SECULAR VARIATIONS IN THE GEOMAGNETIC FIELD AND CALCULATIONS OF FUTURE LOW ALTITUDE RADIATION ENVIRONMENTS

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ABSTRACT

Calculations of the low Earth orbit radiation environment for beyond the year 2000, based on the AE-8 and AP-8 trapped radiation belt models indicate that a very large increase in electron and proton fluxes can be predicted at that epoch. This erroneous result can be partially traced to an inconsistency between field model epochs used to compute B, L coordinates and those used in constructing the particle flux models and in the associated access software. The flux models employ a value of the geomagnetic dipole moment ($M = M_d$) appropriate to the late 1950's. Updating M within the access software does not fully resolve the problem since the Earth's field is shifting, bringing L shells to lower altitude, and it is rather recommended that flux and dose calculations be made using a common epoch for the flux models and the field model. Nevertheless, this does not account for the changes in the field which should have measurable effects on the low altitude environment. A coordinate system displaying improved characteristics, such as allowance for the field evolution and for the effect of atmospheric cut-off should be introduced. The important east-west asymmetries in particle fluxes at low altitude also need to be modelled. Ultimately, high quality flight data obtained at low altitudes are a prerequisite for the development of totally new radiation models appropriate to the year 2000 and beyond.

1. INTRODUCTION

The Earth's internally generated magnetic field is slowly decaying and shifting. Although the magnitudes of the changes are not large ($\sim 0.1\%$/yr decay, ~ 2.5km/yr increase in offset), they can have large effects on predictions of radiation levels in low Earth orbit, where there are strong gradients of particle fluxes resulting from atmospheric absorption.

Geomagnetically trapped energetic particles are tied closely to field so that it is best to describe their morphologies in terms of locations in the field. Problems have arisen because, whereas geomagnetic field models are regularly updated and include field evolution, the NASA models of the trapped radiation environment are static and correspond

Proceedings of the ESA Workshop on Space Environment Analysis,
9-12 October 1990, ESTEC, Noordwijk, The Netherlands, ESA WPP-23.

to mapping with respect to a geomagnetic field epoch of 1960 [Vette, 1989]. The current empirical trapped radiation belt models are AE8 for energetic electrons (0.04-7 MeV) and AP8 for protons (0.1-400 MeV). These are the latest in a series produced by Vette and co-workers at NSSDC [*Sawyer and Vette*, 1976, *Vette*, 1991] since the early 1960's. These models provide time-averaged, integral omnidirectional electron and proton fluxes as functions of particle energy and the geomagnetic coordinates L and B/B_0. The models are simplifications, inasmuch as short-time variations, diurnal variations and flux directionality are not treated (although pitch-angle distributions can be obtained from the B-dependence). They essentially consider the radiation belt populations to be frozen into the magnetic field. The geomagnetic coordinates used to organise the model fluxes were developed by *McIlwain* [1961].

2. NUMERICAL MODELS OF THE GEOMAGNETIC FIELD

A number of numerical models of the geomagnetic field, which describe the internal field and its secular variations by spherical harmonic expansions of the scalar potential V, where

$$\mathbf{B} = -\nabla V \tag{1}$$

exist in the literature, of which the principal ones are those contained in the International Geomagnetic Reference Field (IGRF) Series [*IAGA*, 1986]. The potential expansion is

$$V = a \sum_{n=1}^{k} \left(\frac{a}{r}\right)^{n+1} \sum_{m=0}^{n} (g_n^m \cos m\phi + h_n^m \sin m\phi) P_n^m(\theta) \tag{2}$$

where a is the radius of a reference sphere and has a value of 6371.2 km in the IGRF models, corresponding to the mean Earth radius. The position of a point of interest is specified with r, θ and ϕ, the geocentric distance, co-latitude and longitude respectively; g_n^m and h_n^m are the model coefficients and P_n^m are associated Legendre functions.

The IGRF models released since 1960 have had 120 spherical harmonic coefficients (to degree and order 10) and a further 80 (to degree and order 8) describing the secular variations of the corresponding main field coefficients in a linear fashion.

From these comprehensive models, a centred dipole model can be derived by simply limiting the expansion to degree and order 1 ($n = 1, m = 0, 1$). Equation (2) then becomes:

$$V = \frac{1}{r^2}(g_1^0 a^3 \cos\theta + g_1^1 a^3 \cos\phi \sin\theta + h_1^1 a^3 \sin\phi \sin\theta) \tag{3}$$

Each of the terms represent the contribution to the total dipolar potential from dipoles aligned with the three geocentric cartesian axes. This is easily seen since the scalar potential due to a dipole whose strength and orientation are given by a moment $\mathbf{m}$ is

$$V = \frac{\mathbf{m}.\mathbf{r}}{r^3} = \frac{1}{r^2}(m_z \cos\theta + m_x \cos\phi \sin\theta + m_y \sin\phi \sin\theta)$$

since

$$\mathbf{m} = m_x \hat{i} + m_y \hat{j} + m_z \hat{k}$$

and

$$\mathbf{r} = r \sin\theta \cos\phi \, \hat{i} + r \sin\theta \sin\phi \, \hat{j} + r \cos\theta \, \hat{k}.$$

The total dipole strength (moment) is therefore

$$M = a^3\{(g_1^0)^2 + (g_1^1)^2 + (h_1^1)^2\}^{\frac{1}{2}}. \tag{4}$$

For a given field model, it is possible to extract a value of dipole moment which includes, through secular variations in g and h, changes that take place with time. *Fraser-Smith* [1987] shows how higher order model terms can be used to compute such features as the magnitude of the eccentric dipole offset and the poles of the field.

