Study of the effects of solar activities on the ionosphere as observed by VLF signals recorded at TNU station, Vietnam

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Abstract: A SuperSID monitor installed at Tay Nguyen University (TNU), Vietnam is used to detect the temporal variations of Very Low Frequency (VLF) signals during 2013 and 2014 to understand the responses of the ionosphere to sunset/sunrise transitions and solar flares. Two VLF station signals are tracked, JJI/22.2 kHz in Japan and NWC/19.8 kHz in Australia. Results show that the effects of sunrise, sunset and solar flares on the NWC signal are more significantly different than those on the JJI signal. Sunset and sunrise spikes only occur on the JJI-TNU path because of longitudinal differences between the receiver and transmitter. Two sunset dips and three sunrise dips appear on the NWC signal during summer season. During intense solar flares, the dips occur after the maximum disturbance of the VLF signals for the North-South path. The appearance of these dips is explained by modal interference patterns. Observing temporal variations of sunrise and sunset dips or spikes of VLF signals during different seasons enhances the understanding of the behavior of the ionosphere.

Keywords: ionosphere, VLF signals, sunrise transition, sunset transition, solar flares.

Introduction

The ionosphere of the Earth ranges from an altitude of 60 km – 400 km. The environment includes free electrons and positive ions in equal numbers. The ionosphere enables radio communication over great distances. The D-region, the lowest portion, is the part of the ionosphere below 95 km. This region has a high pressure, which is important for photochemical reactions, and has many sources which contribute to the ionizing of neutral particles (Hunsucker and Hargreaves, 2003). The conductivity of the D region increases exponentially with altitude and this region is characterized by the reference height, h' (in km), and the exponential sharpness factor, β (in km^{-1}). From these parameters, the electron density (N_e) as a function of altitude (h) is determined by (Wait and Spies, 1964)

$$N_e(h) = 1.43\times10^{13}\,\mathbf{exp}(-0.15h')\times \times\mathbf{exp}\left[(\beta-0.15)(h-h')\right] \quad [\mathrm{m}^{-3}] \qquad (1)$$

There are dozens of Very Low Frequency (VLF, 3 – 30 kHz) transmitters in the world to serve the purposes of navigation, positioning and research. The VLF signals from these transmitters are very stable in amplitude and phase. VLF signals can propagate in the environment between the D region and the ground, creating an Earth-Ionosphere Waveguide (EIWG) with low attenuation in the range of 0.5 to 2 dB/Mm (Ferguson and Snyder, 1980). When disturbances of these VLF signals are detected by a receiver, we can identify the characteristics of the ionosphere along their propagation paths (Dahlgren, et al., 2011).

Radiation generated from the Sun during solar flares causes sudden perturbations to the lower ionosphere. These are known as Sudden Ionospheric Disturbances (SIDs). Solar flares can occur at any time but are often associated with the appearance of sunspots and sometimes related to the release of material from the corona. This ejected plasma material is called a Coronal Mass Ejection (CME), and contains embedded magnetic fields from the Sun. CMEs travel away from the Sun at about 2 million kilometers per hour. It could take them anywhere from 1 to 5 days to reach the Earth. The high energy of particle streams causes disordering, compression, and stretching of Earth's magnetosphere, which creates currents with high power hitting the upper atmosphere. These phenomena disrupt communications, cause magnetic storms, and generate aurora in the polar regions (Scherrer et al., 2009; Hargreaves, 1992). This "space weather" encompasses conditions on the Sun, the solar wind, the magnetosphere, the ionosphere, and the neutral atmosphere. Space weather can influence the performance and reliability of space- borne and ground- based technological systems and endanger human and animal life or health (WMO, 2008). Studies of the ionosphere to inform prediction of space weather events become imperative.

In 2012, a SuperSID receiver (ID 0325) from Stanford University (Scherrer, et al., 2008) was installed at Tay Nguyen University (TNU), Vietnam to record VLF signals. These receivers are distributed as part of the United Nation's International Space Weather Initiative (ISWI). The ISWI was established to advance space weather science (ISWI website). A SuperSID monitor can detect the effects of X-rays on the D-region of the ionosphere during solar flares by tracking the intensity variations of VLF radio waves reflecting in the ionosphere. SID network data are shared on a website at the Stanford Solar Center (SID data website). In this website, solar flare events are compared with the changes of VLF intensity. Therefore, using data from the SID network, researchers can easily compare the reaction of VLF waves at different sites with the intensity of X-rays emitted from the Sun during solar flares.

