32nd URSI GASS, Montreal, 19-26 August 2017

Daytime sensitivity of the lower ionosphere to solar X-ray flares evaluated from VLF signal measurements

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Abstract

Solar X-ray flares produce enhancement of ionization in the daytime lower ionosphere that modifies the propagation of Very Low Frequency (VLF) radio signals. Considering the lower ionosphere as a detector of solar X-ray photons, we investigate its sensitivity. This sensitivity is defined as the minimum X-ray fluence (F_{min}) necessary to produce a disturbance of the quiescent ionospheric conductivity detectable by the VLF technique. We define F_{min} as the photon energy flux integrated over the time interval from the start of a solar X-ray flare up to the beginning of the ionospheric disturbance. F_{min} is computed for ionospheric disturbances, which occurred between December and January since year 2007 till 2016. The computation made use of the X-ray flux in the energy band less than 2 Å and the amplitude of VLF signals emitted from The USA (NAA), France (HWU) and Turkey (TBB), and recorded in Brazil and Peru (NAA), and northern Finland (HWU and TBB). We found a solar cycle dependence of F_{min}, as well as, a dependence on the solar illumination conditions. Our results suggest that the lower ionosphere is more sensitive to X-ray flares during the minimum epoch of solar cycle 24 and that the sensitivity decreases when the Sun is more active. Similarly, our results suggest that the ionospheric sensitivity improves when the solar zenith angle has lower values. Our findings also agree with previous results showing that the height of the lower boundary of the ionosphere varies during the solar activity cycle.

1. Introduction

Very Low Frequency (VLF: 3 - 30 kHz) radio signals propagate inside a natural waveguide which is called the Earth-ionosphere waveguide. The upper boundary of this waveguide is formed by the lower ionosphere and its electrical conductivity can be sensed by the VLF technique. In this technique, the properties of the lower ionosphere are represented by the Wait parameters [1]: reference height (H_0) and conductivity gradient (β).

During daytime, the quiescent lower ionosphere is formed by the solar Lyman-α (Ly-α) radiation [2]. However, during solar flares there is a considerable increase in the X-ray flux. Photons with wavelength less than 2 Å can penetrate down to the lower ionosphere, and even below, and produce enhancement of ionization there [3]. Due to the flare ionization the ionospheric conductivity changes and it reveals variations in H_0 and β. The variation of these parameters are observed as anomalies in the phase and amplitude of the VLF signals.

Raulin et al. [4] studied the statistical occurrence of X-ray flare that disturbed the lower ionosphere at low and mid-latitudes. They reported that the ionospheric sensitivity depends on the phase of the solar cycle. Confirmation about the solar cycle dependence of the ionospheric sensitivity were reported by Pacini and Raulin [3] and Raulin et al. [5]. However, there are very few quantitative analyses of the ionospheric sensitivity. Particularly, studies that show similarities or differences of the daytime ionosphere sensitivity at high-latitude, and low and mid-latitude regions have not yet been suggested.

The sensitivity of the lower ionosphere is defined as the minimum X-ray fluence (F_{min}) needed to produce a detectable disturbance of the quiescent ionospheric conductivity. The aim of the present study is to determine the sensitivity of the lower ionosphere and to test whether this sensitivity depends on both the solar activity cycle and the solar zenith angle (χ). To implement this study, the data of two different VLF receiver have been used. One located in polar regions and the other located in tropical regions. An explanation of these receivers and the methodology applied in the analysis are presented in the next section.

2. Instrumentation and Data Analysis

In the analysis were used data obtained by two different kinds of VLF receivers. One is the Kannuslehto VLF receiver, located in polar regions, and the other belongs to the South American VLF NETwork (SAVNET), located in tropical regions. At Kannuslehto the receiver consists of two square loop antennas [6]. The receiver operates in wideband since 2006 and record all the transmitter signals below 39 kHz. SAVNET is composed of various VLF receivers located in South America and the Antarctic [7]. The receivers consist of one vertical and two square loop antennas. SAVNET is in operation since 2006 and record the phase and the amplitude of VLF radio signals from transmitters located mainly in The USA.

In this study the amplitude of VLF signals emitted by HWU (France) and TBB (Turkey) and recorded at Kannuslehto, Finland, were used. The amplitude of the NAA transmitting signal (The USA) recorded by the

SAVNET receivers located in Peru and Brazil was also used. We selected all the amplitude variations caused by simple solar X-ray flares, occurred during quiet geomagnetic conditions, in the period of time between December and January since 2007 till 2016.

