Particle precipitation in the ionospheric $F_2$ region at locations in the vicinity of the south-atlantic magnetic anomaly

by

R.P. KANE

Instituto de Pesquisas Espaciais – INPE
Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq
12200 — São José dos Campos – SP — Brasil

ABSTRACT. — The $f_0 F_2$ daily variation characteristics were compared for IGY equinox months for pairs of stations at roughly similar dip angles, geomagnetic latitudes and L-shell values. One station in each pair was in the South-African Continent and another in the South-American Continent. It was found that locations on the west coast of South-Africa showed larger $f_0 F_2$ in the afternoon hours as compared to locations on the east coast of South-America. It is suggested that at least a part of this excess may be due to particle precipitation effects in the South-American mid-latitude region. The particles could be either ions of few MeV energies or secondary electrons of a few hundred eV, or, if from plasmasphere, electrons of only a few eV energies. In low latitudes, Buenos Aires showed larger afternoon $f_0 F_2$, indicating its probable vicinity to the anomaly region.

SUMMARY. — On a comparé les caractéristiques des variations journalières de $f_0 F_2$ pour les mois d’équinoxe de l’Année Géophysique Internationale pour des paires de stations à des valeurs voisines des angles d’inclinaison, des latitudes géomagnétiques et des couches L. Une station de chaque paire est dans le continent Sud-Africain et l’autre dans le Continent Sud-Américain. On a trouvé que les stations sur la côte ouest d’Afrique du Sud enregistraient des valeurs plus grandes de $f_0 F_2$ l’après-midi par rapport aux stations de la côte est d’Amérique du Sud. On suggère qu’au moins une partie de cette différence peut être due aux effets de précipitations de particules dans la région Sud-Africaine de moyenne latitude. Les particules pourraient être soit des ions de quelques MeV ou des électrons secondaires de quelques centaines eV, ou s’ils proviennent de la plasmasphère, des électrons de quelques eV. Aux basses latitudes, Buenos Aires enregistrait un important $f_0 F_2$ l’après-midi, indiquant le voisinage probable de l’anomalie.

1. Introduction

The geomagnetic field has a minimum at about 25°S, 45°W. This region is called the Brazilian Magnetic Anomaly. Due to the hemispherical asymmetry of the mirror point altitudes, this anomaly region is susceptible to particle precipitation from the magnetospheric regions. According to the theoretical calculations of Toth et al. (1975), electrons and protons of energies exceeding 40 KeV precipitate not exactly in the above region but in a wide area to its south-east known as South-Atlantic Magnetic Anomaly. For electrons, the maximum precipitation is centered roughly at about 45°S, 20°W and for protons, it is centered at about 60°S, 30°E. Thus, whereas the proton precipitation region is near the Antarctic Continent but very far away from the African or South-American Continents, the electron precipitation region is in between the African and South-American Continents (see map Figure 1).

Paulikas (1975) and Gledhill (1976) have reviewed the existing information about the precipitation of particles at low and middle latitudes and the aeronomic effects of the South-Atlantic Magnetic Anomaly. Except for a few islands, the region covered by this anomaly is mostly sea. Most of the direct observations in this region have been by satellites (see Gledhill, 1976 and references therein) and refer to electrons of energies of several keV and protons of energies of several MeV. However, the absence of evidence for electrons of lower energies is not due to the actual absence of such particles but due to technological difficulties of observing the same. Gledhill (1976) concludes that there is good evidence for increased ionization in the ionospheric $F_2$ region in the whole of the anomaly region. From the data obtained for a few days from a shipborne ionosonde at Gough Island (40.4°S, 9.9°W), Haggard and Gledhill (1978) reported a marked increase in $f_0 F_2$ in the anomaly region. Recently, Gledhill et al. (1981)
greater than 40 keV in the D region. The maximum precipitation region around 45°S, 20°W indicated by Torr et al. (1975) refers to electrons of energies of 40 keV or more. For lower energies, the region would probably shift. The experimental data AE-C, as discussed by Haggard et al. (1979) for electrons below 26 keV indicated an additional maximum nearer to the South-American coast.