Using our SuperSID monitor, we observed changes of NWC and JJI signals recorded at TNU, Vietnam during day-night transitions to understand the behavior of the ionosphere. In this paper, we compare the effects of sunrise and sunset on the JJI-TNU path with those on the NWC-TNU path. We also discuss some specific solar flare events which enhance the intensity of the VLF signals and explain their physical processes.

Experiment setup

The SuperSID receiver system installed at TNU includes a square wire-wrap antenna with 1m sides, a preamplifier, a sound card with 96 kHz sampling rate, a computer using the Microsoft Windows operating system, and SuperSID software. Figure 1 illustrates the transmission path between two VLF stations and the receiver installed at TNU.

The receiver (12.65° N, 108.02° E) can clearly detect the JJI/22.2 kHz signal from Japan (32.04° N, 130.81° E) and NWC/19.8 kHz signal from Australia (21.8° S, 114.2° E). Our SuperSID monitor records the relative intensity of VLF waves into files having the extension "csv". The data are recorded from 00:00:00 to 23:59:55 UT (Universal Time) every day. The VLF data recorded from 2013 – 2014 are considered in our work.

Results

In Figure 2a, during sunset transitions (labeled SS) the JJI signal strength reduces to a minimum around 9:00 UT. After sunset, this signal steeply increases to the first spike (labeled SP1). Before dawn, a second spike (labeled SP2) occurs, and at dawn the signal drops to a minimum (labeled SR) around 22:30 UT. The JJI signal increases after a minimum and forms a sharp wedge, then the intensity slightly decreases for a moment before rising again. The signal between the NWC transmitter and TNU reduces to a minimum (or dip) around 10:30 UT during sunset transition. Two minima (labeled as SR1 and SR2) occur around 22:00 UT and 22:36 UT during sunrise transition (Figure 2b). The signal strength of the NWC-TNU path dramatically increases after the first dip and gradually increases after the second dip and recovers to the normal levels. The spikes do not appear on the NWC signal after the dips during sunset transition nor before the dips during sunrise transition. Note that, in the daytime some SID events occur on the NWC signal (Figure 2b).

Figure 3 shows the time of sunset and sunrise at the locations of the JJI transmitter and the receiver, as well as the spikes and dips of the VLF signal during 2013. In Figure 3a, the sunset dips appear from 8:35 to 10:54 UT and the sunrise dips appear from 20:54 to 22:37 UT for the JJI signal. The sunset dips appear after the Sun sets over the location of the transmitter and before the Sun sets over the local site. The sunrise dips appear after the Sun rises at the transmitter and before the Sun rises at the receiver. In Figure 3b, the sunset spikes occur

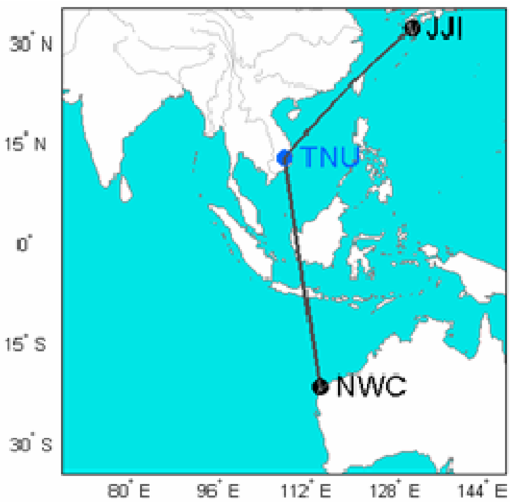

Figure 1: The path between the JJI and NWC VLF transmitters and the receiver installed at TNU.

