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Historical review of the different procedures used to compute the L-Parameter

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Foreword

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Voorwoord

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Historical Review of the Different Procedures Used to Compute the L-Parameter

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Abstract. We describe in a historical perspective the different procedures proposed to calculate the drift shell parameter L when the secular variation of the geomagnetic field is taken into account. We compare the secular variation of the average particle flux along low-altitude circular orbits, obtained with the AP-8 and AE-8 trapped radiation models by using these different procedures. It is shown that the secular variation of the geomagnetic dipole moment is not the only cause of the unrealistic secular increase of the predicted flux, as was first assumed. The effect of the secular variation of the quadrupole terms as well as of the higher-order terms cannot be neglected. Until new trapped radiation models become available, an interim procedure is suggested to avoid unrealistic predictions of particle fluxes at low altitudes. The proper way to use the AP-8 and AE-8 models is to calculate B, L with the Jensen and Cain 1960 magnetic field model for AP-8 MIN, AE-8 MIN, and AE-8 MAX, and with the GSFC 12/66 model, updated to 1970, for AP-8 MAX, and to use McIlwain's value 0.311653 Gauss R_E^3 for the magnetic moment of the Earth.

Samenvatting. We beschrijven in een historisch perspectief de verschillende procedures voorgesteld om de L-parameter te berekenen wanneer de seculiere variatie van het geomagnetische veld in rekening genomen wordt. We vergelijken de seculiere variatie van de gemiddelde deeltjesflux die men bekomt met de verschillende procedures uit de modellen AP-8 en AE-8 over lage cirkelvormige banen. Het blijkt dat de seculiere variatie van het geomagnetisch dipoolmoment niet de enige oorzaak is van de onrealistische toename van de voorspelde flux, zoals eerst werd aangenomen. Het effect van de seculiere variatie van de quadrupooltermen en van de hogere orde termen mag niet verwaarloosd worden. Een voorlopige procedure, te hanteren tot wanneer er nieuwe modellen beschikbaar zijn, wordt voorgesteld waarmee onrealistische voorspellingen van deeltjesfluxen op lage hoogte vermeden worden. De modellen AP-8 en AE-8 moeten gebruikt worden met B, L waarden die berekend werden met het magnetisch veld model van Jensen en Cain voor AP-8 MIN, AE-8 MIN en AE-8 MAX, en met het model GSFC 12/66, geëxtrapoleerd naar 1970, voor AP-8 MAX. Verder moet voor het geomagnetisch dipoolmoment de waarde 0.311653 Gauss R_E^3, voorgesteld door McIlwain, gebruikt worden.

Résumé. Dans une perspective historique, nous décrivons les différentes procédures proposées pour calculer le paramètre L caractérisant une coquille magnétique, en tenant compte de la variation séculaire du champ géomagnétique. Nous comparons la variation séculaire des flux moyens le long de trajectoires circulaires de satellites artificiels en orbite à basse altitude. Les flux moyens sont obtenus à partir des modèles AP-8 et AE-8 donnant le flux des particules piégées dans les zones de radiation de Van Allen, en utilisant les différentes méthodes de calcul de L décrites dans la première partie de ce travail. On montre que la variation séculaire du moment magnétique dipolaire n'est pas la seule cause de l'augmentation des flux moyens calculés, comme on l'avait supposé initialement. L'effet de la variation des termes quadripolaires et d'ordre plus élevés ne peut pas être négligé. En attendant de nouveaux modèles donnant la distribution des flux des particules dans les zones de Van Allen, une procédure de calcul temporaire a été suggérée afin d'éviter des prédictions de flux et de dose de radiation irréalistes aux basses altitudes. La manière correcte d'utiliser les modèles AP-8 et AE-8 consiste à calculer les valeurs des coordonnées magnétiques B, L avec le modèle géomagnétique de Jensen et Cain correspondant à l'époque 1960, lorsqu'on utilise les modèles AP-8 MIN, AE-8 MIN et AE-8 MAX, et le modèle géomagnétique GSFC 12/66, pour l'époque 1970, lorsqu'on utilise AP-8 MAX. Dans tous les cas il est alors nécessaire d'employer dans l'algorithme permettant de déterminer L la valeur 0.311653 Gauss R_{E}^3, initialement proposée par McIlwain, pour le moment magnétique de la Terre.