Of course, an increase in precipitation does not necessarily ensure invariably an increase in $f_0F_2$. As demonstrated by Torr and Torr (1967) the corpuscular bombardment of the ionosphere may give rise to two competing effects: an increase of electron density due to direct ionization and, a decrease, as a result of a possible temperature increase which may increase the scale height as well as the effective recombination rate. Serafimov et al. (1978) and Prange and Bruston (1980) have indicated possibilities of other complicating effects too such as transport along field lines and a strong dependence on magnetic field declination. During quiet conditions, the only tangible effect likely to be noticed is probably enhancements in $f_0F_2$. At least, this is the assumption we will make and test in the present study keeping in mind its limitations. As mentioned earlier, there are unfortunately no permanent observatories in the South-Atlantic anomaly region itself. In the present study we propose to examine and compare the quiet-time (monthly median) $f_0F_2$ daily variation patterns at several locations on the east coast of the South American continent and the west coast of the African continent. Table 1 gives details of the stations and the locations are marked on the map in Figure 1. Full dots represent locations for which data were used in

<table>
<thead>
<tr>
<th>South-American Continent</th>
<th>South-African Continent</th>
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<tr>
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<tr>
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<td>Ellsworth</td>
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Fig. 1
Map of the South-American and South-African continents. Full dots represent locations for which ionospheric data were used.

have estimated from satellite measurements of electron fluxes that the $f_0E$ at about 40°S, 20°W should increase from about 0.5 MHz to 0.75 MHz around midnight. It is not unreasonable to assume that some increases may be seen in the $F_2$ region too; because, as mentioned by Gledhill (1976), it is a useful approximate rule that electrons with energies less than 2 keV will lose most of their energy in the $F$ region, those with energies between 2 and 40 keV in the $E$ region and those with energies

Table 1
Details of stations

Average
(Sep. to
Nov.)

the phenomena also
Old-World
the present
landmass.
In Table 1, details of stations of the South-American continent are given in the left half and those for stations of the South-African continent in the right half. The dip is the “Computed dip” as given in Report UAG-30 (Catalogue of data) of WDC-A for Solar Terrestrial Physics. Other coordinates and parameters are also taken from the same source.

2. Data Analysis

An examination of the data showed that the $f_0 F_2$ range was largest during equinoxes. Figure 2 shows the average median $f_0 F_2$ daily variation for the equinox months Sep. Oct. 1957; Mar. Apr. Sep. Oct. 1958. However, some locations did not have complete data and for these, months for which data were available are indicated in Figure 2. Complete data (for all six months) are marked as ALL. For the South-American continent (Fig. 2a), data for Trelew and Ushuaia, besides being incomplete, seem to show abnormally low $f_0 F_2$ range as compared to other locations on either side in latitude. We concluded, therefore, that these data were unreliable and hence omitted the same.

A. Comparison for similar dip angles

Since the latitude distribution of $f_0 F_2$ (equatorial anomaly) is due to transport effects which are guided by dip latitude, we first examine and compare locations having similar dip angles. Figure 3 shows the plots for the following pairs:

a) Buenos Aires (dip = 32°) and Concepcion (dip = 36°) versus Lwiro (dip = 29°);

b) Port Stanley (dip = 43°) versus Elizabethville (dip = 47°);

c) Deception (dip = 56°) versus Tsumeb (dip = 57°);

d) Halley Bay (dip = 64°) versus Cape Town (dip = 66°).