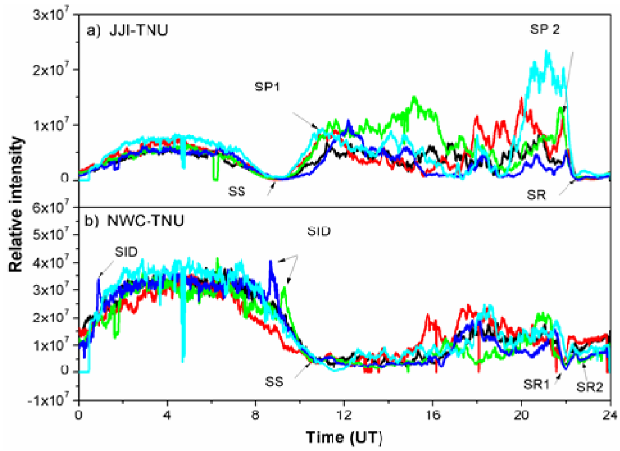

Figure 2: The diurnal variations of the JJI and NWC signals during January 2013.
(SS = sunset; SP1 = spike after sunset; SP2 = second spike; SR = sunrise;
SR1 = sunrise minimum #1; SR2 = sunrise minimum #2))

from 10:33 to 12:52 UT and the sunrise spikes occur from 20:03 to 22:05 UT. The sunset spikes occur after the Sun sets over the locations of both receiver and transmitter. The sunrise spikes appear near sunrise at the transmitter and appear before sunrise at the receiver. This indicates that the ionosphere is ionized before the Sun rises and after the Sun sets. This means that the level of ionization has changed, thus the VLF intensity has changed. Figure 3 also shows that the time variations of sunrise and sunset dips or spikes follow the variations of sunrise and sunset times at the transmitters.

Figure 4 shows the diurnal variations of the average intensity of the NWC signal from January - December, 2014. The *y* axis shows the VLF intensity with a logarithmic scale. In the summer months (May – August) and an equinox month (April), the first dips occur around 10:30 UT and the second dips occur around 11:30 UT. During summer months (May - July), there are three minima during sunrise transition.

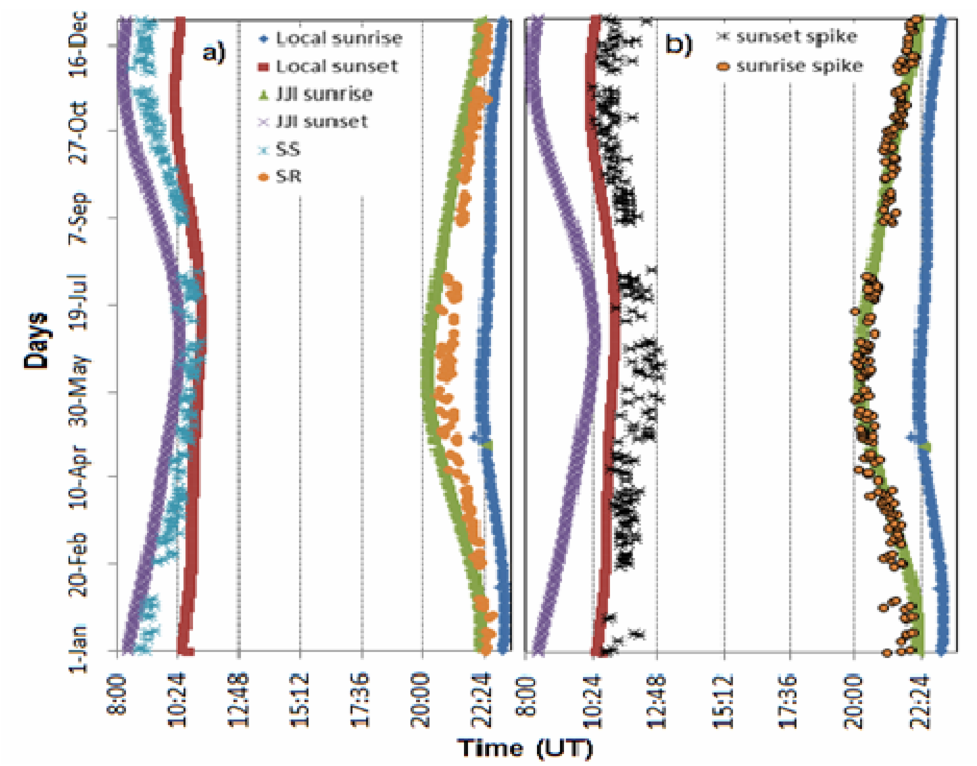

Figure 3: The effects of sunrise and sunset on the JJI signal during 2013.

