Localization of VLF ionospheric exit point by comparison of multipoint ground-based observation with full-wave analysis

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Received 9 January 2008; revised 6 August 2008; accepted 26 September 2008
Available online 21 November 2008

Abstract

In order to estimate the dynamic structure of the VLF ionospheric exit point, we conducted multipoint ground-based observation of the natural VLF emissions at three unmanned sites: West Ongul (69°01′ S, 39°30′ E), Skallen (69°40′ S, 39°24′ E), and H100 (69°18′ S, 41°19′ E) around Japanese Syowa station, Antarctica, during a whole year of 2006. In this observation, we developed three sets of unmanned autonomous observation systems for natural VLF emissions. Each observation system consists of two crossed vertical loop antennas to pick-up North—South (NS) and East—West (EW) magnetic components, a multi-channel analyzer, and a data logger. The intensity and polarization of NS and EW magnetic components are obtained in 4 spaced frequency (0.5, 1.0, 2.0, and 6.0 kHz) channels by the multi-channel analyzer.

The VLF emissions observed at the three sites exhibit an interesting difference in the wave intensity as well as the polarization that allows important information about the locations of their ionospheric exit point to be determined. Firstly, to find the distinct exit point, we have theoretically calculated the spatial distributions of the wave intensity and the polarization on the Earth for VLF whistler mode waves coming down from the magnetized ionosphere, by using the full-wave analysis. Then, we have compared the calculated results with the observed data, to evaluate the possible locations of the ionospheric exit point for the auroral hiss events.

As an example, the direction of the estimated ionospheric exit point for the auroral hiss event at 31 March 2006 was found to be consistent with a bright aurora region. However, in this case, the estimated ionospheric exit point was located a few hundred kilometers equatorward of the associated aurora. This would suggest that the ray paths for the auroral hiss could be different from the directions of the geomagnetic field lines for auroral precipitation.

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Keywords: Unmanned observation; Natural VLF emissions; Ionospheric exit point; Full-wave analysis; Antarctica

1. Introduction

VLF emissions of magnetospheric origin, propagating ducted or non-ducted, penetrate the ionosphere down to the ground (Helliwell, 1965). The spatial distributions of the observed VLF emission intensity and the polarization...
on the ground strongly depend on the locations of their ionospheric exit points (as experimentally shown by Machida and Tsuruda, 1984; and theoretically by Nagano et al., 1986). At an observation site on the ground just below the ionospheric exit point, the polarization will generally appear to be right-handed, while at another site distant away from the exit point, we will possibly observe linear or left-handed polarization. Therefore, the ionospheric exit point and its spatial extent could be inversely determined by the ground-based observations of the VLF emissions at multiple sites. The localization of the ionospheric exit point yields significant information on investigating the propagation mechanisms, and generation processes through wave–particle interaction of VLF emissions, and their roles in ionospheric and magnetospheric dynamics. Over the last five decades, natural VLF observations in the polar regions have been a crucial component of ionospheric and magnetospheric researches.

In previous researches and observations, a variety of direction-finding techniques have been developed for determining the location and movement of the ionospheric exit point over the polar regions. First, the “VLF goniometer” was used to estimate the direction to the exit point from the two (NS and EW) horizontal magnetic components measured by crossed loop antennas on the ground (Bullough and Sagredo, 1973). The VLF goniometer easily estimates the azimuth angles-of-arrival of the VLF emissions, but the estimated results depend strongly on the polarization and incident angles of them.

The second direction-finding technique is based on the Poynting vectors calculated from two horizontal magnetic components and a vertical electric component observed on the ground (Cousins, 1972; Tsuruda and Hayashi, 1975; Okada et al., 1977; Leavitt et al., 1978). This technique has several advantages over the VLF goniometer. For instance, the 180° ambiguity in azimuth angle estimation raised in the goniometer is resolved, the estimation errors caused by down-going elliptically polarized whistler mode waves (the polarization errors) are eliminated, and both the azimuth and elevation angles can be determined. Especially, “No Polarization Error (NPE) method” by Tsuruda and Ikeda (1979) can estimate the azimuth angles without any polarization errors. However, the errors due to the multiple reflections of the down-going whistler mode waves entering the Earth–ionosphere waveguide cannot be eliminated (Crarty, 1961; Strangeways and Rycroft, 1980).