Zusammenfassung. In einer historischen Perspektive beschreiben wir die verschiedenen Verfahren zur Berechnung des Parameters L als Kennzeichen einer Magnetschale unter Berücksichtigung der Sekulärvariation des erdmagnetischen Feldes. Wir vergleichen die Sekulärvariation der mittleren Ströme entlang der Kreisbahnen künstlicher Satelliten auf niedrigen Umlaufbahnen. Die mittleren Ströme errechnen wir aufgrund der Modelle AP-8 und AE-8 die die Ströme eingefangenen Teilchen in Van Allens Strahlungszonen, unter Einsatz der im ersten Teil dieser Arbeit beschriebenen Berechnungsmethode für L, angeben. Es wird gezeigt, dass die Sekulärvariation des magnetischen Dipolmomentes nicht wie anfangs angenommen die einzige Ursache für die Zunahme der berechneten mittleren Ströme ist. Die Variationswirkung der vierpoligen und höheren Glieder darf nicht ausser Acht gelassen werden. Bis neue Modelle die Verteilung der Teilchenströme in den Van Allen-Zonen angeben, wird ein vorläufiges Rechenverfahren vorgeschlagen, damit unrealistische Prognosen der Ströme und Strahlungsdosen in geringer Höhe vermieden werden. Um die Modelle AP-8 und AE-8 richtig zu verwenden sind bei den Modellen AP-8 MIN, AE-8 MIN und AE-8 MAX die Werte der magnetischen Koordinate B, L mit dem der sechziger Jahre entsprechenden erdmagnetischen Modell von Jensen und Cain zu benützen und beim Modell AP-8 MAX nehme man das erdmagnetische Modell GSFC 12/66 für die siebziger Jahre. In allen Fällen ist es dann erforderlich, in dem Algorithmus zur Berechnung von L den ursprünglich von McIlwain für das magnetische Moment der Erde vorgeschlagenen Wert 0.311653 Gauss R_{E}^3 zu verwenden.

1 Introduction

Data related to particles trapped in the Earth's magnetosphere are commonly treated in systems of magnetic coordinates. Usually, the first coordinate is the magnetic field intensity at the location of the measurement, and the second coordinate is a label of the drift shell the particle is confined to. McIlwain (1961) introduced as second coordinate the parameter L, in the form of a function that relates the second adiabatic invariant for the actual geomagnetic field to the second adiabatic invariant for a pure dipole field. The function yielding L depends on the magnetic field model that is used. In particular, the magnetic moment M was set to the conventional value M_{m}=0.311653 Gauss R_{E}^3 in McIlwain's software.

In Sect. 2, we review the definition of L. The history of the AP-8 and AE-8 models is briefly outlined in Sect. 3. In Sect. 4, we describe in a historical perspective the different procedures proposed to calculate L when the secular variation of the geomagnetic field was being taken into account. Section 5 is devoted to a comparison of the secular variation of the orbit-averaged particle flux along low-altitude circular orbits, obtained with the AP-8 and AE-8 trapped radiation models by using these different procedures.

Until new trapped radiation models become available, an interim procedure is suggested to avoid unrealistic predictions of particle fluxes at low altitudes with the NASA models. This procedure is presented in Sect. 6.

2 Definition of the L-parameter

Data related to the Earth's trapped radiation environment are conveniently organised in terms of adiabatic invariants (Northrop and Teller, 1960). When the total momentum of a particle moving in the magnetic field of the Earth is conserved, the mirror point magnetic field intensity B_{m} and the quantity

$$I \equiv \int_A^{A'} \sqrt{1 - \frac{B(s)}{B_{\mathrm{m}}}}\, ds\,, \qquad (1)$$

where the integration is along the field line between the conjugate mirror points A and A', are invariants of the particle motion.

