The South America VLF Network (SAVNET): Providing new ground-based diagnostics of Space Weather conditions

Jean-Pierre Raulin [1]

[1]Centro de Radio Astronomia e Astrofísica Mackenzie (CRAAM/EE), Rua da Consolação 896, São Paulo, Brasil, raulin@craam.mackenzie.br

Abstract

In this paper we present recent results obtained by the South America VLF Network (SAVNET). The use of the VLF technique by tracking subionospheric propagation anomalies appears as a very promising tool to study various aspects of Space Weather disturbances. On long timescales it is possible to indirectly monitor the solar Lyman-α radiation along the solar cycles. Short time phenomena like solar explosive events can be observed with 100% probability, even for the small intensity events. Finally, the same technique is relevant to study the low ionospheric perturbations caused by geomagnetic storms on typical timescales of a day to few days.

1. Introduction

The Very Low Frequency (VLF) technique is a sensitive and efficient mean of probing the lower ionosphere regions D and E at altitudes between 60 - 90 km, where the electron density varies in the range 10^2 - few 10^3 cm^{-3} depending on the solar illumination conditions and, to a lower extent, on the solar activity. VLF waves can propagate over long distances (few Mm) without attenuation in the Earth-Ionosphere Waveguide (EIW) between two conductive boundaries namely the Earth surface and the low ionosphere. The VLF wave properties are described using the well-known Wait parameters [1], the reference height h' (in km) and the conductivity gradient β (in km^{-1}), which parameters describe the electrical conductivity in the low ionosphere.

During quiescent times, the solar Lyman-α radiation is the main responsible for the formation and maintenance of the D region [2], exceeding the effects of non flaring soft X-rays [3]. Therefore, the monitoring of the lower ionosphere can bring valuable information on this solar radiation which can only be detected outside the atmosphere of the Earth. During flares the incoming X-ray flux increases by few orders of magnitude and the spectrum hardens significantly. In this case, ≥ 6 keV photons can enter the Earth atmosphere and reach altitudes below the quiescent reference height (h' ~ 70 km) and change the conductivity parameter. These changes can be easily detected using the VLF wave diagnostic, and therefore the temporal behavior of h' and β parameters can be monitored. Therefore, the study of the ionospheric response to transient solar activity using the VLF technique can be helpful for, not only studying the low ionosphere physics but also to better understand the solar events. This is the case for example, when satellites sensors saturate during large solar events like it was the case during the 2003, November 4 event [4]. For this particular event, it was possible to recover the incoming X-ray flux that would have been detected at 1 AU, only because the ionosphere acted like a huge sensor of external radiation and responded to this large solar flare. Similarly, for very faint solar events, [5] have shown that the ionosphere is an extremely sensitive detector, responding to incoming powers as low as 2.7 x 10^{-7} W/m^2. Such a power would be barely detected above the X-ray background (few 10^{-6} W/m^2) during solar maximum period. During nighttime conditions, the low ionosphere is even more sensitive due to the reduced electron density, and the upper boundary of the EIW is now formed by the bottom side of the region E. In this case, ionization excesses can be observed as a response to disturbed geomagnetic conditions.

In this paper we present an overview of results obtained by the South America VLF NETwork since the array was installed in 2007. In particular, we want to illustrate how the VLF wave diagnostic, which utilizes the ionosphere as a large sensor is a powerful tool to monitor the long-term solar activity as well as transient solar and geomagnetic disturbances. Although not discussed in this paper, we want to emphasize that SAVNET is also able to diagnose atmospheric perturbations, is an efficient tool to study remote extra-terrestrial sources [6], and a well suited instrument to perform genuine researches on the search for seismic-electromagnetic effects in the low ionosphere [7].

2. The South America VLF Network - SAVNET

The South America VLF NETwork (SAVNET) is an array of 8 tracking receivers located in Brazil, Peru, Argentina and the Brazilian Antarctic research station Comandante Ferraz (EACF). Each station tracks VLF signals from powerful transmitters, some of them were part of the deactivated Omega network. In Figure 1 we show the SAVNET receivers

978-1-4244-6051-9/11/$26.00 ©2011 IEEE

location, along with some example of VLF propagation path from NPM (Hawaii, US), NDK and NAA (US), and NWC (Australia).