Only data for common months (indicated) are used. The following may be noted:

i) In Figure 3(a), the morning values of $f_0 F_2$ at Buenos Aires, Concepcion and Lwiro are almost the same. However, in the dusk hours, Concepcion and Lwiro show similar values while Buenos Aires shows larger $f_0 F_2$. Thus, whereas the fountain effect, in general, seems to be similar in the two continents, the excess at Buenos Aires at dusk could be due to precipitation effects of low energy electrons occurring near the east coast of Argentina in agreement with Haggard et al. (1979). On its face value, this implies precipitation effects preferentially at dusk hours at Buenos Aires. In the pre-dawn hours, $f_0 F_2$ at Lwiro is larger than $f_0 F_2$ at Buenos Aires or Concepcion. Thus, precipitation effects at Lwiro in the pre-dawn period are indicated. A major difference between the South-American and South African magnetic field configuration is that in the
South-American continent, the magnetic equator is at about \(-13^\circ S\) in the Peruvian region whereas to its east, it swerves northwards, crosses the geographic equator in the sea off Fortaleza on the east coast of Brazil and is at about \(10^\circ N\) in the African continent (See Fig. 1). Serafimov et al. (1978) have reported considerable longitudinal variations in the ion density and temperature as measured by OGO-6 at 400-650 km altitude for night hours in the South-Atlantic Magnetic anomaly region and interpret the observed strong dependence of the ion density profile on the magnetic declination as evidence for a dominating influence of the neutral winds from the summer to the winter hemisphere. However, our analysis refers to the equinox periods when trans-equatorial wind effects are expected to be negligible. Also, even though the magnetic declination is quite large in the South-Atlantic Magnetic anomaly region, the declination is almost zero for both Buenos Aires and Concepcion as well as for Lwiro. Thus, whereas some neutral wind effects are not completely ruled out, these may not be a major cause of the above-mentioned differences.

(ii) In Figure 3(b), 3(c), 3(d), there are considerable differences between the \(f_a F_2\) patterns of the South-American continent and the South-African continent. Firstly, the dawn values in the South-African region are invariably lower. Secondly, the dusk values are invariably higher. In the case of Figure 3(c) and 3(d), the \(f_a F_2\) values in the South African continent are very much higher throughout the day. We suspect that, even though the dip angles are reasonably matched, the geographical vicinity of the South-American locations to the Antarctic region is causing complications. In other words even though the pairs considered have similar dip angles, those in the African continent are at geographical mid-latitudes while those in the South-American continent are near auroral latitudes. The comparison may not be therefore, completely valid. However, in Figure 3(b) we are on somewhat safer grounds. Here, at least near noon, the \(f_a F_2\) values match. Hence, the dusk excess of \(f_a F_2\) at Elizabethville as compared to Port Stanley could be considered a significant difference. In terms of particle precipitation, this could imply that Elizabethville may be nearer to the anomaly center than Port Stanley.

**B. Comparison for similar geomagnetic latitudes**

Since the comparison for similar dip angles seemed unsatisfactory specially for large dip angles, we attempted a comparison for similar geomagnetic latitudes. Here, as seen from Table 1, the maximum geomagnetic latitude in the African zone is only about \(-34^\circ\). Hence very few pairs could be compared, as follows:

- a) Buenos Aires (geom. lat. \(-23^\circ\)), Concepcion (geom. lat. \(-25^\circ\)) versus Tananarive (geom. lat. \(-24^\circ\));
- b) Port Stanley (geom. lat. \(-40^\circ\)) versus Grahamstown (geomag. lat. \(-34^\circ\)).

Figure 4 shows the plots. In Figure 4(a), \(f_a F_2\) at Tananarive is smaller than that at Concepcion or Buenos Aires. This could be because the dip angle of Tananarive is \(-54^\circ\), much larger than that of the other two locations (about \(-35^\circ\)). Thus, whereas the other two locations are near the “equatorial anomaly” crest (about \(-30^\circ\) dip), Tananarive is far beyond. However, if one allows for this fact by shifting the Tananarive curve upwards by, say, 2 MHz, so that \(f_a F_2\) values match roughly at noon, there still remains an excess \(f_a F_2\) at Buenos Aires.