The locus of points in space associated with constant values of B_{m} and I is formed by two rings, one in each hemisphere. A particle associated with these values B_{m}, I will remain on the surface or shell described by the magnetic field lines connecting the rings. Consequently, the particle motion is described by the coordinate pair B_{m}, I, in the guiding centre approximation.

Since the quantity I has no intuitive physical significance, other more appealing parameters related to I have been proposed. The most commonly used parameter is McIlwain's (1961) L-parameter. Alternative parameters have been suggested, such as Roederer's (1970) L^* which is related to the third adiabatic invariant. However, since the calculation of this alternative class of L-like parameters involves tracing a whole shell of field lines instead of just one field line in the case of McIlwain's L-parameter, a significant amount of extra computing time is involved. Furthermore, the conservation of the third adiabatic invariant is more difficult to maintain due to the continuous large-amplitude variations of the geomagnetic field over time periods shorter than the longitudinal drift periods of trapped particles. For these and other reasons, McIlwain's (1961) L has become the most commonly used parameter to label magnetic drift shells.

In a dipole magnetic field, a field line is described by

$$R = L_\mathrm{d} \cos^2\lambda \,, \tag{2}$$

where R is the radial distance from the dipole centre, λ is the magnetic latitude, and L_d is the radial distance of the intersection of the field line with the magnetic equator. There is a class of functions $F(B, I)$ which are exactly constant along dipole field lines. By subsituting the equation for the dipole magnetic field intensity in Eq. (1) and using Eq. (2), a relation between L_d, I_d, B_d, and M_d can be written:

$$\frac{L_\mathrm{d}^3 B_\mathrm{d}}{M_\mathrm{d}} = F\left(\frac{I_\mathrm{d}^3 B_\mathrm{d}}{M_\mathrm{d}}\right) \equiv F(X_\mathrm{d})\,. \tag{3}$$

The subscript "d" denotes functions or values for the case of a dipole field. Even for a dipole field, there is no analytical expression for the function $F(B_\mathrm{d}, I_\mathrm{d})$. Therefore, McIlwain (1961) provided a polynomial fit to F in terms of $\ln(X_\mathrm{d})$, with five sets of coefficients for different ranges of X_d.

In the Earth's magnetic field, there are no functions of B, I that are constant along a line of force. However, the variation of F along a field line is small, so that McIlwain defined the magnetic shell parameter L for the real geomagnetic field as

$$\frac{L^3 B}{M} = F\left(\frac{I^3 B}{M}\right) \equiv F(X)\,, \tag{4}$$

where B, I, and M are to be computed using the best representation of the Earth's magnetic field, and F is the dipole function defined in Eq. (3).

The value $M = 0.311653\,\mathrm{Gauss}\,R_\mathrm{E}^3 \equiv M_\mathrm{m}$ for the magnetic moment was implemented as a constant in McIlwain's subroutines and in a subroutine developed by Hilton (1971), who derived a simpler approximation for the function F with only three coefficients:

$$\frac{L^3 B}{M} = 1 + 1.35047\,X^{1/3} + 0.465376\,X^{2/3} + 0.0475455\,X\,. \tag{5}$$

The software developed by McIlwain and Hilton still is widely used, and it is our experience that the value M_m still is used as well and has implicitly been implemented over the years.

It should be reminded that, according to its original definition, L is merely a label to identify drift shells, i.e. to order them. L should not be related to the actual equatorial distance of magnetic field lines, nor should it be considered as an Euler coordinate to identify a magnetic field line as it has been common practice, unfortunately, for almost thirty years, mainly because of the early attempts to promote L^* instead of L. L^* can be considered as an Euler coordinate while L cannot since it is not constant along geomagnetic field lines. To avoid further confusion, a symbol different from L should be used for alternative coordinates. In the following, we will only consider McIlwain's (1961) definition of L, since it is commonly implemented in standard software routines and was used in the construction of the trapped radiation models AP-8 and AE-8.