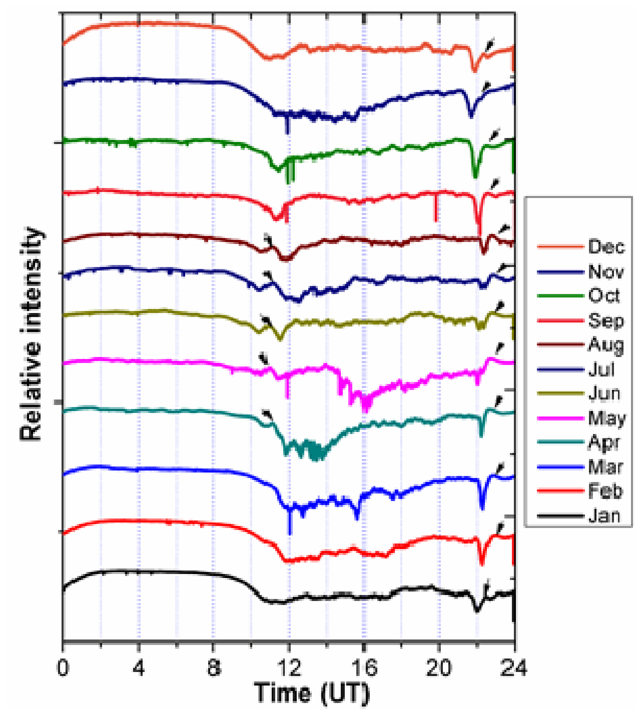

Figure 4: The diurnal variations of the NWC signal during quiet days of 2014.

Now we present some special cases of the responses of the VLF signals to solar flares. Figure 5 shows the variations of the JJI and NWC signals recorded at the TNU station from 0:00 to 11:00 UT on 13 January 2013. The variations of the intensity of the NWC (Figure 5b) and JJI (Figure 5c) signals are compared with those of X-ray intensity recorded by GOES (Geostationary Operational Environmental Satellite)(Figure 5a). The VLF signals increase when solar flares with classes of C2.7, C3. 2, M1.0 and M1.7 occur. The increases of the VLF signal strength for C3.2, M1.0 and M1.9 are clear. A C1.9 class flare occurs after dawn, which does not affect the intensity of the VLF signals.

In 2013, the SuperSID receiver at TNU detected three SID events in which the dips occurred after the peaks of VLF intensity. The intensity minima are lower than the initial values. The VLF intensity then recovers and returns to the normal value after a period of time. The responses of the NWC and JJI signals recorded at the TNU station are also compared with those recorded at the DAISY (1.37° N, 103.8° E) transmitter in Singapore.

The responses of the VLF waves to the flare classes of M2.9, M5.0 and X1.1 on 25 October, 3 and 8 November 2013 are presented in Figure 6a, b, c, respectively. There are no JJI signals from two stations on 08 November 2013. The dips after the maxima of the VLF intensity are also detected for the NWC-DAISY path. We did not find these phenomena in either the JJI-TNU or JJI-DAISY paths which have longitudinal differences between the transmitters and receivers.

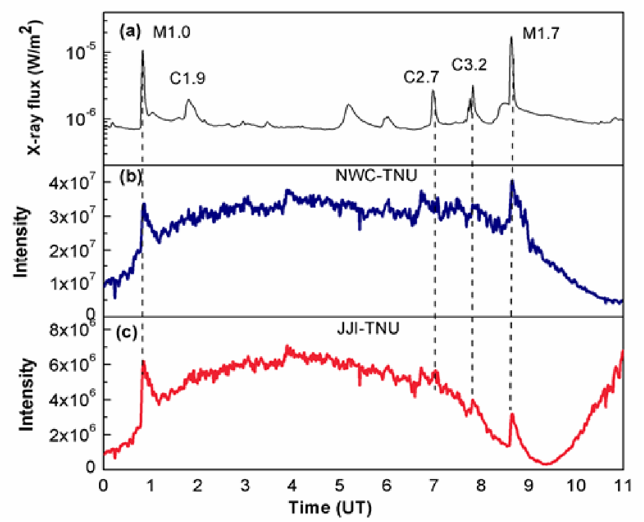

Figure 5: The variation of the intensity of the NWC and JJI signals on 13 January 2013.