In Figure 4(b), Port Stanley (dip \(-43^\circ\)) shows larger \(f_a F_2\) than Grahamstown (dip \(-66^\circ\)) probably for the same reason as above, viz. Port Stanley is nearer to the anomaly crest. If Grahamstown plot is shifted upwards by about 1 MHz to match at noon, the dawn values at Grahamstown are still lower than those at Port Stanley; but the dusk values at Grahamstown are higher. Thus, excess \(f_a F_2\) at dawn in the South-American continent and at dusk in the South-African continent is indicated.

**C. Comparison for similar L-shell values**

If stations are compared for similar L-shell values, the following groups could be considered:

- a) Buenos Aires (L = 1.20), Concepcion (L = 1.20) versus Elizabethville (L = 1.16);
- b) Port Stanley (L = 1.58) versus Johannesburg (L = 1.55) and Tsumeb (L = 1.34);
c) Deception (L = 2.17) versus Cape Town (L = 1.83).

Figure 5 shows the plots. In Figure 5(a), Buenos Aires still shows excess $f_0F_2$ in the dusk hours. However, Elizabethville (dip = 47°) is further away from the anomaly crest. If the Elizabethville plot is shifted upwards by about 2 MHz, its night values are still lower than those at Buenos Aires; but the daytime values match or exceed. Thus, Elizabethville could be considered as having the same precipitation effects as Buenos Aires. In Figure 5(b), the night values at Tsumeb and Johannesburg are smaller than those at Port Stanley; but dusk and afternoon values are higher in the South African continent. In Figure 5(c), Cape Town $f_0F_2$ values are smaller than those at Deception in the night but larger in the day. The dip angle of Cape Town is -66° while that of Deception is -56°. Thus, Deception is nearer to the anomaly crest (-30°) and should have larger $f_0F_2$. Thus, the excess at Cape Town is not easily understandable. One could invoke the possibility that, whereas Port Stanley has more precipitation effect in the night, Cape Town has more precipitation effect during the day, specially afternoon and dusk.

3. Discussion

From the above analysis it seems that, no matter which parameter is considered (dip, geomagnetic latitude, L-shell values), the following seems to be true.

i) Buenos Aires seems to have excess $f_0F_2$ at dusk hours as compared to Concepcion on the same continent but to its west or as compared to Lwiro and Tananarive in the African continent. Allowing for the fact that Elizabethville is farther away from the anomaly crest than Buenos Aires, $f_0F_2$ at the two locations are alike in the day time, but Elizabethville $f_0F_2$ is smaller in the night.

ii) For other locations too, allowing for their distances from the anomaly crest, $f_0F_2$ in the South-African continent is lesser during night and greater during day (afternoon and dusk) as compared to the $f_0F_2$ in the South-American continent.

In general, there is a peculiarity which must be noted. In the South-African continent, the day-time $f_0F_2$ peak is broad, from about noon to dusk while in
the South-American continent, the peak is comparatively sharp, near noon. Hence, afternoon and dusk \( f_0 \) \( F_2 \) is in excess in the South-African continent. In contrast, night \( f_0 \) \( F_2 \) is in excess in the South-American continent.

The formation of the anomaly crest is largely dependent on the equatorial electroject electric field and the associated fountain effect. Thus, larger electric fields would cause stronger fountains and hence larger \( f_0 \) \( F_2 \) at the anomaly crest at about \( \pm 30^\circ \) dip angle. Lyon and Thomas (1963) have shown that there are considerable longitudinal differences in the development of the equatorial anomaly in the Asian, African and American longitudes. Thus, for the IGY equinox period, they report an earlier development, at about 1000 LT, in the African sector in contrast to about 1200 LT in the American sector. Also, the anomaly persists longer in the African sector, as is seen from the broader peaks. Anderson (1973) examined theoretically the role of changes in (a) the geomagnetic field configuration, (b) neutral winds and (c) \( E \times B \) drifts, for explaining these differences. He concluded that whereas the differences in the geomagnetic field configuration could explain some north-south asymmetries, the differences at the magnetic equator could not be accounted for. If the neutral winds were different in the different sectors, a maximum equatorward velocity around 2200 LT in the Asian sector and a wind with phase retarded by about four hours in the American sector could account for the equatorial differences. However, since the driving force for the neutral winds is dependent on neutral pressure gradients, it is unrealistic to imagine different neutral winds in different longitude sectors.