3 NASA's trapped radiation environment models

The trapped radiation environment models currently used in the U.S. and Western Europe are AE-8 for electrons of energy greater than 40 keV and AP-8 for protons of energy greater than 0.1 MeV (Vette, 1991). There are two versions, MIN and MAX, corresponding to minimum and maximum solar activity conditions. The models consist of arrays of omnidirectional electron and proton fluxes, and are distributed by National Space Science Data Center (NSSDC) as discrete functions of particle energy E, B/B_0, and L, where

$$B_0 = \frac{M_{\mathrm{m}}}{L^3} \tag{6}$$

(Sawyer and Vette, 1976, p. 8; Singley and Vette, 1972, p. 10). It should be noted that B_0 differs from the value of the magnetic field intensity at the point where the field line crosses the magnetic equator, since L is not constant along field lines.

The satellites that provided the data used to build the solar minimum models (AE-8 MIN and AP-8 MIN) were tracked by Goddard Space Flight Center (GSFC) and the Satellite Control Facility (SCF) at Sunnyvale, California, where ephemerids and B, L coordinates were computed. Since the calculation of B, and especially L, demanded large computer resources in that period, NSSDC used the B, L values supplied by GSFC and SCF. According to Vette (1993), GSFC used the Jensen and Cain (1962) geomagnetic field model for this purpose until about 1980, and SCF at least through 1967. This magnetic field model is a Gauss-normalised spherical harmonic expansion of the geomagnetic potential with 48 terms, without secular variation, for epoch 1960.

The situation for the solar maximum models was different. AP-8 MAX and AE-8 MAX are partly based on data from the German satellite AZUR (Hovestadt et al. 1972). The AZUR data were provided by the Max-Planck-Institut (MPI) für Physik und Astrophysik, together with B, L values calculated with the GSFC 12/66 model (Cain et al. 1967) updated to December 1969. Since NSSDC did not recalculate B, L, the MPI B, L coordinates were used in constructing AP-8 MAX and AE-8 MAX, which consequently consist of data ordered with B, L coordinates obtained with both magnetic field models. Since the magnitude of the AP-8 solar cycle effect is based solely on AZUR data, we suggest to associate AP-8 MAX with the GSFC 12/66 model, updated to 1970. As the AZUR electron data do not play a crucial role in AE-8 MAX, this model should be accessed with the Jensen and Cain (1962) field model (Vette, 1993).

4 Extrapolation of the NASA models

The NASA models AE-8 and AP-8 have been in use for over a decade. Over the years, it became common practice to employ contemporary, epoch-dependent geomagnetic field models to compute more accurate values of B and L[1]. The resulting B, L coordinates were used as input to retrieve particle fluxes from the empirical NASA models.

At the 37$^{\text{th}}$ IAF Congress in 1986, McCormack (1988) emphasized the significant differences in dose predictions with the NASA models for the Space Shuttle when the magnetic field distribution is or is not extrapolated into the future. The doses obtained at GSFC with projection of the magnetic field into the future were roughly one order of magnitude higher than the doses calculated at Johnson Space Center (JSC) with no such projection. Konradi et al. (1987) demonstrated that with B, L values calculated with the IGRF 1975 model extrapolated to the year 2025 (but keeping $M = M_{\text{m}}$), the AP-8 MIN model produces the absurd result of non-zero proton fluxes below sea-level.

In order to resolve the issue of the large differences in calculated radiation dose levels between results based on updating the magnetic field and those based on no update, a panel of scientists was convened at NASA HQ on February 25, 1986 (cfr. McCormack, 1988). The representatives of GSFC (E. Stassinopoulos) and JSC (A. Konradi, S. Nachtwey and A. Hardy) outlined the procedures used at their institutions. The recommendation of the panel was that "on an interim basis, dose calculations for future missions should be based on the use of the AP-8 MAX/MIN models with one of the reputable magnetic field models for the epochs 1970 and 1964, respectively, i.e. no projection of the magnetic field into the future."

