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Research Paper

Ionosphere D-layer lowering in the region of the South Atlantic Magnetic Anomaly

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A B S T R A C T

In this paper we analyse the effects of 25 solar flare events over long VLF propagation paths, one of them with the very remarkable property of crossing nearly the centre with the lowest magnetic field intensity in the South Atlantic Magnetic Anomaly (SAMA). The phase of the VLF transmitter signal (NPM: 21.4 kHz) on Lualualei, Hawaii, was recorded at the stations Punta Lobos (PLO, Peru) and Atibaia (ATI, Brazil) between 2007 March and 2011 September. Both paths NPM-PLO and NPM-ATI are collinear, and the comparison of the recorded phases suggests a descent of the lower ionosphere quiescent reflection height, possibly associated with the weakening of the Earth magnetic field in the SAMA region.

1. Introduction

The Earth surface and the lower ionosphere D-region (50–90 km) are the conducting walls of a spherical waveguide where the very low frequency (VLF: 3–30 kHz) radio waves can propagate over very long distances with little attenuation (2–3 dB/Mm). The ground electrical conductivity [Siemens/m] is almost time constant; except during some relatively rare geophysical events like, for instance, earthquakes (Reddy and Nagabhushanam, 2011). However, the upper wall of the Earth ionosphere VLF waveguide (EIW) is much more variable as it is strongly dependent on the degree of ionization of the atmospheric constituents at this height. The main ionizing agents are extreme ultraviolet, Lyman-α (1216 Å) solar photons (Nicolet and Aikin, 1960) as well as X-ray (<10 Å) radiation. The solar photons deposit their energies in the lower ionosphere and modify the electrical conductivity of the region by photoionization. Another way of changing the electrical conductivity is ionization by particle interaction when energetic electrons and protons precipitate. During the night the photo-ionization disappears. It can be only vestigial owing to lightning discharges, faint star illumination or other cosmic sources. In daylight and quiet Sun activity conditions, the less energetic X-ray photons cannot reach the D-region altitude because they are absorbed at about 90–100 km (Satori et al., 2005; Pacini and Raulin, 2006). On the other hand, flares being very energetic events of the solar activity can change significantly the Wait's parameters: the reference height H' [km] and the conductivity gradient or sharpness factor β [km^{-1}] (Wait and Spies, 1964). The X-ray photons during flares can reach the ionosphere producing changes on the conductivity of the D-region and below. This episode is known as Sudden Ionospheric Disturbance (SID). One case of the SID's which is more important in the scope of this work is the Sudden Phase Anomaly (SPA). The SPA is observed at the VLF stations receiving distant and powerful transmitter waves as a sudden increase in phase of the recorded signals. The effect of each flare over the propagation path is dependent on the event strength and the length of the solar illuminated path. Thus, the monitoring of VLF signal propagation over long distances constitutes a very useful tool to study the physical phenomena involving the lower ionosphere and its correlation with the solar activity. Moreover, since 1977 is known the existence of an ionization enhancement in the lower ionosphere over the South Atlantic Magnetic Anomaly (SAMA) (Abdu et al., 1981). The enhanced ionization and concomitant increase of conductivity could result from precipitation of energetic particles from the inner radiation belt during magnetically disturbed conditions (Abdu et al., 2005). Similarly, and under magnetically quiet conditions, Abdu and Batista, 1977 pointed toward a regular night-time ionization source over the SAMA region in the E-layer. In this paper, we present such an evidence during quiet times in the ionospheric D-region.

We analyse the effects of 25 solar flare events over two VLF propagation paths. One of them (NPM-ATI) is a long (13.06 Mm) VLF propagation path with the very remarkable property of crossing nearly the centre of the SAMA with the weakest magnetic field intensity as shown in Fig. 1. The other propagation path (NPM-PLO) is almost collinear with NPM-ATI, and mostly outside SAMA. The comparison of the effects produced by each flare disturbance over these two propagation paths provides the means to identify any differences which could be attributed

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to the SAMA.

The following sections II and III deal with instrumentation and data analysis as well as data reduction and discussion. Conclusions emerging from our study are given in section IV.

2. Data selection and methodology

For each one of the solar events selected from our database, two kinds of data were taken as input to this work:

(a) X-ray flare power flux, as recorded by GOES satellites (http://www.swpc.noaa.gov);
(b) phase of the VLF signal emitted by the NPM radio station (Lualualei, Hawaii) and recorded at the receiving stations PLO (Punta Lobos, Peru)and ATI(Atibai, Brazil) of SAVNET (South America VLF Network).