Now, for the density redistribution process, what is significant is the drag due to the neutral wind along the magnetic field line. Thus, the motion of the ions along the field lines depends on the component of the zonal wind on the total magnetic field vector \( \mathbf{B} \) and hence on the magnetic declination. This aspect was emphasized by Serafimov et al. (1978) for the South-Atlantic anomaly region, where the magnetic equator is twisted and declination values are large. Thus, the same neutral winds as at any other longitude could give altogether different effects in the South-Atlantic anomaly region. It may be noted, however, that none of the locations we considered are in the South-Atlantic anomaly as such. In the South-American continent, the location most eastward is Halley Bay at 27°W. In the African region, the most westward location is Tsumeb at 18°E. For these as also for all other locations we considered, the magnetic declination is very small. Thus, magnetic declination effects as pointed out by Serafimov et al. (1978), though important in the South Atlantic anomaly region itself (about 45°S, 20°W), may not be important for locations considered by us.

Thus, as concluded by Anderson (1973), neither the geomagnetic field configuration nor any realistic patterns of neutral winds could explain the longitudinal differences, specially in the equatorial region. On the other hand, Anderson found that the development of the anomaly was most sensitive to the electric field configuration and, the longitudinal differences in the equatorial region could be attributed to differences in the \( E \times B \) drift patterns in the two sectors.

Now, whether the basic difference in the \( f_0 \) \( F_2 \) patterns in the African and the South-American sector viz. smaller \( f_0 \) \( F_2 \) at night and larger \( f_0 \) \( F_2 \) in the afternoon and dusk hours in the African sector, is due to corresponding differences in the equatorial electrical field configurations in the two sectors, is a moot ques-

Fig. 6

Average median \( f_0 \) \( F_2 \) for (a) Tsumeb and Tananarive, (b) Cape Town and Johannesburg and, (c) Cape Town and Grahamstown for common IGY equinox months, (d) Port Stanley and South Georgia for July-Dec. 1970 and (e) Port Stanley and Tsumeb for all the there seasons, J, E, D of IGY.
No experimental observations are available for the two sectors. From the results presented here, the mixing of $f_0 F_2$ at Concepcion in South-America and Joao in Africa seems to indicate that the fountain effects in the two regions are similar. If so, the excess $f_0 F_2$ at dusk at Buenos Aires, the excess of $f_0 F_2$ at the night hours at locations further south of Buenos Aires and excess of $f_0 F_2$ in the afternoon and dusk hours at some locations near the west coast of the South-American continent may well be, at least partly, due to possible precipitation effects. In Figures 6, we show a comparison of $f_0 F_2$ patterns for locations in the same continent. Figure 6(a) shows a comparison of Tsumeb and Tanaanarive, the latter about 30° to the east of the former. For the afternoon hours, Tanaanarive $f_0 F_2$ is lesser, which would be as expected if a part of $f_0 F_2$ at Tsumeb is due to particle precipitation, which should be less effective for Tanaanarive. Figure 6(b) compares Cape Town and Johannesburg. Not much difference is noticed. In Figure 6(c), Cape Town shows larger afternoon $f_0 F_2$ as compared to Grahamstown. However, the contrary is indicated for the morning hours. To us, it seems that there is a possible error of real time involved here. Thus, the Grahamstown plot shows a morning minimum at about 0400 LT, in contrast to about 0600 LT at Cape Town and other locations. If the Grahamstown plot is shifted to the right by 2 hours, $f_0 F_2$ values at the two locations almost match. In the South-American side, data for 6 months (July-Nov. 1970) were available for South Georgia, a location about 30° to the east of the Port Stanley. Fig. 6(d) shows the plots. The values of $f_0 F_2$ at South Georgia are lower than those at Port Stanley in the night and morning hours but slightly higher in the afternoon hours. The geographic, geomagnetic and dip latitudes of South Georgia are larger than those of Port Stanley by a few degrees. Hence, lesser $f_0 F_2$ at South Georgia is expected. If the South Georgia plot is shifted upwards by about 1 MHz, the night and morning values match; and the afternoon values at South Georgia exceed those at Port Stanley, thus indicating the possibility of South Georgia being nearer to the anomaly center, probably for both electrons as well as protons.

