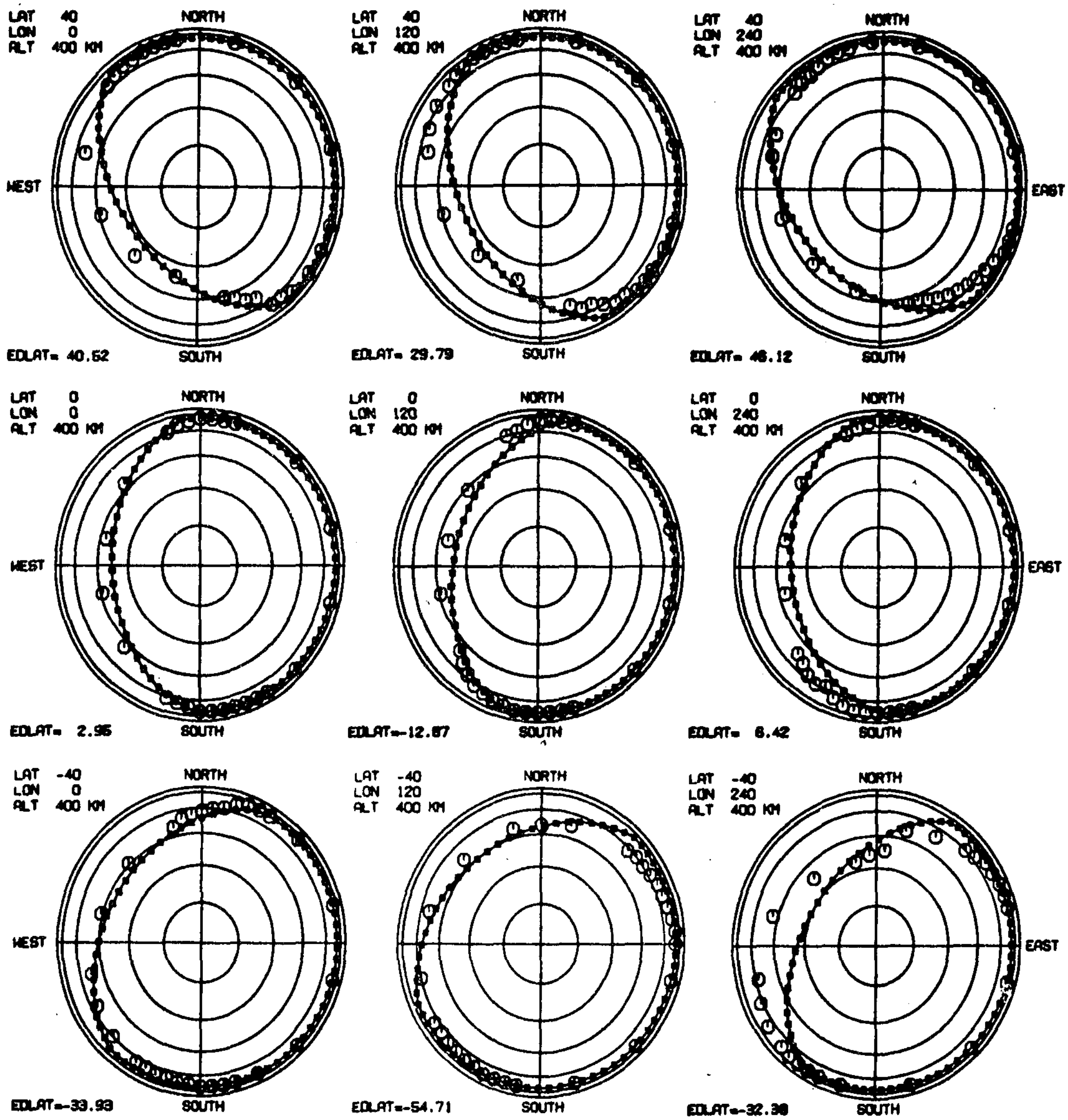

Figure 1. Polar projections of the downward hemisphere beneath an orbiting satellite. The occluded area beneath a satellite to which access is completely forbidden to galactic cosmic radiation of any energy is the area enclosed by the large dots in each projection. In this projection the observer is at the center of the spacecraft. This projection is looking downward from the center of the spacecraft; concentric rings represent 15 degree projections from the spacecraft equator to the nadir. Zero degrees is upward from the top of the spacecraft, 90 degrees is the spacecraft equator, and 180 degrees is in the nadir direction. At the 400 km altitude the local satellite-earth horizon is 109.8° from the zenith. The large open dots in each panel indicate where the maximum accessible zenith directions were determined by the cosmic ray trajectory-tracing method. The line connected with small solid squares indicates the result of applying the model described in this paper.