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Abstract

Very low frequency (VLF) signals are propagated between the ground-ionosphere. Multimode interference will cause the phase to show oscillatory changes with distance while propagating at night, leading to abnormalities in the received VLF signal. This study uses the VLF signal received in Qingdao City, Shandong Province, from the Russian Alpha navigation system to explore the multimode interference problem of VLF signal propagation. The characteristics of the effect of multimode interference phenomena on the phase are analyzed according to the variation of the phase of the VLF signal. However, the phase of VLF signals will also be affected by the X-ray and energetic particles that are released during the eruption of solar flares, therefore the two phenomena are studied in this work. It is concluded that the X-ray will not affect the phase of VLF signals at night, but the energetic particles will affect the phase change, and the influence of energetic particles should be excluded in the study of multimode interference phenomena. Using VLF signals for navigation positioning in degraded or unavailable GPS conditions is of great practical significance for VLF navigation systems as it can avoid the influence of multimode interference and improve positioning accuracy.

Full Text

Preamble

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Observation and Analysis of VLF Nocturnal Multimode Interference Phenomenon based on Waveguide Mode Theory

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Abstract

Very low frequency (VLF) signals propagate within the ground-ionosphere waveguide. During nighttime propagation, multimode interference causes the phase to exhibit oscillatory variations with distance, leading to abnormalities in received VLF signals. This study utilizes VLF signals received in Qingdao City, Shandong Province, from the Russian Alpha navigation system to investigate the multimode interference problem in VLF signal propagation. The characteristics of multimode interference effects on phase are analyzed based on VLF signal phase variations. However, VLF signal phase is also affected by X-rays and energetic particles released during solar flares; therefore, both phenomena are examined in this work. It is concluded that X-rays do not affect VLF signal phase at night, while energetic particles do influence phase changes. Consequently, the effect of energetic particles must be excluded when studying multimode interference phenomena. Using VLF signals for navigation and positioning under degraded or unavailable GPS conditions holds great practical significance, as understanding multimode interference can help improve positioning accuracy in VLF navigation systems.

Key words: waves -methods: data analysis -Sun: flares -Sun: X-rays -gamma-rays

1. Introduction

The Global Positioning System (GPS) provides crucial positioning capabilities to military, civilian, and commercial users worldwide. However, in many complex environments, GPS access is restricted or signals can be lost entirely. GPS is particularly susceptible to interference during solar storms. Establishing radio navigation based on very low frequency (VLF) radio signals offers the possibility of positioning, navigation, and timing using VLF signals when GPS is degraded or unavailable (Curro et al. 2018). The VLF radio frequency range of 3–30 kHz is widely utilized for navigation, timing (Niu et al. 2009), earthquake prediction (Singh et al. 2005), submarine communication (Shi et al. 2011), mineral resource detection (Niu et al. 2016), and space environment monitoring (Su et al. 2019) due to its long wavelength, low attenuation, stable amplitude and phase, and strong penetration capability.

VLF waves propagate through the ground-ionosphere waveguide. Under ideal single-mode propagation conditions, the daily variation curve of VLF phase exhibits a consistent trapezoidal shape. When the entire propagation path is in daylight or darkness, the phase stabilizes at respective fixed values, with the daytime phase leading the nighttime phase. When the diurnal boundary intersects the propagation path, creating a transition between day and night, the propagation phase drifts and shifts along two oblique lines. However, during actual sunrise and sunset transition periods, mode-conversion interference causes the propagation phase curve to deviate from monotonic smoothness, exhibiting "step-shaped" changes and sometimes even complete cycle "phase slip" phenomena (Wang 2006).

Based on distance, VLF signal propagation can be divided into near-field, far-field, and waveguide regions (Niu et al. 2021). In the waveguide region, where multiple waveguide modes of various orders coexist, the superposition of these modes causes the total electromagnetic field' s amplitude and phase to vary oscillatory with distance—a phenomenon known as multimode interference. In the VLF ground-ionospheric waveguide, numerous lower-order waveguide modes can typically be excited simultaneously. Each mode propagates with different excitation power, attenuation rate, and phase velocity, with attenuation increasing with mode order. Within a few thousand kilometers from the transmitting antenna, higher-order modes maintain sufficiently strong amplitudes compared to the lowest-attenuation first-order mode, causing the field strength and phase to vary non-monotonically with distance. This region is called the multimode interference region. At greater distances, higher-order modes attenuate significantly and become negligible, leaving only the first-order modes with minimal decay; this region is known as the single-mode region. Generally, interference is more significant at night than during the day, and higher-frequency waves experience more pronounced interference than lower-frequency waves (Pan 2004). At specific points in the interference zone, signals can become much weaker, and the phase stability of the received signal deteriorates significantly, negatively impacting VLF radio communication, navigation, timing, and frequency comparison.