In Figure 6(d), Port Stanley and Tsumeb are compared for other seasons too besides equinoxes. In every case, Tsumeb $f_0 F_2$ is larger than Port Stanley $f_0 F_2$ during the afternoon and dusk hours, and lesser during dawn hours.

4. Summary and Conclusions

A comparison of the $f_0 F_2$ monthly median daily variation patterns for locations in the South-American and South-African continents revealed the following:

i) The $f_0 F_2$ patterns at Concepcion (dip = 36°) and Joao (dip = 29°) looked similar. Hence, the fountain effects in the two continents are probably similar at least near the crest. In contrast, Buenos Aires (dip = 32°) showed excess $f_0 F_2$ in the afternoon and dusk hours, indicating possible precipitation effects near the Argentinian coast at low latitudes.

ii) A Comparison of $f_0 F_2$ patterns for locations having similar dip or geomagnetic latitude or L-shell values on the two continents showed that the South-African continent showed lesser $f_0 F_2$ at night and larger $f_0 F_2$ at afternoon and dusk hours. At least a part of this could be interpreted as particle precipitation in the South-American sector in the night and the South-African sector in the afternoon and dusk.

iii) Comparison of $f_0 F_2$ patterns for stations in the same continent showed that locations nearer the South-Atlantic Magnetic Anomaly center showed larger $f_0 F_2$ in the afternoon hours.

The evidence presented here is by no means conclusive and is rather crude. It is only roughly indicative of a possibility of detecting precipitation effects even at distances far off from the anomaly center. In particular, it is not clear whether the diurnal variation effects seen here (different for dawn and dusk) are in the basic precipitation phenomenon itself and are, in some way related to the westward drift of the protons from the nightside magnetosphere, the eastward drift of the electrons and the relative location of their precipitation zone both sides of the B min curve (Torr et al. 1975) in the Atlantic anomaly. The diurnal effects may as well be only in the final result of the precipitations viz. the increase in the electron density. This needs further exploration. Complications like possibilities of increases as well as decreases in $f_0 F_2$ (Torr and Torr, 1967), effects of neutral winds and transport along field lines (Serafinov et al. 1978; Prange and Bruston, 1980) would probably be still present. A detailed and thorough analysis should include data from a larger network, simultaneous data for F-region heights, at least some data for locations in the anomaly region e.g. at Gough island and other islands in this region such as Ascension, St. Helena, Trinidad, and Tristan da Cunha, and some supporting data from satellites. These could be supplemented with measurements of total electron content (De Mendoça, 1965, Massambani, 1978), of phase and amplitude of VLF signals (Mendes et al., 1970; Mendes and Ananthakrishnan, 1972), with riometers (Abdu et al., 1973; Trivedi et al., 1973) and studies of sporadic E (Abdu and Batista, 1977) which have already proved important tools for the study of particle precipitation. Theoretically, whereas precipitation zones for particles of several keV are known (Torr et al., 1975), similar calculations for primary electrons of about 2 keV or less and their secondaries would be needed, as these are the ones relevant for the F region. Also, precise calculations about the fountain effects in the two sectors are needed, to eliminate the possibility that the diffe-
rences seen in the South-American and South-African sector are due to the differences in the electric field structures in their equatorial regions.

The plasmasphere is known to have a dusk-time bulge. It is likely that particles from this bulge precipitate preferentially in the South-Atlantic anomaly. If so, protons and electrons of different energies and their secondaries will have different effects in different regions of the ionosphere. A simultaneous study of satellite observations of ion density and temperature and of $F$ region parameters as observed by ground ionosondes should prove very fruitful.

Acknowledgments

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