Stassinopoulos then reported on a model adjustment proposed by Vette and Sawyer (1986) to account for the depletion of the trapped radiation population rather than the static procedure stated above. This adjustment consists of replacing M_{m} by $M(t)$, the actual dipole moment of the geomagnetic field at the projected epoch, which is derived from the three first-order coefficients of the spherical harmonic expansion of the magnetic field potential:

$$M(t) = R_{\text{E}}^3 \sqrt{[g_1^0(t)]^2 + [g_1^1(t)]^2 + [h_1^1(t)]^2}\,. \tag{7}$$

In this way, it was inferred from Eq. (4) that L becomes nearly independent of $M(t)$, i.e. independent of the magnetic field epoch t. The quantity B/B_0, with $B_0 = M(t)/L^3$, then also is nearly independent of t. The expectation was that these $B/B_0, L$ pairs would yield integral fluxes $J(> E, B/B_0, L)$ that also are nearly constant in time.

Subsequently, JSC, and later MSFC, modified their procedure to use the IGRF 65 model (extrapolated backwards to 1964) and the Hurwitz et al. (1966) model (extrapolated to 1970), respectively, and the values $M(t = 1964)$ and $M(t = 1970)$ rather than M_{m} (Watts, 1991). In addition, NSSDC released a new version of the model software to calculate $B/B_0, L$, which now uses updated magnetic field models and an epoch dependent value of the geomagnetic moment.

[1] A third (non-standard) definition of L is sometimes used, whereby L is determined as $L^3 = M(t)/B_0$. This alternative procedure is adopted by some groups to avoid computing the integral I.

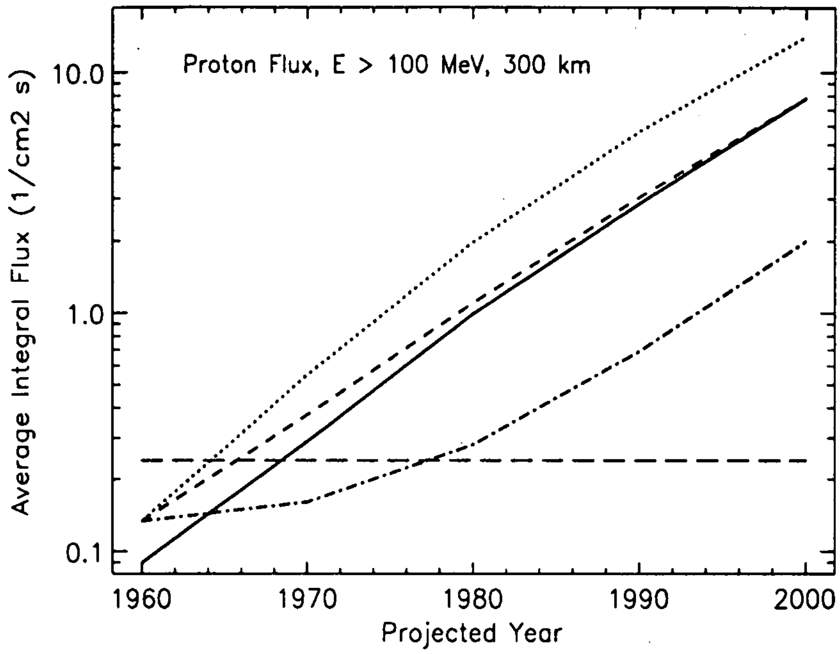

Figure 1. Average integral proton flux for $E > 100\,\text{MeV}$ over 13 circular orbits at altitude 300 km and inclination 28.5°, obtained with the AP-8 MIN model. The different line types represent the results obtained with the different procedures discussed in the text. The results obtained with the procedure used before 1986, i.e. with an updated geomagnetic field model but with $M = M_{\mathrm{m}}$, are represented by the dotted line. The short-dashed and dot-dashed lines were also calculated with this procedure, but with the secular variation of first the dipole, and then in addition the quadrupole terms inhibited. The solid line indicates fluxes calculated with the alternative procedure of Vette and Sawyer (1986), i.e. with $M = M(t)$. The results of the recommended procedure, consisting of using the Jensen and Cain (1962) magnetic field model and $M = M_{\mathrm{m}}$, are indicated by the horizontal long-dashed line.