Numerous researchers have investigated multimode interference phenomena. Crombie (1964) used mode conversion concepts to explain phase steps and amplitude decay at dawn and dusk. Wang (2006) discovered that periodic phase slipping is a peculiar multimode interference phenomenon during sunrise and sunset transitions. Chand & Kumar (2017) investigated VLF modal interference distance and nighttime VLF reflection height for east-west propagation paths using amplitude minima at sunrise and sunset. He et al. (2018) analyzed multimode interference and phase standard deviation of VLF wave propagation in anisotropic ground-ionospheric waveguides. Xin (2019) studied the propagation attenuation of the first four modes at very low frequencies. In contrast, this article examines characteristics of close-range multimode interference phenomena at night, differing in both research period and distance. By receiving VLF signals at 11.9, 12.6, and 14.9 kHz from the Alpha Navigation System' s East Sub-station in Qingdao, we analyzed phase changes and investigated VLF multimode interference.

2.1. Principle of Very Low Frequency Propagation

VLF signals primarily propagate within the ground-ionosphere waveguide formed between the lower boundary of the low ionosphere and the Earth' s surface, typically analyzed using waveguide mode theory. The propagation pattern is shown in Figure 1 [Figure 1: see original paper]. The ionosphere is typically divided into three regions from low to high altitudes: the D, E, and F layers. The D layer, located approximately 70 km above Earth' s surface, absorbs significant short-wave radio energy and contains many electrons during daytime but essentially disappears at night. The E layer, at roughly 90 km altitude, exhibits diurnal and seasonal variations in electron density, being significantly lower at night than during the day while increasing in height. The F layer, about 130 km above Earth' s surface, is present both day and night, splitting into F1 and F2 layers during daytime and merging into one layer at night, containing irregular anomalies. The upper boundary of the ground-ionosphere waveguide is the ionospheric D layer during the day; at night, when the D layer disappears, the E layer becomes the reflecting upper boundary (Devi et al. 2008). When VLF signals propagate in the waveguide space between transmitter and receiver, they undergo multiple refractions within the ground-ionosphere waveguide and propagate forward within the waveguide cavity (Zhao et al. 2023).

2.2. Transmitting and Receiving Systems

The VLF signal transmission stations analyzed in this paper consist of the East Sub-station in Khabarovsk, the Main Station in Novosibirsk, and the West Sub-station in Krasnodar from the Russian Alpha navigation system (Huang & Ji 2005), with the receiving station located in Qingdao, Shandong Province. This article primarily analyzes VLF signals propagating from the Alpha navigation system to Qingdao. Table 1 provides basic information about the VLF transmitting and receiving stations.

The block diagram of the VLF signal receiving system is shown in Figure 2 [Figure 2: see original paper]. The system, developed using software radio technology, exhibits good reliability and consists of a receiving antenna, digital VLF software radio receiver, rubidium atomic frequency standard, and computer

(Niu et al. 2009, 2014b; Niu & Bi 2016). The VLF signal received by the antenna is sampled after passing through a low-noise amplifier, anti-aliasing filter, and automatic gain control. The sampling pulse circuit' s standard sampling interval is provided by the rubidium atomic frequency standard. After sampling, A/D conversion is performed and the data is input to the computer, which provides feedback to the automatic gain control loop based on the received signal to ensure accuracy. The phase measurement accuracy of this system is \$±\$1 s.

Figure 3 [Figure 3: see original paper] shows the propagation paths from the Alpha VLF navigation system to Qingdao. Qingdao Station, located in Qingdao City, Shandong Province, has geographical coordinates (36°07'N, 120°42'E) (Niu et al. 2015). It receives VLF signals at three operating frequencies—11.9, 12.6, and 14.9 kHz—from the East Sub-station (HAB), Main Station (NOV), and West Sub-station (KRA) of the Alpha Very Low Frequency Navigation System. The digital VLF software radio receiver designed as shown in Figure 2 records and monitors data every 3 minutes, receiving VLF signals continuously throughout the day.

3.1. Theory and Data Analysis

VLF signals propagate in the ground-ionosphere waveguide and are analyzed using waveguide mode theory. During VLF signal transmission, multimode propagation occurs because the transmitting antenna excites multiple waveguide modes at relatively close distances. However, as propagation distance increases, higher-order wave modes attenuate significantly (Niu et al. 2017).

