Multiple Thin Layers of Enhanced Ionization in the Ionospheric E-Region
Derived from VLF Wave Measurements

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Observations of the ionospheric electron density were made during winter nighttime using a NDT-VLF wave receiver and a DC probe onboard the S-310-21 rocket. We have examined the variation of wave intensity with altitude and the standing wave characteristics, and have derived the absolute electron density from the latter. It is found that there were layers of high electron density in the ionospheric E-region at 89 km, 102 km, and 111 km. The vertical width and the enhancement factor of these layers were of the order of 1–3 km and 390–530%, respectively, and the maximum electron densities of these layers were lower than 1.1 x 10⁴ cm⁻³, which is below observable levels by ionosondes. This finding of multiple sporadic E (Es) layers is important for the studies of wave coupling between free space and the magnetosphere, long-distance propagation in the Earth-ionosphere waveguide, and the formation of the Es layer.

1. Introduction

The propagation characteristics of VLF waves in the lower ionosphere have been investigated in connection with the occurrence of whistlers (e.g. Cartwright, 1964; Pitteway and Jesperson, 1966; Thomas and Horowitz, 1971), natural VLF emissions observed on the ground (e.g. Srivastava, 1974), and satellite observations of waves transmitted from the ground (e.g. Aubry, 1968). These studies used average ionospheric models or the standard International Reference Ionosphere (IRI), (Rawer and Bilitza, 1989) which does not take into account small-scale structures. Recent studies have shown that the small-scale structures such as the sporadic E layers (Es) in the 100–120 km altitude range, and field-aligned irregularities (FAI) in the E and F-regions are important to our understanding of the VLF phenomena in the ionosphere. For example, Brittain et al. (1983) detected standing wave patterns in VLF hiss which were interpreted as E-region reflection due to enhanced electron densities. Nagano et al. (1987) demonstrated that the doublet whistlers can be produced when a downgoing whistler is strongly reflected by the Es layer. Also, MF waves are reflected significantly and sky waves propagate over long distances in the presence of Es layers (Mambo et al., 1989). Furthermore, FAIs affect radio links between satellites and ground at VHF/UHF bands (Ogawa et al., 1989). The mechanism of the formation of the Es layer has been studied in relation to gravity waves (Tsunoda et al., 1994).

In spite of the need of the knowledge for the detailed structure of the lower ionosphere, only a few studies have been made because of the difficulty of observation. A possible technique is to use the ionogram or the vertical sounder transmitting pulsed waves at the short band, the lowest frequency of which is usually limited to avoid interferences to the MF broadcasting. Because the ionosonde typically cannot measure plasma density below 3 x 10⁴ cm⁻³ (plasma frequency below 1.6 MHz), it is not effective for the nighttime ionospheric E-region. A more promising technique is the direct measurement of electron density on a rocket. A series of such experiments in the D- and E-regions have been made at mid-latitude (e.g. Hall and Fooks, 1965; Smith, 1970; Maeda, 1971). However, the altitude resolution in these measurements was insufficient to resolve thin layers of enhanced electron density. Also, there have been
very few simultaneous observations of VLF wave and electron density at high altitudinal resolution in the nighttime ionosphere. This paper discusses the propagation characteristics of VLF waves in the ionospheric E-region in the presence of multiple layers of enhanced electron density from a rocket experiment at mid-latitude during the winter nighttime. Following a brief explanation of the experimental equipment in Section 2, we present the observation results, discussions, and finally conclusions in Sections 3, 4, and 5, respectively.

2. Experimental Equipment

The VLF wave at 17.4 kHz transmitted from the NDT station is received by a loop antenna system which is nearly identical to the one used in the earlier experiment of Okada and Nagano (1990). The loop element has an area of 0.106 m², and is wound 10 times along the triangular aluminum framework, and electrostatically shielded. The loop antenna is deployed in such a way that the loop framework is parallel to the rocket spin axis as shown in Fig. 1. The effective height is 0.17 m and the detection threshold of wave electric field intensity is given as 5.5 µV/mHz¹/² at 17.4 kHz. Note that the unit of magnetic field $H$ is given in the unit of electric field $E$ using the relation $E$ (V/m) = $Z_0 H$ (AT/m), where $Z_0$ (=120π ohms) is the impedance of free space.