To compute F_{min}, first, it was determined the X-ray flux in the energy band below 2 Å. To obtain that energy band we proceeded as described by Pacini and Raulin [3]. In our computation we assumed that the X-rays are emitted by a hot isothermal plasma associated with the flaring active region. To represent the characteristics of this plasma we have used two solar abundances models: coronal and photospheric. In our procedure, the only difference with the method applied by Pacini and Raulin [3] is that to estimate the temperature (T) and the emission measure (EM) of the flaring plasma we used the CHIANTI spectral model [8]. Finally, we end with two time profiles in the energy band below 2 Å, one for each model of abundances.

The sensitivity of the lower ionosphere, defined by F_{min}, is computed by the integration over time of the X-ray flux in the energy band less than 2 Å since the start of the flare up to the beginning of the VLF deviation. Figure 1 shows the temporal variation of the amplitude of a VLF signal and the time evolution of the associated X-ray flare (black and blue continue lines, respectively). The vertical dashed red and green lines are the onset times of the X-ray flare and the amplitude deviation used for the computation of the F_{min}, respectively. The results of F_{min} calculated for every selected event are shown in the next section.

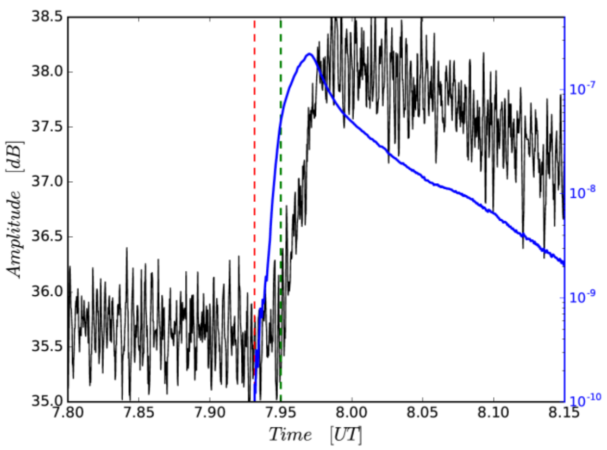

Figure 1. Temporal behaviour of the amplitude of a VLF signal recorded at Kannuslehto (black line) and the temporal variation of the X-ray flux with wavelenght less than 2 Å (blue line). The vertical dashed red and green lines represent the initial time of the flare and the start time of the VLF amplitude deviation, respectively.

3. On the Sensitivity of the Lower Ionosphere

F_{min} was computed for every event and is plotted according to its time of occurrence in Figure 2. In the figure the events are distinguished according to the model of abundances (stars and circles for photospheric and coronal models, respectively) and according to the received system used (black for Kannuslehto and red for SAVNET receivers). The magenta line is the 15-months smoothed time evolution of the solar Ly-α radiation used as a proxy of the behavior of the solar cycle 24. In Figure 2 we observe that F_{min} obtained by the coronal model has lower values than those obtained by the photospheric model. It is also possible to differentiate that the dispersion of F_{min} is higher for the photospheric values than for the coronal values. Furthermore, sometimes the dispersion is approximately of one order of magnitude, especially for those events recorded by the SAVNET receivers. Despite the dispersion, we observe that in average during solar minimum the values of F_{min} are slightly lower than the values obtained during solar maximum. We also verified that the value of F_{min} does not depend on the size of the flare.

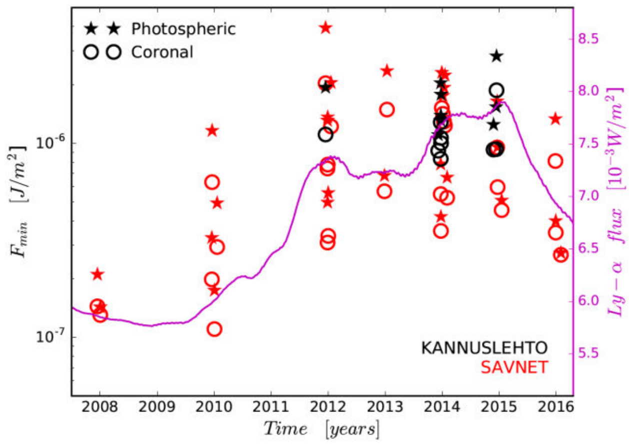

Figure 2. The values of F_{min} according to their time of ocurrence, obtained by the photospheric (stars) and coronal (circles) models and using VLF data from Kannuslehto (black) and SAVNET (red). The magenta line is the smoothed time variation of the Ly-α radiation used as a proxy of the solar cycle 24.

Figure 3 shows the average of F_{min}, with its error bars, for every period of analysis shown in Figure 2. To calculate the average, it was considered the events for which the average solar zenith angle (χ), along the propagation path, was lower than 60 degrees. To obtain χ, every propagation path was divided in several parts (i = 1, n) of 10 km each one. A solar zenith angle was computed for each part and then the average of those values were estimated. As in Figure 2, the results in Figure 3 are differentiated according to the model of abundances used (yellow starts for photospheric model and filled green circles for coronal model). The magenta line is the temporal evolution of the solar Ly-α radiation during solar cycle 24. From the figure we observe that F_{min} has lower values when the solar cycle was at minimum phase and higher values when the solar cycle was maximum. Thus, it suggests that the lower ionosphere is more sensitive to X-ray flares during the minimum epoch of solar cycle 24 and that the sensitivity decreases as the Sun is becoming more active. The same result was found for both models of solar abundances. Thus, the following analyses will be made considering F_{min} values obtained by the coronal model.