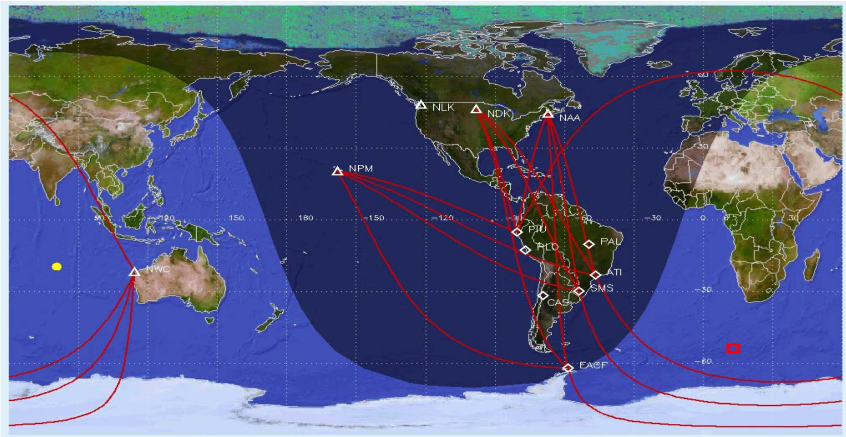

Figure 1. Examples of VLF propagation paths from transmitters (triangles) NAA, NDK, NPM and NWC to the receiver stations of SAVNET (diamonds).

Each receiver station is composed of 3 electromagnetic sensors, and the signals received are amplified and digitized using a commercial audio card. The crystal of the audio card provides a clock signal which is locked to a GPS internal clock (1 PPS) signal. This allows to determine the phase of the incoming wave without any drift. As a result, the typical error in the received phase signal is in the range 5 x 10^{-8} - 7 x 10^{-8} s which corresponds to about less than 1 degree depending on the frequency of the incoming wave. This is essential to provide a stable phase determination for long periods of days, or months. Daily data (~10 MB) are send regularly using network connections. More details on the SAVNET installation and first results are reported elsewhere [8,9].

3. Long-term monitoring of Space Weather effects

In Figure 2 we present ~ 4 years of measurements of daily amplitudes recorded using NDK - PIU path. The seasonal variations are understand in terms of the mean solar illumination as shown by the variations of the mean solar zenith angle χ_M . However, one can see that the trend of daily amplitudes is lower during periods of minimum of solar activity, as for example in mid-2009, and as indicated by the solar Lyman-α time curve.