The third technique is based on a multipoint ground-based observation of the VLF emissions (Nishino et al., 1981; Tsuruda et al., 1982; Strangeways et al., 1982; Smith and Carpenter, 1982). This has higher accuracy than the above mentioned direction-finding techniques based on single-site observations, because in this method we can make use of more information such as, the spatial distribution of electromagnetic fields and times and directions-of-arrival of the incoming waves at the observation sites. However, in the harsh and remote environment of Antarctica, this method requires the unmanned observation techniques such as autonomous power supply, data storage, and data telemetry. In fact, the autonomous ground-based observational techniques in Antarctica are absolutely significant to study the geophysics (e.g., Smith, 1995; Dudeney et al., 1998).

These direction-finding techniques have been used successfully to study the exit points of whistlers (Bullough and Sagredo, 1973), of auroral hiss as compared with all-sky auroral images (Nishino et al., 1981), and of artificial VLF emissions triggered by the Siple transmitter at its conjugate point (Tsuruda et al., 1982). However, all of the above direction-finding techniques still have assumed that the down-going whistler mode waves like the VLF emissions are treated as plane waves, and the effects of the Earth–ionosphere waveguide propagation and of the magnetized ionosphere are ignored. Such assumptions may introduce locational errors in the estimated ionospheric exit point. For taking account of the Earth-ionosphere waveguide propagation and the geomagnetic field line in the ionosphere, it is necessary to rigorously evaluate the propagation of down-going whistler mode waves by theoretical calculation such as full-wave analysis, which analytically calculates not only the simple plane wave propagation, but also the whistler beam propagation (Nagano et al., 1986, 1987; Wu et al., 1996).

In this study, we try to estimate the ionospheric exit point by examining the multipoint ground-based observations of VLF emissions, and by evaluating the propagation characteristics of the down-going whistler mode waves calculated by the full-wave analysis. Our estimation method of the exit point is based on the basic pattern recognition techniques, which estimates the most plausible location of the exit point, where the calculated electromagnetic distribution becomes consistent with the observed one. We estimate quantitatively even the time evolution of the ionospheric exit point by combining both the observed and calculated intensity and polarization of the VLF emissions. This enables us to estimate the ionospheric exit point with a more realistic model than before, by taking account of the effects of the Earth–ionosphere
waveguide propagation of a whistler beam and of the magnetized ionosphere.

In this paper, first we describe three sets of the autonomous observation systems of natural VLF emissions developed for our multipoint ground-based observation in Antarctica, and show an example of observation result in Section 2. Then in Section 3 we explain the full-wave analysis for down-going whistler mode waves, and how to estimate the VLF ionospheric exit point. Then in Section 4 we give an example of the time evolution of the VLF ionospheric exit point estimated by comparing between the multipoint ground-based observation and the full-wave calculation of the down-going whistler mode waves for an auroral hiss event on 31 March 2006.

2. Multipoint ground-based observation around Syowa station, Antarctica

2.1. Observation system for natural VLF emissions

To study the dynamic spatial distribution of the ionospheric exit point of natural VLF emissions, we developed three sets of autonomous observation systems of VLF magnetic fields for the multipoint ground-based observation in Antarctica with an extremely low background electromagnetic field noise. The three sets of developed systems were respectively installed at three unmanned sites ("West Ongul", 69°01′ S, 39°30′ E, "Skallen", 69°40′ S, 39°24′ E, and "H100", 69°18′ S, 41°19′ E) around Syowa station, Antarctica. We conducted multipoint ground-based observation of the natural VLF emissions at these three sites during one whole year of 2006. Fig. 1 shows the locations of the manned Syowa station and the three unmanned observation sites: West Ongul, Skallen, and H100, which are located at the tips of a triangle of about 80 km on a side.