3. GEOMAGNETIC COORDINATES

The B and L coordinate system mentioned previously has now become the standard method for organising charged particle data with respect to the geomagnetic field. B is the magnetic field strength and in an ideal dipole field L is the equatorial radius of the field line or its azimuthal surface of revolution, the L shell. L is a constant on a given dipole shell and so is a convenient labelling parameter for the shell. Particles drift around the Earth while they bounce between their mirror points where the field is B_m. To completely describe a *drift shell* both B_m and L are needed. (Note the distinction between dipolar L shell and a mirror-bounded drift shell). In regions where the true geomagnetic field is a perturbed dipole arising from solely internal sources, and described by the field models of the previous section, L is nearly a constant on a drift shell and so retains its utility [1]. For many applications the pair B, L are sufficient to define a location in the field because of the field's azimuthal symmetry and the particle azimuthal drifts. The value of L at a point P is defined by means of a function of the adiabatic integral invariant I at P:

$$I = \int_{P}^{P'} (1 - B/B_m)^{1/2} dl \tag{5}$$

where the integral is evaluated along the field line between the two conjugate mirror points P and P', and B_m is the field at the mirror points. I is a constant on a drift shell. The definition of L is then written as [*McIlwain*, 1961, *Hess*, 1968]:

$$\frac{L^3 B}{M_d} = f\left(\frac{I^3 B}{M_d}\right). \tag{6}$$

Where M_d is a constant, chosen by McIlwain to be numerically equivalent to the geomagnetic dipole moment of epoch 1955 [*McIlwain*, 1966]. When expressed in units of Gauss.Earth-radii^3, M_d=0.311653 and this allows L to be interpreted as a distance in units of Earth radii. Of course, as has already been indicated previously, this leads to L being identifiable as the equatorial radius of a field line in a *perfect dipole* of moment M_d.

Note that in this paper we use M_d to represent McIlwain's constant value for the geodipole moment, while M represents the value derived from the field model coefficients (Equation (4)) which can vary with time.

[1] In regions where the field is distorted or particle motions perturbed, e.g. at high altitudes or high latitudes, "shell splitting" [*Lemaire et al.*, 1990, *Lyons and Williams*, 1984] results - particles which mirror at different fields, B_m, on the same line of force will not follow the same drift shell. Nevertheless, a value of L computed from purely internal sources is still a valuable and comonly used *ordering* parameter at high altitudes.

The function f is derived from a dipole representation of the field but is evaluated using I and B values for the true field computed from a field model. L is found to be nearly constant on a drift shell. *McIlwain* [1961] provided a numerical recipe for f which consisted of sets of coefficients for a 9^{th} order polynomial. This yielded an accuracy in the computation of L of better than 0.3% and in some regions better than 0.03%. *Hilton* [1971] found that the function f is more simply represented by the function

$$f(X) = 1 + a_1 X^{1/3} - a_2 X^{2/3} - a_3 X \tag{7}$$

where $X = (I^3 B / M_d)$ and

$$a_1 = \frac{3(2)^{1/2}}{\pi} \approx 1.35047, \; a_2 \approx 0.456376, \; a_3 = \left(2 + 3^{-1/2}\ln(2 + 3^{1/2})\right)^{-3} \approx 0.0475455$$

According to Hilton, the error in L is less than 0.01% for all L. Note that a_1 and a_3 are strictly numeric while a_2 is determined by an error minimisation procedure. (Hilton's paper contains a typographical error in omitting the minus sign from the (-1/2) exponent in the expression for a_3). It should be noted that the NASA trapped radiation flux models were constructed using McIlwain's method.

At the geomagnetic equator, which corresponds to the position on a field-line with the minimum B, $I = 0$, and therefore

$$B = B_0 = \frac{M_d}{L^3}. \tag{8}$$

By transforming orbital locations into the $B/B_0, L$ coordinate system and accessing the radiation environment models throughout the orbit, predictions can be made of satellite radiation exposures. Most software for accessing the trapped particle models make use of McIlwain's algorithm for computing L and the definition of B_0 in Equation (8).

4. ESA'S *UNIRAD* RADIATION ENVIRONMENT ANALYSIS TOOL

ESA uses the *UNIRAD* system for routine analysis of terrestrial radiation environments, [*Daly*, 1988]. The principal components of this system are:

- an orbit generator, *SAPRE*
- the *SHELLG* geomagnetic field program
- geomagnetic field models
- the *TREP* program for accessing environment models and providing orbital fluxes and average spectra;
- models of energetic trapped particle fluxes
- the *SHIELDOSE* code for computing radiation doses

UNIRAD is itself incorporated into the *ESABASE* multidisciplinary spacecraft systems analysis framework [*De Kruyf*, 1988] as shown in Figure 1.

The orbit generator and geomagnetic field model programs provide geomagnetic B/B_0 and L coordinates at points on a user defined orbit which the *TREP* program uses to access the NSSDC trapped particle models AE8 and AP8. *TREP* uses these positional flux data to compute fluxes as a function of orbit time and orbital-average spectra. Use of a geomagnetic field model requires that an appropriate epoch be defined, and problems arising when the field model epoch is set to times incompatible with that epoch used in establishing the particle models are dealt with in the next section.

5. EXTRAPOLATION OF TRAPPED PARTICLE FLUXES

It has been pointed out by *McCormack* [1986, 1988] and by *Konradi et al.* [1987] that, as a consequence of the secular evolution of the geomagnetic field, the low-altitude trapped radiation fluxes predicted for the year 2000 increase dramatically when calculated using standard methods and software.