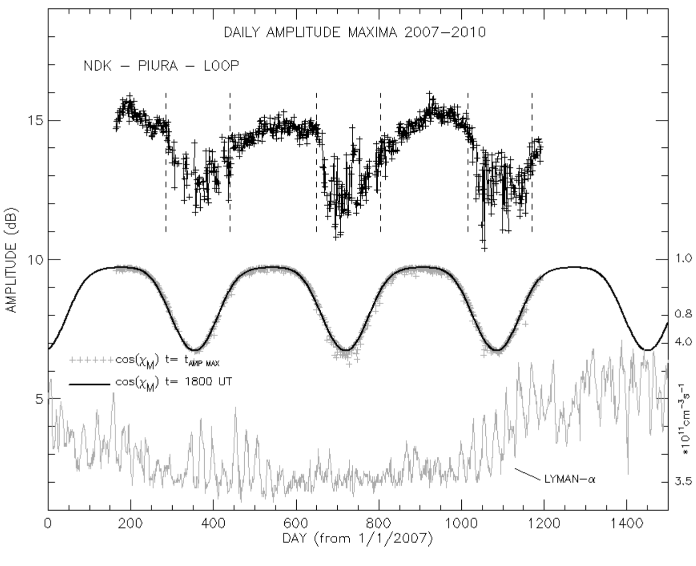

Figure 2. Daily measured amplitudes compared to mean solar illumination

4. Transient Space Weather disturbances

On shorter timescales solar flares produce excesses of ionization in the low ionosphere. In Figure 3 we present the minimum soft X-ray flare power that has been associated with a ionospheric disturbance for different periods of solar activity as characterized by the level of solar Lyman-α radiation. About 500 solar events were studied during the solar minimum in 2007-2009 [5], giving a lower X-ray threshold of 2.7 x 10^{-7} W/m^2 (point 8). Similar lower limits were obtained (observational points 1-7) for higher solar activity levels using already published observations [10-16]. This figure clearly suggests that the lower X-ray threshold Px increases with solar activity. Moreover this result also agrees with the idea that the solar Lyman-α radiation is the main agent to form and maintain the quiescent ionospheric D-region [2].

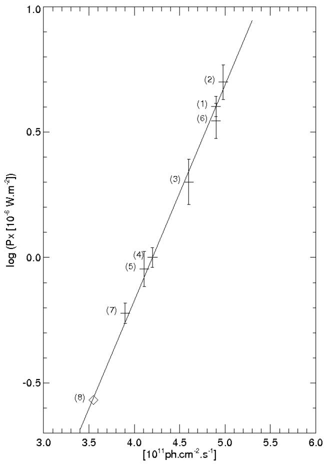

Figure 3. Soft X-ray lower limit power in order to produce a detectable ionospheric disturbance, as a function of the solar Lyman-α flux (adapted from [5]). Observational points 1-7 and 8 refer to references [10-16], and [5] respectively.

We mention that the power Px ~ 2.7 x 10^{-7} W/m^2 will be barely detected during solar maximum when the quiescent background level can reach few 10^{-6} W/m^2. Finally, Figure 3 indicates that the X-ray threshold was somewhat higher for the minimum of solar activity in 1995-1997 (point 7) compared to the last solar minimum of 2008-2009 (point 8). This can be an indication that the last solar minimum was different from the previous ones.

During nighttime periods the ionosphere is more sensitive than during daytime, due to the lower electron density. On 2010, April 11 a geomagnetic storm initiated at 23:00 UT and reached its maximum Kp ~ 6 value on April 12 between 00:00 and 03:00 UT, with a Dst index always below 50 nT, indicating that the storm was moderate. In Figure 4 we show the nighttime phase records (red curve) registered using the NDK - CAS VLF propagation path. It is compared with the mean phase measured during quiescent (Kp < 2) nighttime conditions for a period spanning +/- 15 days around April 12. Between 00:00 UT and 05:00 UT the phases are higher than the mean value by about 50 degrees, indicating a lowering of the nighttime reference height. The phase advance is particularly marked at the time of > 2 MeV electron precipitation between 02:00 UT and 04:00 UT.

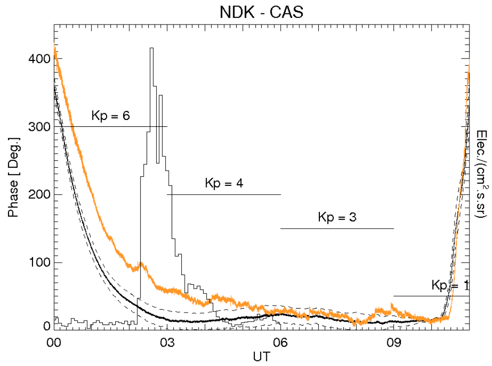

Figure 4. Nighttime phase records, compared to a mean value estimated during quiet days. The histogram indicates an increase of > 2 MeV electron flux.

5. Conclusions

We have shown that the VLF tracking technique does provide relevant diagnostic of Space Weather conditions. On long timescales of the order of the solar cycle, this technique can inform on the solar Lyman-α radiation which can only be measured in space. On shorter timescales, we have demonstrated that the low ionosphere is very sensitive to solar explosive events, and that the SAVNET instrumental facility is able to detect 100% of solar events above an X-ray level of 4.0×10^{-7} W/m^2. The same technique can also be used to study geomagnetic disturbances.