In view of Vette's (1993) statement that GSFC and SCF used the Jensen and Cain (1962) geomagnetic field model, a further modification should be made to the JSC procedure. Instead of using the IGRF 65 and the Hurwitz et al. (1966) model, the Jensen and Cain (1962) model and the GSFC 12/66 (Cain et al. 1967) model, updated to 1970, should be used to calculate B, L. In addition, M_{m} should be used instead of $M(t)$, and B_0 should be calculated as in Eq. (6).

5 Application to a LEO orbit

In this section, we illustrate the effect of updating the geomagnetic field model on the low-altitude particle fluxes obtained with the NASA models. We have calculated the integral electron and proton fluxes with the AE-8 MIN and AP-8 MIN models along circular low-Earth orbits (LEO) at altitudes of 300 km and 500 km, with an inclination of 28.5°. Geodetic coordinates were generated along 13 consecutive orbits, in order to cover all geographic locations. The B, L coordinates were obtained with the GSFC 12/66 magnetic field model for five epochs between 1960 and 2000 with a ten year interval. We used the GSFC 12/66 model since the Jensen and Cain (1962) model is not dependent on time. With the resulting B, L coordinates, the integral electron fluxes above 2 MeV and proton fluxes above 100 MeV were calculated and averaged over the 13 orbits. The results for the proton fluxes at altitude 300 km are shown in Fig. 1 for the different procedures used to calculate B, L.

The dotted line in Fig. 1 represents the proton fluxes obtained by updating the magnetic field and using $M_{\rm m}$. The solid line shows the results obtained by adopting the alternative procedure proposed by Vette and Sawyer (1986), i.e. by using $M(t)$.

As was already noted by Daly (1989), the projected fluxes obtained with the procedure commonly used before 1986 (dotted line) increase drastically toward the year 2000, especially at the lowest altitude. For protons of energy $E > 100\,\mathrm{MeV}$, the orbit-averaged flux at 500 km increases by a factor of about 7 over 40 years. For electrons of energy $E > 2\,\mathrm{MeV}$, the increase is by a factor of 13 over the same period of time. At 300 km altitude, the increases are even steeper. This unrealistic secular variation was recognised as resulting from the secular variation of the geomagnetic field, and was mainly attributed to the decrease of the dipole moment of roughly 0.5% per decade.

With the alternative procedure of Vette and Sawyer (1986), one obtains a reduction by a factor of two in the secular variation of the fluxes. In order to illustrate the influence of the secular decrease of the dipole moment, we calculated the projected fluxes with the old procedure, but with the secular variation of the dipole terms suppressed. The results are represented by the short-dashed line in Fig. 1 and are close to those obtained using the procedure of Vette and Sawyer (1986), as expected. The difference at epoch 1960 is due to the fact that $M(1960) \neq M_{\rm m}$.

However, the remaining increase of the projected flux is still too high to be realistic. It has been suggested by Lemaire et al. (1990) that the remaining variation in the predicted fluxes is mainly due to the secular increase of the eccentric displacement of the geomagnetic dipole with respect to the centre of the Earth. This displacement is currently more than 500 km and increases at a rate of 2.5 km/yr (Fraser-Smith, 1987). This means that in a period of 40 years the eccentric displacement has increased by about 100 km, which is comparable to the atmospheric density scale height at 300 km altitude. Note that the eccentric displacement is determined by the dipole and quadrupole coefficients in the expansion of the geomagnetic potential.