This is an artifact of the use of an updated field model for computing B (Equations 1 and 2) while computation of B_0 and L (Equations 6 and 8) use the "hard-wired" value for the geomagnetic dipole $M = M_d = 0.311653$ Gauss.R_E^3, corresponding to 1955. *Vette and Sawyer* [1986] suggested the use of $B/B_0, L$ rather than B, L with B_0 and L computed using a geodipole moment consistent with the epoch of B computations. It was thought that this would lead to "more reasonable" results. *Konradi et al.* [1987] and *McCormack* [1988] reported this suggestion which involves making use of Equation (4) to compute M and replacing M_d in Equations (6) and (8) by this M. Figure 2 shows the variations in M for the period 1945 to 1985.

Daly [1989] investigated this solution by running the *UNIRAD* system for circular low Earth orbits at both 300 km and 500 km altitudes at an inclination of 28.5°. In this study, B, L coordinates were generated for a large number of points on 13 consecutive orbits, thereby giving reasonable coverage of the low-altitude geomagnetic and radiation environments for subsequent orbit average flux computations. In order to be consistent with the method used in creating the flux models, McIlwain's algorithm was used for computing L.

The IGRF geomagnetic field model of 1980 was used, and extrapolated backwards and forwards in time to cover the period 1960-2000. Two methods were used to compute $B/B_0, L$ coordinates: (i) retain "McIlwain's" M_d in the equations for B_0 and L; and (ii) replace M_d with M. To complete the comparison, computations were also made using the NASA/GSFC/1960 geomagnetic field model of *Jensen and Cain* [1960]. Some of the results thereby obtained by *Daly* [1989] are reproduced in Figures 3 and 4.

These figures show the orbit averaged integral fluxes of protons above 100 MeV (Figure 3) and of electrons above 2 MeV (Figure 4). Within each figure, plot (a) corresponds to 300 km and plot (b) to 500 km altitude.

The cross at epoch 1960 corresponds to the result obtained with the GSFC-1960 geomagnetic field model and using M_d to compute L. The curves labelled "IGRF with McIlwain's M", correspond to case (i) above (using M_d) while the curves labelled "IGRF-1980" correspond to case (ii) (using M).

It can be seen from Figures 3 and 4 that the low altitude fluxes of protons and electrons calculated for the year 2000 increase drastically, and most dramatically, at low altitudes. When the actual magnetic moment M is used instead of McIlwain's standard value, the secular increase in intensity is much less dramatic.

Equations (6) and (7) show that in case (i), since B will decay in proportion to M, and I and M_d are constant, to a first approximation the computed L will vary in proportion to $M^{-1/3}$. L will increase slightly and the steep flux gradients at low altitude lead to the observed increase in Figures 3 and 4. In case (ii), M_d is replaced by M and Equations (6) and (7) show that the computed L is invariant to changes in M. Therefore the residual variation in fluxes is not related to changes in L induced by a decaying field. For the source of the residual variation we must consider higher-order terms of the secular variation, in particular, those describing the position of the field with respect to the Earth. The secular variations of the quadrupole terms in the expansion cause a slow variation in the position of the magnetic centre (the "eccentricity"). The centre of the dipole is receding from the Earth's centre at a rate greater than 2 km/year. Figure 5, from *Fraser-Smith* [1987] shows the secular variation of the projection of the eccentric dipole position on the geographic equatorial plane during the interval 1600-1985. This eccentric displacement, in the direction of the North Pacific means that physical locations in the South Atlantic anomaly region will have L values in the future which at previous times were at higher altitudes, containing higher particle fluxes. Particle shells are gradually dipping deeper into the atmosphere over the South Atlantic, apparently enhancing the South Atlantic Anomaly. Over the period 1955-1985, the offset of the geodipole has increased by some 70km. This is large compared to the scale height of particle flux variations and explains the results obtained by Daly. However, since the lifetimes of particles at typical LEO altitudes are only of the order of a few years, the "lowered" South Atlantic anomaly will be diminished by the atmosphere and the predicted increase will not occur.

6. PARTICLE RESPONSES

The discussion above on the response to changes in M were related to the computation of the geomagnetic coordinates for a point in space and did not refer to changes in particle properties induced by secular field variations.

Heckman and Lindstrom [1972] and *Schulz and Paulikas* [1972] indicate that the secular variation of M has an important effect on the stable energetic protons trapped in low L drift shells with long characteristic lifetimes (centuries).

The third adiabatic invariant of a particle's motion is the flux invariant:

$$\Phi = \oint \mathbf{B}.d\mathbf{A} = \frac{2\pi M}{L} \text{ in a dipole.} \tag{9}$$

So in a slowly decaying dipole, a particle will move to a lower L value. This secular inward drift is accompanied by an energy gain, a process known as betatron acceleration. These betatron effects are not modelled by the static radiation belt models, and are therefore not implicated in the results shown in Figures 3 and 4. Those figures relate solely to physical variations of $B - L$ space and not to particle effects. These adiabatic effects are important in establishing the steady-state distribution function for inner-zone protons [*Farley et al.*, 1972].

The changes in dipolar eccentricity discussed in the previous section also move particles so some effect is expected. Changes to higher order field terms will also produce effects on the particles and their locations due to the field deformations they describe.

The above effects are expected to be largely washed out by atmospheric absorption. All must compete at low altitudes ($\sim$ 500km) with atmospheric absorption; particle lifetimes here are only of the order of a few years. Particles are partially replenished by Albedo Neutron Decay, where cosmic rays generate neutrons in the upper atmosphere which subsequently decay into protons and electrons within the radiation belts. This process refreshes particle fluxes in a manner independent of the field so that a steady-state is established and to a first approximation one can think of the environment being static. This leads to the conclusion that the best procedure to adopt for predicting particle fluxes in the low altitude region is to use geomagnetic field models, and procedures for computing L and B_0, which are as close as possible to those adopted when the flux models were created. For current models, this means using the Jensen and Cain model field with the year set to 1960, using McIlwain's algorithm for computing L and employing McIlwain's dipole constant M_d [*Lemaire et al.*, 1990].