NPM is a US Navy transmitter and radiates a nominal power of 1000 kW. It is operating at 21.4 kHz without interruption except during scheduled maintenance periods. The stations ATI and PLO are part of the South America VLF Network (SAVNET) operational since 2006. The receiving systems of SAVNET at ATI and PLO are identical and have one RMS precision of time of about 50–70 ns, which corresponds to less than 1° of phase at 21.4 kHz. More details of SAVNET may be found in Raulin et al., 2009. Table 1 shows some characteristics of the stations involved.

At the time of each flare, the whole path between the transmitter (TX) and the receiver (RX) was illuminated by the Sun. Table 2 shows the data set used: the phase deviations recorded at the RX stations PLO and ATI as well as the corresponding phase errors. For all but one (the #18) of the events below, no energetic particles reached GOES satellites. However, NOAA Space Weather Prediction Centre (SWPC) reported a greater than 10 MeV proton event, at geosynchronous orbit observed from 8 to 10 March 2011. The event began at 08/0105Z, reached a maximum flux of 50 pfu on 08/0800Z, and ended at 10/12. Though this event involved also particles, their moderate energy (<10 MeV) might not be enough to penetrate deep into the atmosphere. Finally, we note that only the solar flares that occurred isolated in time were selected, in order to avoid superposition of solar events and the subsequent difficulty to measure the phase deviation.

Table 1
Geometry of the stations.

Station code or call sign	Latitude (°)	Longitude (°)	Distance to the transmitter (Mm)	Bearing from the transmitter (°)
NPM	21.420 N	158.151 W	0	–
PLO	12.504 S	76.598 W	9.651	75.192
ATI	23.185 S	46.559 W	13.058	74.132

3. Observational results

In Fig. 2 we compare the phase advances expected to be recorded at ATI and those actually observed. For each SPA the expected values at ATI were calculated as follows:

$$\Delta\phi_{ATI}expected = \Delta\phi_{PLO}observed^{*}\left(1+\frac{d_{PLO-ATI}}{d_{NPM-PLO}}\right)$$

where $d_{PLO-ATI}$ = distance from PLO to ATI = 3407 km
$d_{NPM-PLO}$ = distance from NPM to PLO = 9651 km

The dashed line along the diagonal of Fig. 2 indicates equal expected and observed phase advances at the receiver ATI.

Fig. 2 presents the following feature:

For all studied flares, the expected phase advance at ATI is systematically higher than that was actually observed.

The variation of the reflection height is related to the observed phase change by the following relation (Muraoka et al., 1977):

$$\Delta h = \frac{\Delta\phi}{360\frac{d}{\lambda}\left(\frac{1}{2a}+\frac{\lambda^{2}}{16h^{3}}\right)}\ldots.(*)$$