Fig. 1. Configuration of a loop antenna and a DC probe sensor onboard the S-310-21 rocket. The triangular-shaped loop antenna detects the VLF wave transmitted from the NDT station at 17.4 kHz, while the cylindrical 31-cm DC probe sensor collects electrons around the rocket. The spin frequency of the rocket was 1.1 Hz.
The DC probe collects electrons of the plasma around the rocket. The sensor of the probe is a stainless cylinder of 310 mm in length and 3 mm in diameter. The surface of the electrode is gold-plated. The sensor is mounted on the rocket as shown in Fig. 1, and is positively biased to 5.3 V with respect to the rocket body, in order to collect the saturation current (Oyama and Hirao, 1976). However, as the sensitivity of the DC probe (conversion factor from current to electron number density) was not calibrated and the potential of the probe was not measured in flight, we cannot obtain absolute electron density from the measured current. However, we can determine the order of magnitude of the electron density and its relative distribution with altitude from the probe measurement. The absolute electron density was obtained by the VLF measurements as discussed in Section 4.

3. Observation Results

The S-310-21 rocket was launched from Kagoshima Space Center (KSC) at 21:00 JST on January 28, 1992. Its trajectory was in the South-East direction (30° from South) as shown in Fig. 2. The nose cone of the rocket was opened at 46 s (59 km alt.) after lift-off, and both the loop antenna and DC probe sensor were deployed at 49 s (66 km alt.). The apogee was 223 km at 234 s.

![Fig. 2. Illustration of the trajectory of the S-310-21 rocket flight and the site of the NDT VLF station. The rocket was launched in the South-West direction from Kagoshima Space Center (KSC), and reached an apogee of altitude 223 km at 234 s. The observation period discussed in this paper is denoted by the thick line on the trajectory.](image-url)
3.1 Current measurement by DC probe

Figure 3 shows the profile of electron currents versus altitude measured by the DC probe on the upleg. The horizontal axis is the current in the range from 3 nA to 10 µA, while the vertical axis is the altitude from 70 km to 150 km. There were enhanced peaks of current at 111 km, 102 km, and 89 km altitudes. The altitudinal width of each layer was as thin as 1–3 km. These current peaks are believed to correspond to the sporadic E layers (thin layers of very high plasma density) in the nighttime E-region. The periodic variations in the current data, roughly one oscillation per km, are due to the rocket spin motion at 1.1 Hz; the electron collection efficiency of the probe is believed to vary with the direction of the cylindrical electrode with respect to the Earth's magnetic field and with the probe potential (Oyama and Hirao, 1976).

3.2 VLF wave measurement

Figure 4 shows the observed result of the NDT-17.4 kHz wave intensity versus altitude. The vertical

![Fig. 3.](image)

![Fig. 4.](image)

Fig. 3. Measured currents by the DC probe from 70 km to 150 km altitude. The horizontal axis is the DC probe current and ranges from about 3 nA to 1 µA. The current values at 84 km and 129 km (100 µA) are from system calibration. Currents were detected above 81 km altitudes and increased with increasing altitude, forming the E-region at about from 85 to 120 km. There were layers of enhanced current at 89 km, 102 km, and 111 km.