According to waveguide mode theory (Wait 1959; Liu 1987), for the nth order mode, the phase propagation velocity v_p of the VLF signal has the following expression:

$$v_p = \frac{c}{\sqrt{1-\left(\frac{n\lambda}{2h}\right)^2}} \quad (1)$$

For the first-order mode, substituting $n = 1$ into Equation (1) yields the expression for the VLF signal' s propagation phase velocity v_p as:

$$v_p = \frac{c}{\sqrt{1-\left(\frac{\lambda}{2h}\right)^2}} \quad (2)$$

If the ionospheric equivalent reflection height varies by Δh and the corresponding VLF signal phase varies by $\Delta\phi$, the relationship is:

$$\Delta\phi = -\frac{2\pi d}{\lambda} \cdot \frac{\Delta h}{h_0} \quad (3)$$

The relation between ionospheric equivalent reflection height variation Δh and VLF signal phase variation $\Delta\phi$ can be obtained as:

$$\Delta h = -\frac{\lambda h_0}{2\pi d}\Delta\phi \quad (4)$$

where n represents the propagation mode order; c is the speed of light in space, approximately 2.998×10^8 $\mathrm{m \cdot s^{-1}}$; $\lambda = c/f$ denotes the VLF signal wavelength, where f is the VLF signal frequency (11.9, 12.6, and 14.9 kHz); h_0 indicates the equivalent reflection height of the ground-ionosphere waveguide. At mid-latitudes, h_0 is about 70 km during daytime and 87 km at nighttime in summer, rising somewhat in winter to about 72 km during daytime and 87 km at nighttime (Pan 2004); a is Earth' s mean radius, approximately 6371.4 km; and d is the great-circle path distance between transmitter and receiver.

Due to different observation paths in Qingdao, this paper refits the equation relating peak X-ray flux density to ionospheric equivalent reflection height variation (Niu et al. 2014c). Based on 90 flare phase anomalies observed by VLF receiver from 08:00 to 16:00 in 2000 and 2001, the least squares method is applied to the East Sub-station to Qingdao path, yielding the fitting equation:

$$\Delta h = 0.23\log_{10}(F) + 2.1 \quad (5)$$

By observing extensive solar flare data and using GOES satellite data as a standard, flare levels can be calculated using the VLF method, thereby analyzing solar flare impacts on VLF signal propagation. According to different propagation distances, Equation (1) can be used to calculate multimode phase velocity for close distances, while Equation (2) can be used to obtain first-mode propagation phase velocity for far distances. Combining Equations (3) and (4), the equivalent reflection height change of the ionospheric D-layer and abnormal VLF signal phase changes during solar flares can be calculated. Finally, using fitting formula (5) for the East Sub-station to Qingdao path, the peak X-ray flux density of solar flares can be calculated, and subsequently the flare level can be determined.

3.2. Observation Results

With solar flare onset, significant amounts of energetic charged particles emitted by the Sun reach Earth within 1–3 days, in addition to X-rays that arrive in approximately 8.3 minutes and impact satellite navigation and communication environments. VLF phase changes are highly sensitive to Sudden Ionospheric Disturbances (SID) caused by X-rays (Selvakumaran et al. 2015) and energetic particles (Peter et al. 2006) emitted during solar activity. When influenced by X-rays and energetic particles, VLF signal phase undergoes abnormal changes.

Based on X-ray flux magnitude, flare levels are divided into five categories (Niu et al. 2014a), as shown in Table 2 . Levels A, B, C, and M are each subdivided into sublevels 1-9 based on strength, while level X has no upper limit.

The great-circle path distances from Qingdao to the East Sub-station, Main Station, and West Sub-station are 2029.6 km, 3481.5 km, and 6720.0 km, respectively, calculated using Earth' s great-circle distance formula (Fu 1990). As this article focuses on multimode interference phenomena in VLF signals at night over medium-to-close distances, it is important to note that X-rays generated during solar flares do not affect VLF signal phase at night, while energetic particles do impact phase during both day and night. To prevent analysis results from being compromised, energetic particle interference must be excluded when studying multimode interference effects on nighttime VLF signals.

3.2.1. The Influence of Energetic Particles

Figures 4 and 5 show the amplitude and phase curves of VLF signals transmitted by the Alpha Navigation System' s East Sub-station and received in Qingdao on 2000 January 10 and 2000 July 22. The figures reveal abnormal VLF signal phase changes from 18:00 to 22:00 on 2000 January 10 (black circle in Figure 4) and from 20:00 to 23:00 on 2000 July 22 (black circle in Figure 5). The propagation region from Qingdao to the East Sub-station belongs to the waveguide region and may be affected by both multimode interference and energetic particles.

Table 3 shows solar flare data from 2000 January 7-9 and 2000 July 19-21. Due to the large data volume, only two sets of data with larger flare levels are listed for daily analysis. Here, "Start" indicates flare onset time, "Max" is the peak time, and "End" is the termination time. X-ray flare level corresponds to the solar flare classification based on X-ray emissions during eruption, and "Flux" represents the flare-released flux in units of $\mathrm{W \cdot m^{-2}}$. Since energetic particles generated during solar flares reach Earth only after 1-3 days, solar flares occurring on 2000 January 7-9 and 2000 July 19-21 may have impacted VLF signal phase on 2000 January 10 and 2000 July 22.