Note that this is at variance with one of the suggested procedures of *Konradi et al.* [1987], namely that epochs 1964 and 1970 should be employed for solar minimum and solar maximum respectively. Even a 10-year extrapolation can yield significant spurious enhancements.

The geographical shift in the location of the South Atlantic anomaly is a remaining effect. It is not possible to predict the correct drifted South Atlantic anomaly fluxes with present-day models.

7. ALTERNATIVE COORDINATE SYSTEMS

The 'standard' B, L coordinate system is described by Equation 6. We have already discussed a modification of this where M_d is replaced by a contemporary magnetic moment M. *Hilton* [1971] suggested that $L = L(M)$ should be calculated in this way.

This would seem reasonable from the point of view of retaining the invariance of L with changes in M, for minimising extrapolation effects and for retaining the concept of L as an invariant dipolar radius. However, it does not solve the practical problems because of the changes to the higher-order moments of the field mentioned above (i.e. offset increase). A further disadvantage comes from the fact that each satellite data set should in principle be ordered according to a contemporary value for M. This could cause problems when attempting to inter-compare data sets. It would then be important that particle data be kept in their original geographic coordinate system for subsequent re-evaluation [*Lindstrom and Heckman*, 1968].

Roederer [1970] proposed an alternative L parameter based on Equation 9 and inversely proportional to a particle's flux invariant Φ. This is interesting from a theoretical standpoint in considering betatron effects, etc. (see also *Schulz and Lanzerotti* [1974]), but it is not helpful for practical applications.

It would be more stable and more practical in future applications (constructing new models, etc.) to maintain the use of a constant M_d, while also using contemporary field models for B computation. Note that it is not necessary in the definitions of L and B_0 (Equations 6 and 8) to set M_d numerically equivalent to the geodipole moment. The problem with this is that it leads to a conceptual inconsistency between the allowed secular variations in higher-order term while apparently fixing the geodipole moment.

Pfitzer [1990] has recently shown that orbit-integrated particle fluxes and doses are well-ordered by simply plotting them as a function of atmospheric density. This is a very simple and efficient method but is targeted mainly at total integrated dose calculations. It has a great advantage in that it provides a smooth variation in doses with solar activity (which drives atmospheric density). It does, however, mean employing different coordinate systems in different geospace regions. *Lemaire et al.* [1990] suggested a variant on this, making use of a height parameter corresponding to the height where the local density is equal to the drift-shell averaged density (the "Hassitt shell height", H_s). A hybrid coordinate system might also be possible, if the altitude representing the atmospheric cutoff were made a variable function of atmospheric density n and used to define the cut-off B value, B_c. B/B_0 could be replaced by:

$$b = \frac{B - B_0}{B_c(H_c) - B_0}, \text{ where } H_c = H_c(L, n)$$

So that $b = 0$ at the geomagnetic equator and $b = 1$ at the atmospheric cut-off. The drawback of this might be the rapid variations in particle fluxes close to the $b = 1$. In that case an angular coordinate $\beta = \sin^{-1} b$ could be utilised so β=0 at the geomagnetic equator and $\beta = 90°$ at the atmospheric cut-off. Such a system could be used at high altitudes as well as in LEO.

8. THE EAST-WEST EFFECT

In addition to the secular variations in the geomagnetic field, noted above, the effects of atmospheric cut-off should be taken properly into account in future modelling efforts. This problem is currently being considered by *Watts et al.* [1989] at NASA/MSFC (see also *Armstrong et al.*, this workshop).

Heckman and Nakano [1963] showed that at an altitude of about 400 km in the region of the South Atlantic Anomaly, some 2.3 times as many protons of energy > 57 MeV entered their instrument from the west as from the east. The explanation offered for this effect is that, at this location, the protons moving from west to east, (J_E) had their guiding centres above the satellite while the protons moving from east to west, (J_W) had their guiding centres below the satellite, in regions of higher atmospheric density. The east-west ratio is given by

$$J_E/J_W = \exp\left(2R_0 \cos(I/H)\right) \tag{10}$$

where I is the dip angle of the field line, H the atmospheric density and R_0 the gyroradius. At low altitudes, R_0 for 50 MeV protons is indeed of the order of the density scale height (i.e. H = 50-60 km).

Although, in existing models of trapped radiation belts this east-west effect is not presently included, it would be desirable to incorporate the effect in future models of the low altitude radiation environment. This is a topical problem because future spacecraft, including the space station, will have constrained attitudes with respect to the geomagnetic field so that the anisotropy will be very apparent in on-board effects. This is in contrast to past missions where attitudes were highly variable and anisotropies were averaged-out.

9. CONCLUSIONS

This paper has reviewed some of the problems of coordinate systems and the radiation environment at low altitude. It is clear that relatively little work has been done on this area since the early 1970's and the importance of the LEO altitude regime for future space programmes has stimulated recent interest. The radiation environment and effects community is especially lacking modern flight data on the environment and its evolution. The acquisition of long-term flight data with good positional, temporal, directional and energy resolution is seen as crucial for replacing the ageing environment models. CRRES

[*Gussenhoven et al.*, this workshop] samples the LEO region rather poorly because of its rapid transits through perigee. A dedicated mission is the logical step to take.

We recommend in the meantime that the procedure to be adopted when using AP8 and AE8 is to retain use of McIlwain's algorithm with the constant M_d=0.311653 Gauss.R_E^3 and use the Jensen and Cain field model for epoch 1960. Use of later field models and epochs leads to spurious increases ion fluxes and doses because it causes changes to the L parameter. Although updating the geodipole moment M leads to an invariant L parameter, its use with updated field models and epochs still leads to a residual spurious increase because of the increasing offset of the geodipole ($\sim$ 2.5km/yr), described by higher order field model terms. Nevertheless, "freezing" the field does not account fully for variations in the location of features such as the South Atlantic Anomaly or include the effect of atmospheric cutoff.