Fig. 4. Measured wave intensity at 17.4 kHz along the trajectory from 70 km to 150 km. The horizontal axis is the wave intensity in units of dBµV/m (0 dB = 1 µV/m). The current values at 84 km and 129 km (60 µV/m) are from system calibration. In the altitudes from 70 km to 85 km, the wave intensity changed due to the rocket spin. In the ranges from 89 to 102 km and from 102 to 111 km, there were standing waves that are due to waves reflected by the layers at 89 km, 102 km, and 111 km. Above 111 km, the wave intensity changed smoothly with altitude due to change in refractive index of the upgoing whistler mode wave.
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axis indicates the observation altitude, while the horizontal axis indicates the wave field intensity \( E = Z_0H \) in the range from 50 dB to 80 dB (0 dB = 1 \( \mu \)V/m), where \( H \) is the magnetic field intensity and \( Z_0 \) is the impedance of free space. Characteristic features with altitude are found in the VLF data as follows.

In the altitude range from 70 km to 85 km, the wave field changed at a frequency of 1.1 Hz in the range from about 74 dB to about 54 dB. This \( \geq 20 \) dB intensity modulation was due to the loop antenna plane rotating at the rocket spin frequency. The spin modulation decreased with increasing altitude, to essentially zero at 89 km. This results from the fact that the left-hand polarized component was reflected downward at about 89 km, while the right-hand polarized component, or whistler-mode, continued upward. Therefore this was the effective reflection height for propagation in the Earth-ionosphere waveguide at the NDT frequency (17.4 kHz) during winter-nighttime.

In the altitude range from 88 to 111 km, the wave field exhibited specific variations with altitude. That is, there was a peak of 66 dB at near 88 km. Also, there were four maxima and minima in the altitude range from 91 to 102 km. The difference between the maximum and minimum was about 7 dB. The difference is not due to the rocket spinning motion. The wave intensity had a peak (64 dB) at 102 km, which is almost identical to that at 111 km. Between these two peaks there were three oscillations in wave intensity. The magnitude of the intensity variation was about 3 dB, which is smaller than seen at 90–102 km. These observed variations are attributed to change in the polarization of the VLF wave from linear to right-hand circular at 80–90 km altitudes. The 7 dB-intensity modulation is due to the standing wave resulting from upward- and downward-propagating whistler-mode waves which are partially-reflected by the steep electron density gradients at around 102 km and 111 km, as shown in Fig. 3.

Above 111 km, the mean value of the wave intensity decreased with increasing altitude, reached a minimum of 58 dB at about 130 km, and then increased with increasing altitude. These observed characteristics will be examined theoretically in the next section.

4. Discussions

The order of magnitude and the relative distribution of the ionospheric electron density can be readily determined from the measured electron current shown in Fig. 3. However, in the absence of sensitivity calibration for the DC probe and the measurement of the probe potential, we cannot determine the absolute electron density. We make use of the standing wave characteristics in the VLF data shown in Fig. 4, to derive the electron density as follows.

The standing waves observed in the altitude ranges of 89–102 km and 102–111 km resulted from upward- and downward-propagating whistler-mode which were partially-reflected by the steep electron density gradients around 102 km and 111 km. From the Snell's law the wave normal directions of both waves are found to be vertical in the E-region since the refractive index for whistler-mode is much larger than unity. As the dip angle of the geomagnetic field is about 44° at the rocket site, the quasi-longitudinal (QL) approximation is valid (Budden, 1966), and the refractive index \( n \) for the whistler-mode wave is given approximately by

\[
n = \left( \frac{f_p}{f} \right) \left( \frac{f_H}{f \cos \varphi} \right)^{1/2}
\]

where, \( f \) [kHz] is the wave frequency, \( f_p \) [kHz] the plasma frequency \((=9\sqrt{N}; N [cm^{-3}] \) is the electron number density), \( f_H \) [kHz] the electron gyro-frequency, and \( \varphi \) the angle between the wave normal and the Earth's magnetic field. The magnetic field in the slowly-varying magneto-ionic medium is expressed by
where the first term corresponds to the upgoing wave in the $z$ direction while the second term corresponds to the downgoing wave. The vertical wavelength in the ionosphere is given by $\lambda_z = \lambda_0/n$, where $\lambda_0$ is the wavelength of the wave in free space, and is twice the separation between successive peaks or zeros in the standing wave pattern. Combining Eq. (1) with the relation $\lambda_z = \lambda_0/n$, we finally obtain (Nagano and Mambo, 1978) the electron density $N$ as

$$
N = \left( \frac{\lambda_0}{\lambda_z} \right)^2 \frac{f_f H}{81} |\cos \phi|.
$$

Using Eq. (3), we can evaluate the electron number density from the standing wave in the altitude range of 89–112 km. For example, $N = 1.7 \times 10^3$ electrons cm$^{-3}$ at 98 km. Thus, we can determine the absolute electron density in the altitude range where there are standing waves.