Discussion

Merola (2006) studied the effects of sunrise and sunset on the VLF signal from the NML transmitter (46.37° N, 98.33° W, in North Dakota USA) to her receiver at Rockville Centre, New York USA (40.67°N, 73.64° W). Merola's receiver was east of the transmitter. This author found that the sunrise spike and recovery occurred before the Sun rose over the locations of the transmitter and the receiver. The sunset spike appears after sunset at the receiver and before sunset at the transmitter. Note that official sunrise and sunset are the moments when the upper edge of the solar disc is at the horizon. Refraction causes the Sun to appear at these places, but it is actually higher or lower. The Sun's rays strike the upper part of the ionosphere before they strike the Earth. Therefore, the ionosphere above the transmitter and receiver is ionized before the Sun rises. When the rays of radiation from the Sun come around the Earth, the ionosphere is suddenly ionized. This causes the VLF wave intensity to decrease in a short period of time (Merola, 2006).

In our work, the form of the sunset spikes for the JJI signal recorded at our TNU station is explained as follows. The Sun sets at the location of the JJI transmitter first. The Sun then sets over the location of the receiver because the TNU station is west of the transmitter. The Earth then blocks the radiation from the Sun as the Sun sets above the ionosphere. This means the Sun's radiation cannot reach the ionosphere, so the JJI signal intensity increases rapidly in a short period. The effects of sunrise and sunset on the JJI-TNU path are more significantly different than those on the NWC-TNU path. Observing the temporal changes of sunrise and sunset dips or spikes of VLF signals during different seasons enhances the understanding of ionosphere behavior.

The decrease of VLF signal strength during sunset and sunrise is explained by the modal conversion of Crombie (1966). The attenuation of signals in the EIWG are larger during the day as compared to that during the night and the higher mode will be more attenuated. Therefore, only the lowest modes of the VLF waves propagate in the daytime. However, in the nighttime, the waves can propagate with multiple modes. The reflection height of the EIWG increases. This causes the phase velocities of the waves to decrease, thus the signal will delay at the receiver (Kumar, 2009). The formation of the dips or the minima at the day-night transition is due to the conversion of one mode during the day into multiple modes at night (Cliverd et al., 1983). According to the modal interference work of Crombie, the mechanism of formation of the minima is due to the interference of waves having different modes. This interference reduces the strength of the VLF signals (Crombie, 1966). The minima during sunrise transitions are deeper than those during sunset transitions because dawn reaches the station and the sunlight spreads over the path to increase the attenuation of the second mode of waves (Crombie, 1964).

The appearance of multiple dips in the NWC signal strength during summer sunrise and sunset transitions can be explained. During summer, the ionosphere absorbs VLF waves less significantly than during other seasons, thus waves can propagate with higher modes. Because the path mainly spreads along longitude, the times of the minima on the NWC signal at dusk and dawn change little due to seasonal factors. The sunset dips of the NWC signal occur later than those of the JJI signal do. That is very convenient for detecting the effect of solar flares on the VLF wave intensity. The NWC transmission propagates from Australia to the latitude of 12.65° N, which mostly passes over the ocean, thus the attenuation of wave energy is very low. Moreover, the NWC-TNU transmission path (North-South path) traverses mostly equatorial regions, so this path is convenient for investigating the low latitude D-region ionosphere.

When solar flares occur, X-rays become the primary ionizing source of the lower ionosphere. X-rays less than 1 nm increase the ionization rate of O_2 and N_2 and hence the electron density increases. This causes the sudden changes of amplitude and phase of the VLF signals, which are followed by a recovery period to return to the unperturbed values (Mitra, 1974). Dahlgren et al. (2011) observed nine VLF signals at SANAE IV to find that an M-class solar flare occurring at 11:17 UT on 12 February 2010 caused increases of the VLF signals, followed by a drop in the signal amplitudes. The formation of dips after the maximum disturbances in the VLF amplitude is explained by the modal interference pattern. The distance between the transmitter and receiver, as well as the changes of the ionospheric parameters over time, affect the shape of the signals and cause shifts in the modal interference pattern towards the transmitter. These shifts cause the signal strength to fall below normal levels. During intense solar flares, the ionosphere is ionized at such a