In general, one should use the same procedures in accessing the trapped particle models as were used in their creation since these models do not yet possess the functionality to account for the subtle secular variations. *Lindstrom and Heckman* [1968] recommended that particle data be kept in their original geographic coordinate system for subsequent re-evaluation and we also believe that this is important.

"It is desirable ... that there be the minimum number of representations in use at any one time. The re-computation of L for a large body of data can be quite expensive, therefore the 'standard' magnetic field representation should be changed as infrequently as possible and only when a substantial gain in accuracy can be obtained" [*McIlwain*, 1966]. We believe that the time is right for the community to decide on improved methods.

On the long term, a coordinate system displaying improved characteristics, such as allowance for the effects of field evolution and atmospheric cut-off of particle fluxes should be developed. Ultimately, totally new models are required for epochs beyond the year 2000, and to achieve this aim high quality contemporary flight data obtained at low altitudes are a prerequisite. It should be noted in this context that much of the data employed for the current models are themselves based on extrapolations and are certainly very old.

REFERENCES

Daly E.J., 'The Evaluation of Space Radiation Environments for ESA Projects', ESA Journal 12, 229 (1988).

Daly E.J., 'Effects of Geomagnetic Field Evolution on Predictions of the Radiation Environment at Low Altitudes', ESTEC Working Paper 1531, January (1989).

De Kruyf J., 'ESABASE', ESA BR-54, (1988).

Fraser-Smith, A.C., 'Centered and Eccentric Geomagnetic Dipoles and Their Poles, 1600-1985', Rev. Geophys. 25, 1-16 (1987).

Farley T.A., M.G. Kivelson and M. Walt, 'Effects of Secular Magnetic Variations on the Distribution Function of Inner-Zone Protons', J. Geophys. Res. 77, 31, 6087 (1972).

Hassitt A., 'The drift velocity of trapped particles. ', J. Geophys. Res. 70, 535 (1965a).

Hassitt A., 'Average effect of the atmosphere on trapped protons. ', J. Geophys. Res. 70, 5385 (1965b).

Heckman H.H. and P.J. Lindstrom, 'Response of Trapped Particles to a Collapsing Dipole Moment', J.Geophys. Res. 77, 4, 740 (1972).

Heckman, H.H. and Nakano, G.H., 'East-West Asymmetry in the flux of Mirroring Geo-magnetically Trapped Protons', J. Geophys. Res. 68, 2117 (1963).

Hess W.N., 'The Radiation Belt and the Magnetosphere', Blaisdell Publ. Co. (1968).

Hilton H.H., 'L Parameter - A New Approximation', J. Geophys. Res. 76, 6952 (1971).

IAGA Division 1, Working Group 1, 'International Geophysical Reference Field revision 1985' Geophys. J.R. Astr. Soc. 85, 217 (1986).

Jensen D.C. and J.C. Cain, 'An Interim Geomagnetic Field', J. Geophys. Res. 67, 3568 (1962).

Konradi A., A.C. Hardy and W. Atwell, 'Radiation Environment Models and the Atmospheric Cutoff', J. Spacecraft 24, 284 (1987).

Lemaire, J. and members of the TREND team, 'Study of the Development of Improved Models of the Earth's Radiation Environment', ESA-CR(P)-3126, final report of ESA contract 8011/88 (1990).

Lindstrom P.J. and H.H. Heckman, '$B-L$ Space and Geomagnetic Field Models' J. Geophys. Res. 73, 11, 3441 (1968).

McCormack P.D., 'Radiation Dose and Shielding for the Space Station', paper IAF/IAA-86-380 at 37th International Astronautical Congress, Innsbruck (1986).

McCormack P.D., 'Radiation Dose and Shielding for the Space Station', Acta Astronautica 17, 231 (1988), also paper IAF/IAA-86-380.

McIlwain C.E., 'Coordinates for Mapping the Distribution of Geomagnetically Trapped Particles', J. Geophys. Res. 66, 3681 (1961).

McIlwain C.E., 'Magnetic Coordinates', Space Science Reviews 5, 585 (1966).

Pfitzer K.A., 'Radiation Dose to Man and Hardware as a Function of Atmospheric Density in the 28.5 Degree Space Station Orbit', private communication (1990).

Roederer J.G., 'Dynamics of Geomagnetically Trapped Radiation', Publ. Springer, Berlin, Heidleberg and New York (1970).

Sawyer D.M. and J.I. Vette, 'AP8 Trapped Proton Environment For Solar Maximum and Solar Minimum', NSSDC 76-06, NASA-GSFC (1976).

Schulz M. and L.L. Lanzorotti, 'Particle Diffusion in the Radiation Belts', Publ. Springer, Berlin/Heidelberg/New York (1974).

Schulz M. and G.A. Paulikas, 'Secular Magnetic Variation and the Inner Proton Belt', J. Geophys. Res. 77, 4, 744 (1972).

Vette J.I., 'Trapped Radiation Models', in: Study of the Development of Improved Models of the Earth's Radiation Environment, Technical Note 1, ed. J. Lemaire, ESA contract 8011 (1989).

Vette J.I., 'The AE-8 Trapped Electron Model Environment', National Space Science Data Center, (to be published, 1991).

Vette J.I. and D.M. Sawyer, private communication to P.D. McCormack, 1986.

Watts J.W., T.A. Parnell and H.H. Heckman, 'Approximate Angular Distribution and Spectra for Geomagnetically Trapped Protons in Low-Earth Orbit', in: High-energy Radiation Background in Space, p. 75-85. American Institute of Physics, New York (1989).