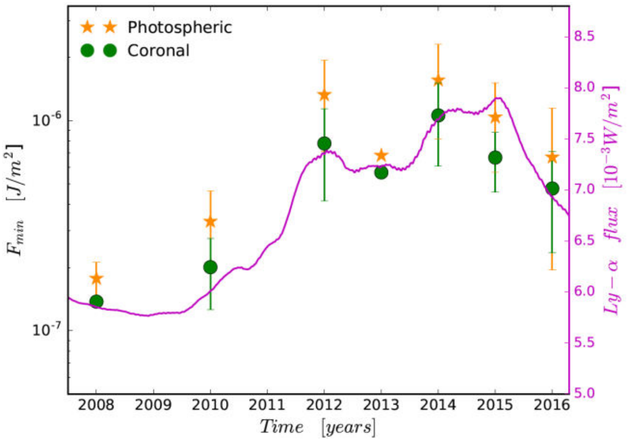

Figure 3. Average values of F_{min} for every period of analysis shown in Figure 2 and for events with average solar zenith angle lower than 60 degree. The results are differentitated acording to the model of abundance used: photospheric (stars) and coronal (filled circles). The magenta line is the smoothed time variation of the Ly-α radiation used as a proxy of the solar cycle 24.

The evaluation of F_{min} against the cosine of χ is shown in Figure 4. In the figure, the events recorded by the Kannuslehto and SAVNET receivers are displayed with black and red symbols, respectively. The events that occurred during solar minimum are exhibited with crosses and those that occurred during solar maximum are exhibited with filled circles. The orange line is the linear regression taking into account the events occurred during solar maximum. In Figure 4 we observe that those events recorded by Kannuslehto have solar zenith angles of higher values while for those recorded by the SAVNET receivers the values of the zenith angle are lower. These characteristics are understandable because for the period of analysis shown here it was winter time in the northern hemisphere. Thus, for the events recorded by Kannuslehto the sun position was closer to the horizon and for those recorded by the SAVNET receivers the sun position was closer to the zenith. From the figure we observe that in general the F_{min} has higher values when the solar illumination condition is not good and these values decrease when the illumination condition improves. Thus, we found that the value of F_{min} depends on the solar zenith angle, that means, the ionospheric sensitivity depends on the angle of incidence of the photons.
The evaluation of F_{min} against the time delay between the onset of the X-ray flare and the beginning of the VLF deviation is shown in Figure 5. As in Figure 4, here the events are differentiated according to the phase of the solar cycle (crosses and filled circles for solar minimum and solar maximum, respectively) and according to the VLF receiver system used to record the ionospheric data (red symbols for Kannuslehto and black symbols for SAVNET). From the figure we observe that there is not a clear difference between the events recorded by Kannuslehto and those recorded by the SAVNET receivers. But, as a whole, we observe that when F_{min} is higher the time delay is also higher. Differentiating according to the phase of the solar cycle we observe that during solar minimum the events have in average lower values of F_{min} and also a shorter time delay. During solar maximum the events have in average higher values of F_{min} and also a higher time delay. Thus, we found that the reaction of the lower ionosphere to solar flares during solar minimum is faster than the reaction of the ionosphere to those occurred during solar maximum. A discussion of the results exposed here is presented in the next section.

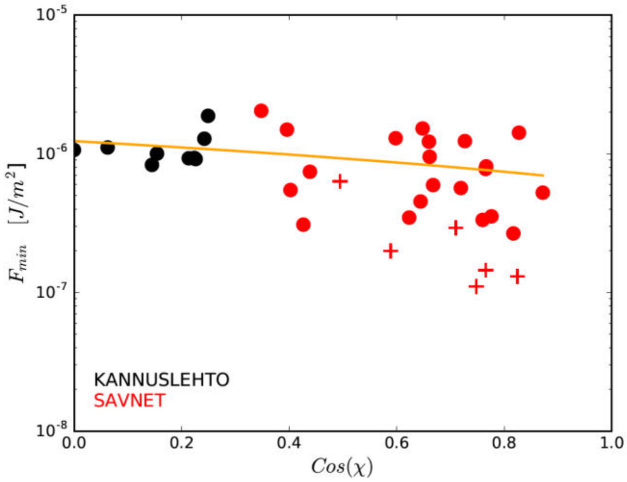

Figure 4. Values of F_{min} obtained by using the Kannuslehto (black) and the SAVNET (red) receiver systems, evaluated against the cosine of the average solar zenith angle of the VLF propagation paths. The crosses refer to events occured during solar minimum and filled circles to events occurred during solar maximum. The yellow line is the linear fit considering the events occurred during solar maximum.