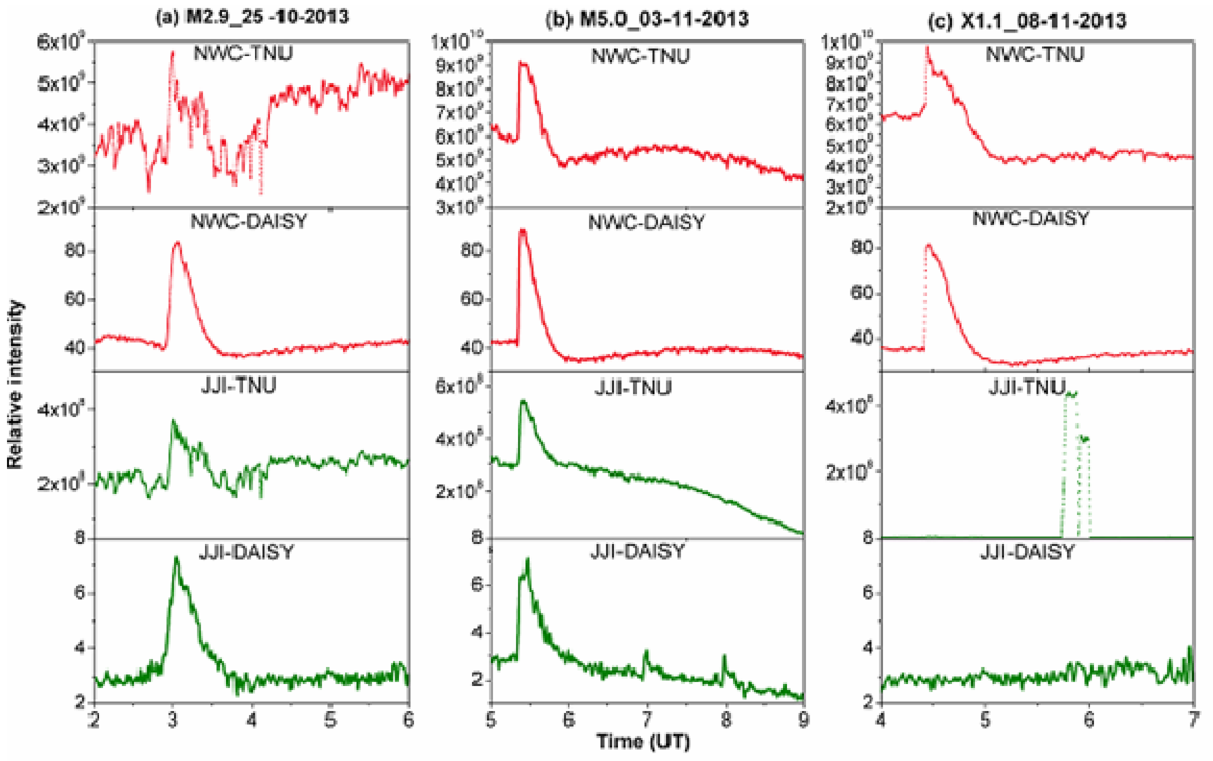

Figure 6: The responses of VLF signals to flare classes of M2.9, M5.0 and X1.1.

great rate that the receiver cannot resolve the initial reduction as a result of the lowering of the reference height *h'*. After maximum of the disturbance, the ionosphere starts to recover and return to initial conditions. The recovery phase of the ionosphere is much slower than the onset phase and leads to a gradual change of *h'*. Hence the VLF intensity gradually returns to normal values (Dahlgren, et al., 2011). We do not see dips for the JJI signal when strong solar flares occur. This It means that the the modal interference pattern cannot be applied for the JJI-TNU and JJI-DAISY paths. The reason could be the longitudinal differences and the distance between the receivers and transmitters.

Conclusions

We used SuperSID monitor installed at TNU to detect the diurnal and seasonal variations of the NWC and JJI signals to understand the behavior of the ionosphere. We found that the effects of sunrise, sunset and solar flares on the NWC-TNU path (North-South path) are more significantly different than those on the JJI-TNU path having the longitudinal differences between the receiver and transmitter.

The sunset and sunrise spikes only occur on the VLF signal of the JJI-TNU path. Overall, in the summer season, two sunset dips and three sunrise dips appear on the NWC signal. The occurrence of the dips of VLF signals during the sunset and sunrise is explained by the modal conversion. Investigating the temporal changes of sunrise and sunset dips or spikes of the VLF signals during different seasons enhances the understanding of behavior of the ionosphere.

During intense solar flares, we only recognized a drop in the VLF intensity after the maximum disturbance for the NWC-TNU path. This phenomenon is explained by the modal interference pattern. The NWC-TNU path goes over the most of equatorial region. Such path is convenient to investigate the equatorial and low latitude D regions.

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