From the absolute electron density at altitudes of the standing waves, and the altitude distribution of relative electron density given by the DC probe current measurement, we obtained the electron density distribution at all altitude of the lower ionosphere. However, the theoretical wave intensity derived from this distribution using the full-wave method differed from the observed value. A possible reason for the difference is due to the error of the DC probe measurement at the thin layers where there were steep gradients in electron density. Therefore, we modified the initial electron density distribution at altitudes where no standing waves were observed and the peak densities of the layers, in such a way that the VLF intensity from the full-wave calculation matched the observed one throughout the altitude range, and obtained the most probable electron density distribution in Fig. 5. The amount of modification was less...
Fig. 6. VLF wave intensity in the estimated ionospheric profile given in Fig. 5. The solid line denotes the wave intensity calculated by the full-wave method. For comparison, the observed wave field (in Fig. 4) is represented in the figure.

than 20% at all altitudes of the initial distribution.

The solid curve in Fig. 6 shows the calculated VLF intensity using the modified electron density distribution in Fig. 5. For comparison, the observed VLF intensity is also shown in Fig. 6. A good agreement is seen between the calculated wave intensity and the measured VLF intensity, i.e., the amplitude decrease with increasing altitude at 70–85 km, the standing wave patterns at 89–111 km, and the amplitude variation above 111 km. The increase of the wave amplitude over 130 km is thought to be due to the increase in the refractive index (n) since the electron density increased in these altitudes of the E-region. In the full-wave calculation, a vertical step size of 5 m was used for stratification of the ionosphere from 70 km to 150 km, which is sufficient to resolve the effect of the electron density enhancement. The collision frequency model used was typical for the middle latitude (Fukami et al., 1991). The electron gyro-frequency was 1.21 MHz and the dip angle of the Earth’s magnetic field was 44°.

We conclude that there were enhanced electron density peaks located at 112 km, 102 km, and less enhanced peak at 89 km. The enhancement factor of the layers is defined as the ratio of the peak density to the background density and is about 390–530%. The vertical width is defined as the separation between the two altitudes at which the density is half of the peak value of the layer, and is about 1–3 km. These layers are believed to correspond to the so-called sporadic E (Es) layers, even though the estimated maximum electron number density (about 1.1 × 10⁴ cm⁻³) was not as high as that observed by the ionosondes. Indeed, the ionogram data from the simultaneous measurements at Yamakawa, Japan, showed no trace that may be indicative of the existence of any Es layer in the frequency band above 1.2 MHz. This is consistent with our estimate of electron density at the ionization enhancements. The fine structure of the lower ionosphere containing multiple layers of enhanced electron density is important in the study of the formation process of the Es layer and the physical process of gravity waves.

5. Conclusions

In-situ measurements of electron currents and VLF wave intensities have been carried out onboard the sounding rocket S-310-21 during the winter nighttime in 1992. The ionospheric electron density profile is estimated by both the VLF field intensity profile and the electron current measured by the DC
probe onboard. In the $E$-region, there were enhanced electron density peaks located at 111 km, 102 km and at 89 km. The enhancement factors of the layers were about 390–530%, and their vertical widths were about 1–3 km. The estimated maximum electron number density was about $1.1 \times 10^4$ cm$^{-3}$. These layers of enhanced electron density are thought to correspond to the so-called sporadic $E$ ($Es$) layers.

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