The magnetic field observation system installed at each unmanned site consists of two crossed vertical loop antennas, a multi-channel analyzer, and a data logger as shown by the block diagram in Fig. 2. The two (NS and EW) horizontal magnetic wideband signals are detected by two crossed vertical loop antennas (each has 10 turns and an area of 16 m²) connected to a dual-channel low-noise preamplifier circuit. The signals are then bandpass-filtered in 4 spaced frequency channels (whose center frequencies are 0.5, 1.0, 2.0, and 6.0 kHz, and each bandwidth is 30% of the center frequency), amplified for gain adjustment, and detected as NS and EW magnetic field intensities and as their phase difference by the multi-channel analyzer (MCA). The three signals (NS and EW magnetic field intensities and their phase difference) in the 4 spaced frequency channels are subsequently A/D converted and stored in a flash memory in the data logger. This system provides continuous information on the magnetic field intensity and polarization in each frequency channel, with the time resolutions of 0.5 s at West Ongul, and 6 s at Skallen and H100, respectively. The observation timing accuracy among the three systems installed at the three unmanned sites is kept by GPS to be less than 1 ms.

In our multipoint ground-based observation, we used two types of data loggers as shown in Table 1. A data logger installed at West Ongul, 5 km away from Syowa station, is simply designed for storing the A/D converted data. On the other hand, the other data loggers installed at Skallen and H100, which are about 80 km away from Syowa station, have been newly developed for a specialized autonomous ground-based observation. These data loggers have the data transmission capability via IRIDIUM mobile phone system at 2.4 kbps (Kadokura et al., 2002), which are transmitted to Kanazawa University, Japan, in quasi-real-time (once per day). Furthermore, via the IRIDIUM system, we can also send the operating commands such as the one to change the sampling times for A/D conversion. With such a telemetry technique, we have big advantage of being able to monitor and control the observation system put in a harsh environment of
Antarctica” from Kanazawa University, Japan. The power consumption of each developed autonomous observation system is about 1 W, which is supplied from four sealed lead acid batteries (each has 100 Ah) and a solar battery panel (max 40 W).

A photograph of the actual system installed at H100, Antarctica, is shown in Fig. 3. The crossed loop antenna and the preamplifier are located 20 m away from the MCA, data logger, and other instruments to reduce the electromagnetic noise interference from these instruments. The system noise level (magnetic sensitivity) is below 1 fT/√Hz, which is sufficiently small for detecting VLF emissions on the ground (Smith, 1995). Specifically, the noise levels for the 0.5, 1.0, 2.0, and 6.0 kHz frequency channels are 0.57, 0.30, 0.25, and 0.22 fT/√Hz, respectively.

### Table 1

<table>
<thead>
<tr>
<th>Item</th>
<th>Skallen and H100 (newly developed)</th>
<th>West Ongul</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/D</td>
<td>16 bit</td>
<td>24 bit</td>
</tr>
<tr>
<td>Sampling</td>
<td>6–60 s (variable)</td>
<td>0.5 s (fixed)</td>
</tr>
<tr>
<td>Others</td>
<td>Temp. sensors</td>
<td>Temp. sensors</td>
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<tr>
<td></td>
<td>GPS receiver</td>
<td>GPS receiver</td>
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<tr>
<td></td>
<td>IRIDIUM phone</td>
<td></td>
</tr>
<tr>
<td>Data storage</td>
<td>Flash memory</td>
<td>Flash memory</td>
</tr>
<tr>
<td>Data transmission</td>
<td>By IRIDIUM</td>
<td>N/A</td>
</tr>
<tr>
<td>Command sending</td>
<td>Possible</td>
<td>N/A</td>
</tr>
</tbody>
</table>