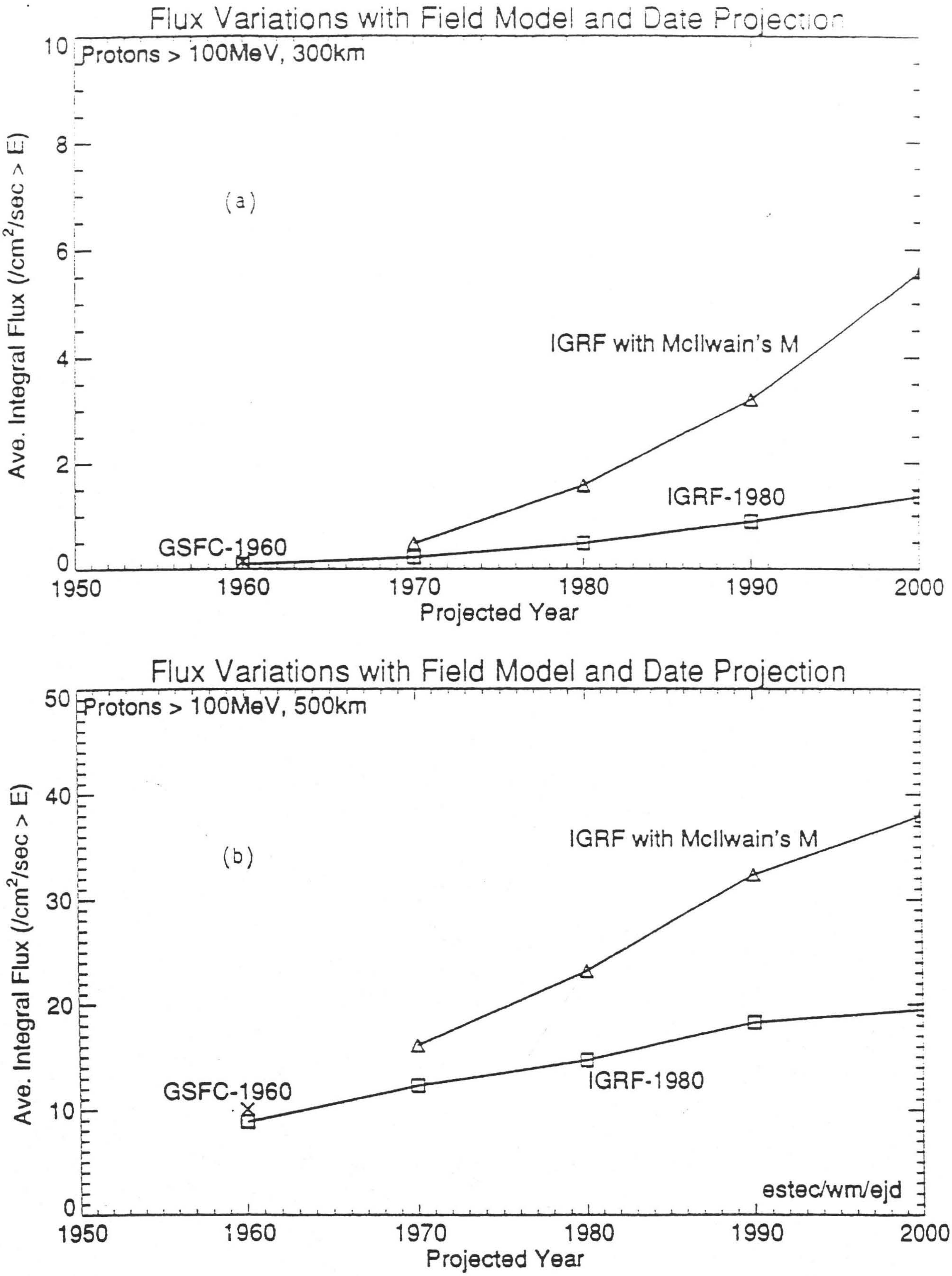

Figure 3: Variations of predicted orbit-averaged >100MeV proton fluxes as functions of extrapolated field date: (a) for 300km, 28.5° orbit; (b) for 500km, 28.5° orbit (after *Daly* [1989]).