7. References

1. J. R. Wait, “Diurnal Change of Ionospheric Heights Deduced from Phase Velocity Measurements”, *Proc. IRE*, **47**, 1959, pp. 998.
2. M. Nicolet, A. C. Aikin., " The formation of the D region of the ionosphere," *J. Geophys. Res.,* **65**, 1960, pp.1469-1483.
3. A. A. Pacini, J.-P. Raulin., " Solar X-ray flares and ionospheric sudden phase anomalies relationship: A solar cycle phase dependence," *J. Geophys. Res.,* **111***,* 2006, A09301.
4. N. R. Thomson, C. J. Rodger, M. A. Clilverd., " Large solar flares and their ionospheric D region enhancements," *J. Geophys. Res.,* **110 (A6)**, 2005, A06306-A06316.
5. J.-P. Raulin, F. C. P. Bertoni, H. R. Gavilan, W. Guevara-Day, R. Rodriguez, G. Fernandez, E. Correia, A. Pacini, T. R. C. Stekel, W. L. C. Lima, N. J. Schuch, P. R. Fagundes, R. Hadano., " Solar flare detection sensitivity using the South America VLF Network (SAVNET)," *J. Geophys. Res*. , 2010, pp. A07301-A07307.
6. Y. T. Tanaka, J.-P. Raulin, F. C. P. Bertoni, P. R. Fagundes, J. Chau, N.J. Schuch, M. Hayakawa, Y. Hobara, T. Terasawa, T. Takahashi, " First Very Low Frequency detection of short repeated bursts from magnetar SGR J1550-5418, " *Astrophys. J. Letters*, **721**, 2010, pp. L24-L27.
7. M. Hayakawa, J.-P. Raulin, Y. Kasahara, F.C.P. Bertoni, Y. Hobara, W. Guevara-Day, " Ionospheric perturbations in possible association with the 2010 Haiti earthquake, as based on medium-distance subionospheric VLF/LF propagation data," *Nat. Hazards Earth Syst. Sci.*, **11**, 2011, pp. 513-518.
8. J.-P. Raulin, P. David, R. Hadano, A. C. V. Saraiva, E. Correia, P. Kaufmann, " The South America VLF NETwork (SAVNET)," *Earth, Moon and Planets,* **104**, 2009, pp. 247-261.
9. J.-P. Raulin, P. David, R. Hadano, A. C. V. Saraiva, E. Correia, P. Kaufmann, " The South America VLF Network (SAVNET): Development, Installation Status, First Results," *Geofísica Internacional*, **48**, 2009, pp. 185-193.
10. P. Kaufmann, M. H. Paes de Barros, " Some relationships between solar X-ray bursts and SPA’s produced on VLF propagation in the lower ionosphere," *Solar Physics,* **9***,* 1969, pp. 478-486.
11. P. Kaufmann, L.R. Rizzo Piazza, J.H. Fernandez, "Solar flares not producing sudden phase advances," *J. Geophys. Res.,* **107(A8)**, 2002, SIA30-1- SIA30-4.
12. P. Pant., " Relation between VLF phase deviations and solar X-ray fluxes during solar flares," *Astrophysics and Space Science*, **209**, 1993, pp. 297-306.
13. W. M. McRae, N. R. Thomson.," Solar flare induced ionospheric D-region enhancements from VLF phase and amplitude observations," *J. Atmos. Sol. Terr. Phys.,* **66**, 2004, pp. 77-87.
14. Zigman, V., Grubor, D., and Sulic, D. "D-region electron density evaluated from VLF amplitude time delay during X-ray solar flares," *J. Atmos. Terr. Phys.,* **69,** pp. 775-792.
15. J. –M. Comarmond, “Contribution à l’étude de la basse ionosphère par dês mesures de phaseet d’amplitude d’ondes électromagnétiques à très basse fréquence”, *Thèse de Doctorat d’Etat*, Université Pierre Marie Curie, Paris VI:1977.
16. A.A. Pacini, "Dependência das propriedades da região-D ionosférica com o ciclo de atividade solar", *Dissertação de Mestrado em Geofísica Espacial*, INPE, São José dos Campos:2006.