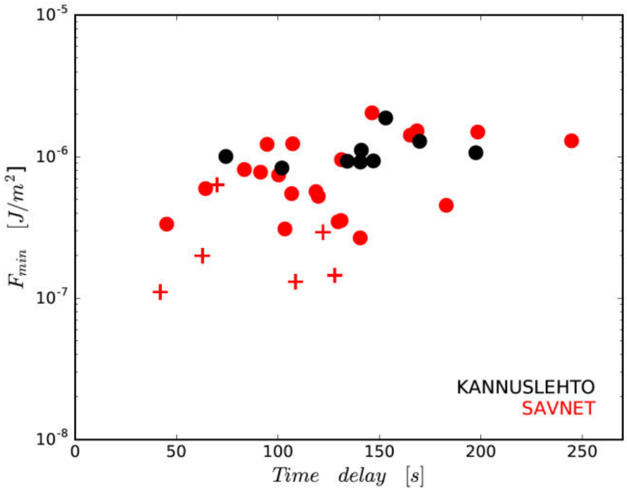

Figure 5. Values of F_{min} obtained using the Kannuslehto (black) and the SAVNET (red) receiver systems, evaluated against the time delay between the onset of the X-ray flare and the begining of the VLF amplitude

deviation. The crosses refer to events occured during solar minimum and filled circles to events occurred during solar maximum.

4. Discussions

We have analyzed the sensitivity of the lower ionosphere by studying the ionospheric response to solar X-ray flares occurred during the solar cycle 24. We used the amplitude of VLF transmitting signals recorded in polar and tropical regions of the Earth. Our results indicate that the height of the quiescent lower ionosphere is not constant along the solar cycle, being lower during solar maximum and higher during solar minimum. This means that during solar maximum the X-ray flare excesses produce enhancements of ionization, measured by the VLF technique, deeper in the atmosphere where there are more neutral constituents. Thus, during solar maximum, it is needed more time and more minima fluence (F_{min}) to produce a significative disturbance of the ionospheric conductivity. Therefore, the ionospheric sensitivity is higher during solar minimum and lower during solar maximum.

The dispersion of F_{min} in Figure 2 can be a result of the calculation of the ionospheric sensitivity for different solar zenith angles and putting all together in the same graphic. Raulin et al. [9] also showed approximately one order of magnitude of difference of F_{min} for different illumination conditions. Examining the events occurred during solar maximum in Figure 4, we observe that for the same solar zenith angle the dispersion of F_{min} has been reduced. However, the solar zenith angle dependence does not explain completely the dispersion observed. The events were recorded by different receivers; therefore, the VLF signal were propagated for different propagation paths and sensed different ionospheric conditions. Furthermore, there are ionospheric anomalies associated with interaction between the lower and upper atmosphere (e.g. atmospheric waves) that can influence in our results. Despite the dispersion, we observed that in average the time evolution of Fmin follows the evolution of the solar activity cycle.

Finally, Raulin et al., [9] reported that the daytime lower ionosphere is less sensitive than the nighttime lower ionosphere, being the F_{min} for nighttime conditions ~10^{-9} J/m^2. The minimum value of F_{min} found in our study for the daytime ionosphere is ~10^{-7} J/m^2. This value indicates that the daytime ionospheric sensitivity is at least 2 orders of magnitude lower than the nighttime sensitivity. Thus, our results agree with their findings.

5. Conclusions

In this study we found that the lower ionosphere is more sensitive to X-ray flares during the minimum epoch of solar cycle 24 and that the sensitivity decreases as the Sun is becoming more active. We also found that the ionospheric sensitivity depends on the angle of incidence of the photons, being more sensitive for better solar illumination conditions. Thus, at a given time, the sensitivity differs for different regions on the Earth. Analyzing the time delay of the events we found that the average initial response of the lower ionosphere to solar flares during solar minimum is in average faster than the initial response during solar maximum. This behavior agrees with previous results about the changes in the reference height of the lower ionosphere, which is higher during solar minimum and lower during solar maximum. Thus, during solar maximum the enhancements of ionization, generated by the X-ray flare radiation and measured by the VLF technique, are produced deeper in the atmosphere where there are more neutral components. The recombination process is high there and thus, it is needed more time and more F_{min} to produce a measurable disturbance in the ionosphere.

6. Acknowledgements

The SAVNET project was funded by FAPESP (Proc. 06/02979), and received partial funds from CNPq (482000/2011-2), and Centre National de la Recherche Scientifique (CNRS).

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