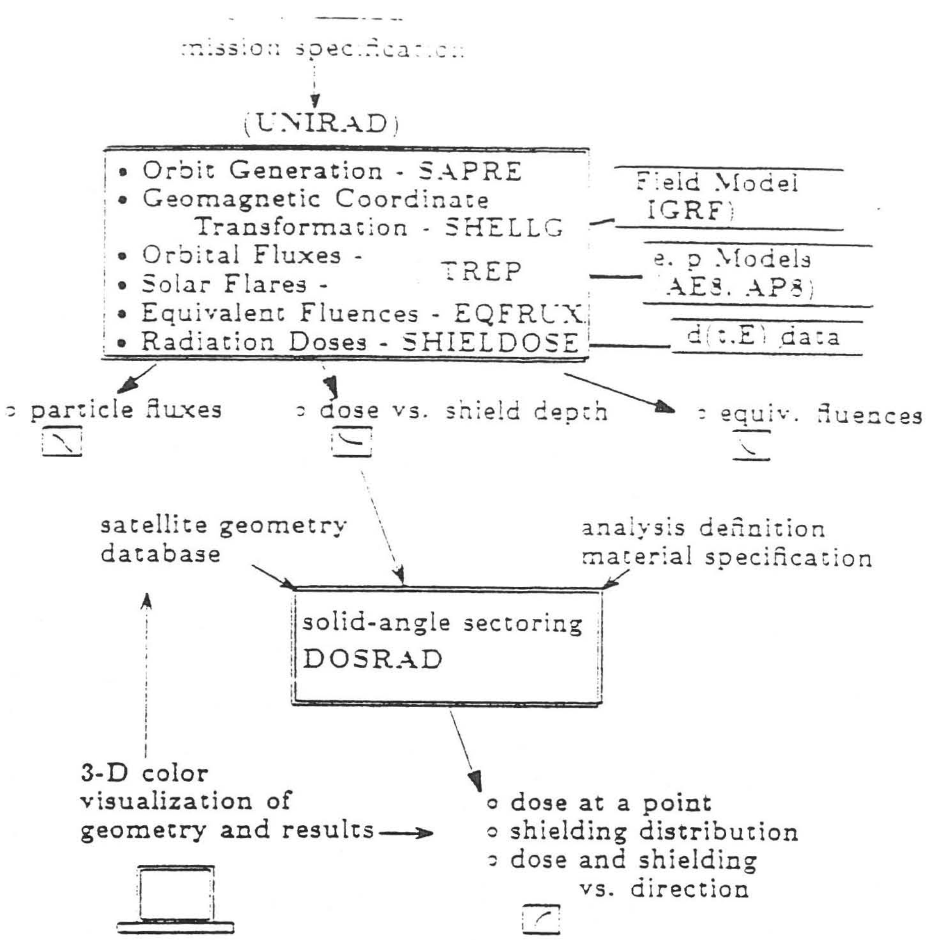

Figure 1: Architecture of ESABASE/Radiation, including the UNIRAD system for flux and dose calculations at ESA.

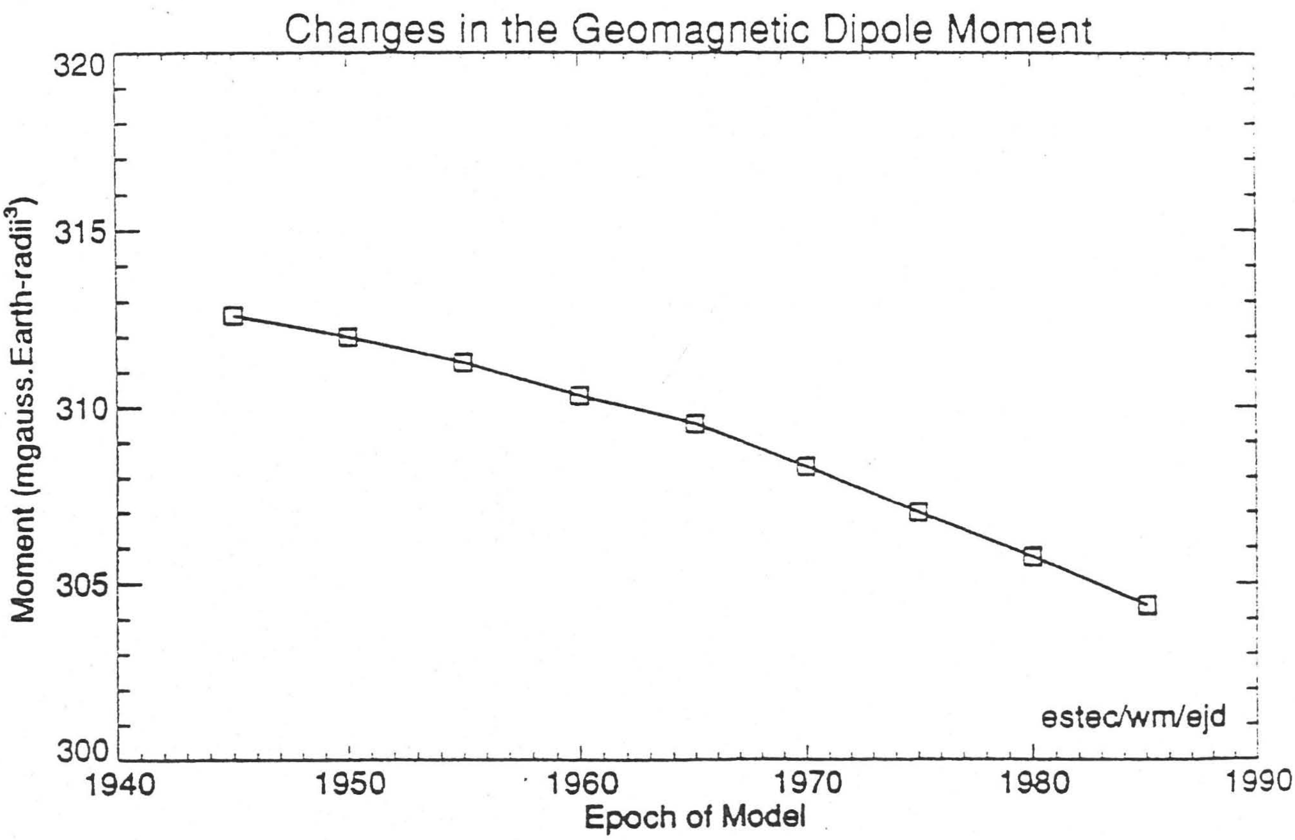

Figure 2: Changes to the geomagnetic dipole moment, as derived from the first 3 terms of IGRF numerical field models, as a function of time.