The dot-dashed line in Fig. 1 shows the fluxes calculated with the old procedure, but now with the secular variation of both the dipole and quadrupole terms set equal to zero. It appears that by suppressing in addition the variation of the quadrupole terms, one obtains a further reduction by a factor two for the predicted flux increase. It can be concluded that the remaining secular variation is due to the higher-order terms in the expansion of the geomagnetic field. These higher-order terms slightly change the shape of the magnetic field lines as well as the value of the invariant I from which L is derived. The time-independent flux obtained with the Jensen and Cain (1962) magnetic field model is represented by the horizontal long-dashed line in Fig. 1.

6 Discussion and recommendations

To avoid unrealistic and unphysical extrapolations of the trapped radiation fluxes with the AP-8 and AE-8 models, the proper way to use these models is to calculate B, L with the Jensen and Cain (1962) magnetic field model for AP-8 MIN, AE-8 MIN, and AE-8 MAX, and with the GSFC 12/66 field model (Cain et al. 1967), updated to 1970, for AP-8 MAX. The value M_m should be used for determining L. B/B_0 should be calculated with $B_0 = M_m/L^3$ instead of the minimum field value obtained by line tracing.

We consider this to be an interim solution which should be used until updated or new trapped radiation models become available. Future trapped radiation models should be built using an IGRF/DGRF geomagnetic field model corresponding to the epoch of the particle flux measurements. This magnetic field model and its epoch should then be attached to the new trapped radiation models in order to avoid any confusion or misuse of the new models. Future radiation belt models, data and results should be presented with comprehensive descriptions of the methods employed, including the geomagnetic field models used to organize the data. External field models can be added in future modelling efforts.

The Jensen and Cain (1962) geomagnetic field was published as an interim field model with a limited number (48) of coefficients. Consequently, it displays significant differences with the later established IGRF 60 model, which in turn lead to significant differences in particle fluxes when these models are used with the NASA trapped radiation models. This difference is illustrated in Fig. 1: the flux calculated with the Jensen and Cain (1962) model differs substantially from the flux obtained with the GSFC 12/66 model for epoch 1960. Therefore, it is important that the Jensen and Cain (1962) model be used with the NASA solar minimum models, and not any other more accurate field expansion for epoch 1960.

We remind that the Jensen and Cain (1962) model coefficients are Gauss-normalised. Consequently, the transformation from Schmidt- to Gauss-normalisation implemented in the standard softwares should be inhibited for this model. Also, the model was constructed with the assumption of a spherical Earth. Therefore, the model should have geodetic coordinates as input, instead of geocentric coordinates, which have been corrected for the oblateness of the Earth (Cain et al. 1965).

In the future, B, L coordinates may well be abandoned for mapping the environmental particle fluxes. They may be replaced by more suitable coordinate systems taking into account the effects of geomagnetic field evolution and the distribution of the atmospheric density, at low altitudes (Hassitt, 1965; Pfitzer, 1990). The current tendency is to keep particle data in their original geographic coordinates in order to facilitate the introduction of new coordinate systems. However, it is likely that the usage of the AE-8 and AP-8 models will continue for some time. In view of this consideration, the recommended interim procedure may continue to be useful. IAGA, ISO, or some other international institution could be helpful to reach a worldwide consensus on this issue.

It should be noted that with the procedure based on static magnetic fields for two fixed epochs, the geographical position of the South Atlantic Anomaly (SAA) associated with the magnetic field models would correspond to the epochs 1960 and 1970, respectively. In addition, the inclination of the geomagnetic dipole axis with respect to the rotation axis of the Earth also changes with time, which causes a secular change in the inclination of trapped particle shells. In order to relocate the SAA at its contemporary geographical position, and to adjust the inclination of the geomagnetic dipole axis for the current epoch, we suggest to apply a transformation of the geographic satellite coordinates (Heynderickx, 1993).

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