where h = D-layer reflection height = 70.55 km

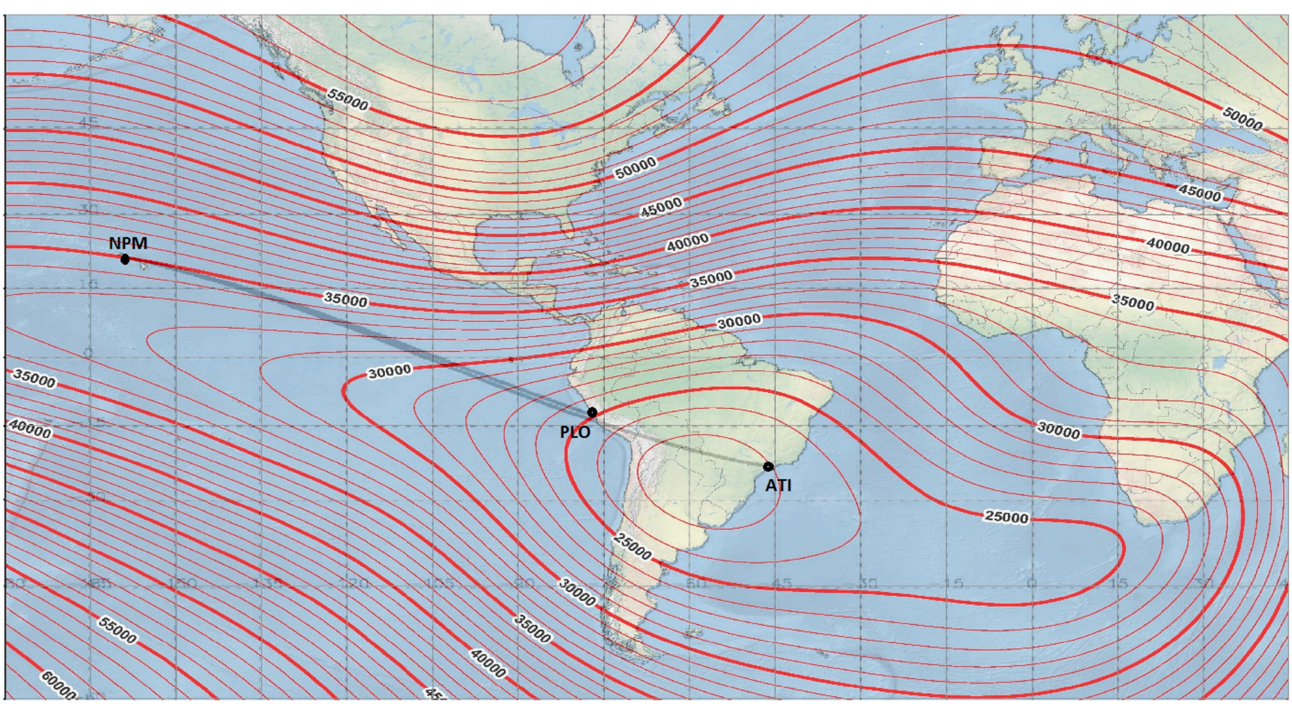

Fig. 1. The VLF paths NPM-PLO, NPM-ATI and the South Atlantic Magnetic Anomaly in 2015. The red contour lines represent the magnetic field intensity in nT (Kudos: http://www.ngdc.noaa.gov).

Table 2
Events data set.

Event no.	Date (yyyy/mm/dd)	Hour (hh:mm)	GOES Class	$\Delta\phi_{PLO}$ (°)	$\Delta\phi_{ATI}$ (°)
01	2007/07/10	17:50	C5.2	121.2 (0.8)	154.8 (2.0)
02	2008/03/25	18:46	M1.7	189.0 (0.6)	229.3 (2.4)
03	2009/12/18	18:48	C7.6	131.7 (0.3)	162.0 (2.8)
04	2010/01/18	19:54	C4.9	105.0 (1.3)	121.3 (3.0)
05	2010/01/19	17:44	C5.1	105.7 (2.0)	135.6 (7.6)
06	2010/01/19	20:23	M1.7	179.2 (0.6)	230.0 (2.2)
07	2010/02/06	18:52	M2.9	234.6 (1.6)	287.8 (4.4)
08	2010/02/06	21:31	M1.3	148.4 (0.7)	175.8 (2.7)
09	2010/02/08	19:06	C2.4	38.3(0.6)	44.6 (2.0)
10	2010/02/08	21:21	M1.0	115.8 (0.5)	137.9 (1.7)
11	2010/02/12	17:59	M1.1	129.2 (1.0)	167.1 (1.8)
12	2010/02/12	20:49	C1.3	14.4(0.8)	16.3 (1.0)
13	2010/03/27	18:26	C3.8	79.5(0.8)	94.4 (2.8)
14	2010/05/05	17:17	M1.2	122.2 (0.2)	154.6 (2.1)
15	2010/07/17	17:27	C2.4	49.7(0.4)	58.2 (0.7)
16	2010/08/07	17:58	M1.0	105.4 (0.4)	129.5 (1.6)
17	2010/08/15	18:28	C5.4	79.2(0.6)	99.8 (1.1)
18	2011/03/08	18:08	M4.4	241.8 (2.2)	293.5 (3.2)
19	2011/03/10	19:00	C4.0	73.3(0.8)	88.2 (2.0)
20	2011/03/15	17:28	C2.9	35.6(1.0)	46.3 (2.0)
21	2011/07/29	17:53	C3.2	45.1(0.6)	55.1 (5.4)
22	2011/08/05	17:40	C1.8	34.5(0.4)	44.7 (6.0)
23	2011/08/08	18:00	M3.5	196.6 (0.6)	244.4 (6.4)
24	2011/09/01	18:13	C2.0	29.9(0.6)	34.3 (5.6)
25	2011/09/03	17:32	C2.5	22.1(0.6)	27.1 (7.2)

Δh = h decrease due to SPA [km]
$\Delta\phi$ = SPA phase increase [°]
d = path length [km]
a = Earth radius [km]
λ = NPM signal wavelength = 14.01 km

(*) There are several other derivations (e.g. Tanaka et al., 2010) giving nearly the same results.

The formula is valid only for the propagation of the first order mode, e.g. during daytime conditions. In this work, as the whole paths were totally sunlit when the flares happened, only the first order mode must be considered as the higher modes are very much attenuated.

The $\Delta\phi$ differences between the phase values expected and that observed at ATI for the 25 SPA events were introduced in the Muraoka equation to calculate the corresponding Δh descents relative to the quiescent reflection level of 70.55 km. These results are plotted in Fig. 3, with the respective error bars representing 1.5 times the RMS value of the signal in a time interval of 10 min before the onset of the SPA. The figure shows a maximum value of Δh around 3.3 km.