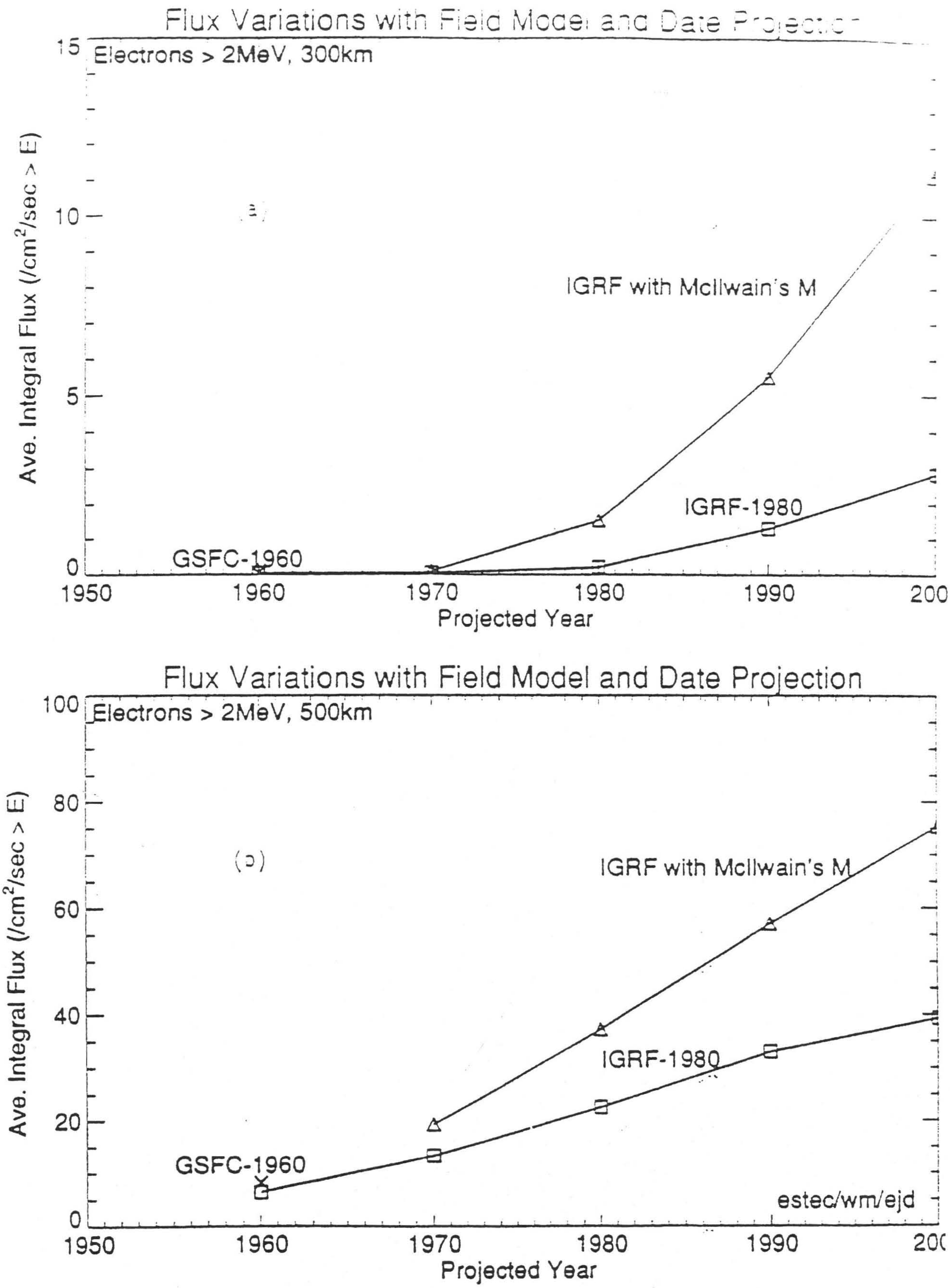

Figure 4: Variations of predicted orbit-averaged >2 MeV electron fluxes as functions of extrapolated field date: (a) for 300km, 28.5° orbit; (b) for 500km, 28.5° orbit (after *Daly* [1989]).

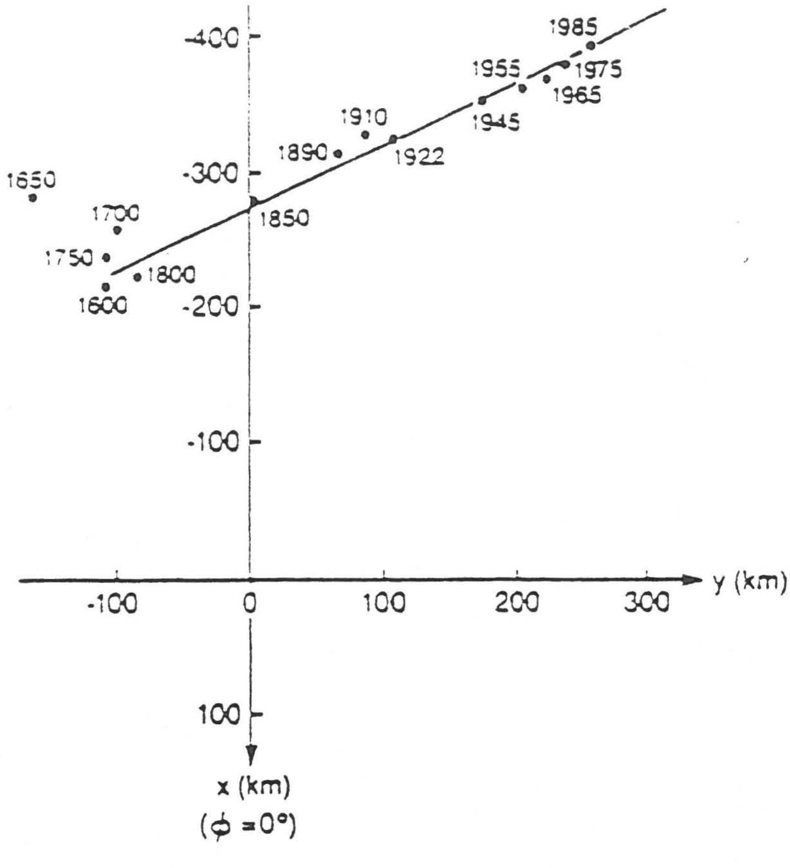

Figure 5: Variation of the projection of the eccentric dipole's position on the geographic equatorial plane during the interval 1600-1985 (after *Fraser-Smith* [1987]).