Figure 6 [Figure 6: see original paper] shows GOES satellite energetic particle flux maps for 2000 January 10 and 2000 July 22. The figures indicate that energetic particle density began increasing significantly at 03:00 on 2000 January 10 and at 20:00 on 2000 July 22. This suggests that the observed VLF signal phase oscillations were caused by energetic particles generated during solar flare eruptions.

3.2.2. The Influence of Multimode Interference

Figures 7 through 12 show amplitude and phase curves of VLF signals received in Qingdao on 2001 November 13 and 2002 February 25. Figures 7 and 8 present data from the East Sub-station to Qingdao, Figures 9 and 10 from the Main Station to Qingdao, and Figures 11 and 12 from the West Sub-station to Qingdao. Figures 7 and 8 reveal abnormal phase changes in VLF signals from 18:00 to 22:45 on 2001 November 13 (black circle in Figure 7) and from 20:00 to 23:00 on 2002 February 25 (black circle in Figure 8). The black circles in Figures 9 and 10 show relatively less oscillation, while those in Figures 11 and 12 approximate regular VLF signal phase diurnal variation curves. This indicates that multimode interference influence on VLF signals decreases with increasing distance. When the range exceeds the multimode region, VLF signal propagation is dominated by the first-order mode and is no longer affected by multimode interference.

Table 4 shows solar flare data from 2001 November 10–12 and 2002 February 22–24. As before, only two sets of data with larger flare levels are listed daily for analysis. Energetic particles from these days may have impacted VLF signal phase changes on 2001 November 13 and 2002 February 25.

Figure 13 [Figure 13: see original paper] shows GOES satellite energetic particle flux charts for 2001 November 13 and 2002 February 25. The charts reveal that energetic particle flux remained relatively stable during these two days. In summary, the phase anomaly changes occurring from 18:00 to 22:45 on 2001 November 13 and from 20:00 to 23:00 on 2002 February 25 are not related to energetic particle eruptions but can be inferred to result from multimode interference phenomena.

3.2.3. The Influence of X-Rays

Although this article focuses on multimode interference impacts on VLF signal phase at night, it is worth noting that X-rays emitted by solar flares do not affect nighttime phase but can impact daytime phase. Figures 7 and 8 show significant VLF signal phase advances during 14:30–15:00 on 2001 November 13 and 11:00–11:30 on 2002 February 25. These phase anomalies were therefore analyzed.

Table 5 shows solar flare data received by the VLF signal receiving system along the Alpha East Sub-station to Qingdao path, where Start, Max, and End have the same meanings as in previous tables, and $\Delta\phi_1$, $\Delta\phi_2$, and $\Delta\phi_3$ represent phase changes caused by sudden phase anomalies in the VLF signal, expressed in centesimal cycles (cec, where 1 cec = 3.6°) (Wang et al. 2022). Table 6 shows solar flare data monitored by the GOES satellite.

Comparison of Tables 5 and 6 reveals that results derived using the flare calculation technique described in the previous section are essentially consistent with flare data provided by the GOES satellite. Solar flares therefore occurred at 14:36 on 2001 November 13 and at 11:12 on 2002 February 25. Consequently, the phase anomalies at these two times can be inferred to result from X-rays generated by solar flare eruptions.

4. Conclusion

In situations where GPS navigation is unavailable, VLF can be used for navigation and positioning. This article analyzes and discusses VLF signals received in Qingdao from the Alpha navigation system and investigates the impact of multimode interference on VLF signals, leading to the following conclusions:

(1) Data received in Qingdao from the East Sub-station show that the phase of the three frequencies is affected to varying degrees in the multimode interference region. The 14.9 kHz frequency is more significantly affected compared to 11.9 and 12.6 kHz. However, on 2002 February 25, the 11.9 and 12.6 kHz frequencies were hardly affected by multimode interference, while 14.9 kHz experienced noticeable interference. This confirms that higher-frequency waves are more significantly affected by multimode interference than lower-frequency waves.

(2) When VLF signal phase undergoes abnormal changes, the cause may be X-rays and energetic particles generated by solar flare eruptions or multimode interference. X-rays emitted by solar flares impact VLF signal phase during daytime but not at night, while energetic particles affect VLF signal phase during both day and night. When studying multimode interference impacts on nighttime VLF signals, it is necessary to exclude energetic particle interference to avoid compromising research results.

This study employs a combined theoretical analysis and observational data approach to investigate multimode interference effects on VLF signal amplitude and phase, carrying significant practical implications for VLF wireless communication, navigation, and positioning systems. However, since this study focuses on multimode interference phenomena in VLF signals at medium-range distances, the applicability of this research method to closer-range paths requires further investigation. Additional analysis and discussion of multimode interference phenomena across different paths and distances are needed to enhance understanding of its impact on VLF signals.

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