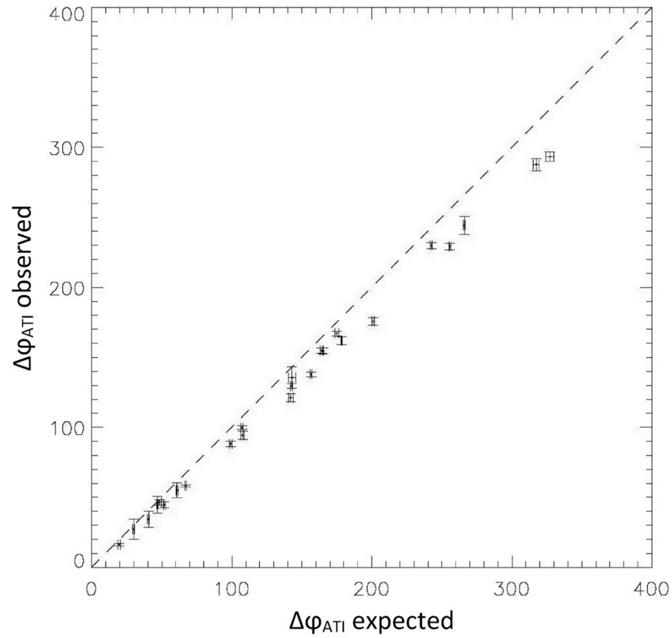

Fig. 2. Comparison of the phase advances expected and observed at ATI. The dashed line along the diagonal indicates equal expected and observed phase advances at the receiver.

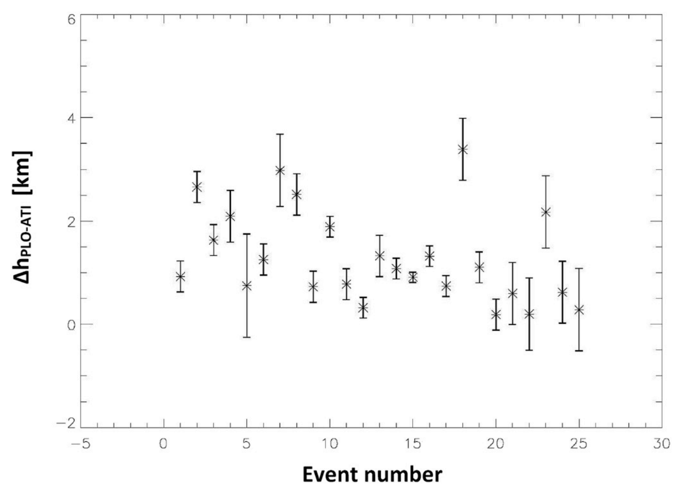

Fig. 3. Decreases of the D-layer reflection level between NPM and PLO as estimated by the Muraoka equation.

4. Discussion

The path illumination of the NPM-ATI course is slightly better than that of NPM-PLO, as the average zenith angles for each path are in the ranges [32°–48°] and [33°–53°], respectively. However, after having tested different algorithms for illumination correction we concluded that the mentioned little difference of illumination does not affect significantly the phase measurements.

The important observational result shown in the previous section is the difference between the expected and observed phase advances at the receiver ATI. In terms of the phase velocity of the wave propagating from NPM, the expected value at ATI is obtained from a very simple argument: it is equal to the observed value at PLO, plus that between PLO and ATI assuming the rate of phase change (degree/Mm) remains the same on the whole path. Thus, the map in Fig. 1 suggest that the wave phase velocity has changed in the portion of the propagation path between PLO and ATI.

As a first explanation, one might think that different ground electrical conductivities (seawater, $\sigma = 4000$ mS; land, $\sigma = 1$–10 mS) could account for the observed effect. However, following Wait and Spies (1964) the decrease of phase velocity between sea and land in our case is of the order 0,25%. That is one order of magnitude below the values of phase noise currently observed at ATI. Therefore, the changes of ground conductivity between sea and land do not affect significantly the phase measurements. Such a conclusion is certainly not valid for amplitude measurements.

An alternative hint is that the difference between the expected and observed phase advances along the NPM-ATI VLF propagation path could be due to the presence of the Brazilian Magnetic Anomaly. This is also suggested when looking at the map in Fig. 1, between receivers PLO and ATI. In this case the effect of the magnetic anomaly might be the decrease of the quiescent reflection height of the ionospheric D-region.

5. Conclusion

From the analysis of the SPA effects produced by 25 low and medium intensity solar flares along two collinear VLF propagation paths, one of them crossing nearly the central region of the South Atlantic Magnetic Anomaly, we conclude that there must be an enhancement of ionization which would be responsible for a lowering of the ionosphere quiescent D-layer reflection height.

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