#### 2.2. Observation results of natural VLF waves

Fig. 4 shows an example of the 24-h plot of the magnetic field intensity \(\sqrt{B_{NS}^2 + B_{EW}^2}\) observed at West Ongul on 31 March 2006 smoothed with the 1-min average to effectively remove impulsive spherics, where 0 dB corresponds to \(10^{-33}\) T²/Hz. The magnetic local time (MLT) of West Ongul near Syowa station is approximately the same as the universal time (UT), which is MLT plus a few minutes. The background enhancement is identified before 3 UT and after 16 UT (both during the local night), which indicates the averaged spheric activity propagating in the Earth-ionosphere waveguide (Barr, 1970a,b; Smith, 1995; Smith and Jenkins, 1998). VLF emission events were seen throughout the day. Chorus emissions were seen in the 0.5–1.0 kHz range between 06 and 13 UT, reaching a maximum of about 50 dB (Smith, 1995; Smith et al., 2004). After 19 UT, auroral hiss emissions were observed intermittently over all the frequency channels (Makita, 1979). This auroral hiss event was accompanied by aurorae, which were simultaneously observed by an all-sky camera installed at Syowa station. The auroral hiss at high latitudes can be classified into two types (see Makita, 1979, Chapter 2). One is a continuous hiss emission in the frequency range of several kilohertz to 15 kHz associated with the stable arc-like aurora. Another type is an impulsive hiss emission in the frequency range of 1–100 kHz associated with the unstable aurora. In this paper, we
have examined the latter impulsive hiss emission between 19:30 and 20:00 UT as indicated by a dotted frame shown in Fig. 4 at the 2 kHz channel, which is insensitive to the spheric activity due to large waveguide attenuation (Smith and Jenkins, 1998).

Fig. 5 shows the 2.0 kHz VLF wave profiles observed at the three sites between 19:30 and 20:00 UT on 31 March 2006. The left panel shows the magnetic field intensity and the right panel shows the polarization calculated from the phase difference, which becomes +1 for the right-handed circular, 0 for the linear, and −1 for the left-handed circular with respect to the direction of the geomagnetic field line. At 19:39:00 UT, the magnetic field intensities were 34.4 dB at West Ongul, 34.5 dB at Skallen, and 37.2 dB at H100, and the polarizations were −0.65 (left-handed) at West Ongul, −0.09 (linear) at Skallen, and 0.72 (right-handed) at H100, respectively. As for the intensities between 19:30 to 20:00 UT, H100 was the strongest, Skallen was the medium, and West Ongul was the weakest. Especially, around 19:39 UT, when the intensities were over 35 dB at all the three sites, the polarization at H100 clearly indicated right-handed, Skallen was linear, while West Ongul became
left-handed. Also as for the polarization between 19:30 and 20:00 UT, West Ongul showed almost left-handed, while at Skallen and H100 the polarizations changed unstably between right-handed and linear.

We may be able to estimate that the ionospheric exit point would be located near H100 from these observational results, because the down-going whistler mode waves would be more intense and have a right-handed polarization just below their ionospheric exit point (e.g., Machida and Tsuruda, 1984; Yearby and Smith, 1994). However, such an estimation is too simple to locate the “exact” exit point. If the distributions of the intensity and polarization on the ground of the down-going whistler mode waves from the exit point are theoretically calculated, it would be possible to evaluate more rigorous location of the exit point by comparing the observed and calculated results. Therefore, as described in Section 3, we have rigorously calculated the horizontal electromagnetic distribution on the ice, of a down-going whistler mode wave injected at the upper ionosphere (Nagano et al., 1986), to estimate the exact ionospheric exit point on the basis of the observational results at the three sites.

3. Estimation of the VLF ionospheric exit point

3.1. Full-wave analysis for the propagation of a down-going whistler beam

In order to examine the propagation characteristics of down-going whistler mode waves and to compare them with our observations, we have used the full-wave analysis developed by Nagano et al. (1986). As a calculation model, we consider the “ground”—“ice”—“free space”—“ionosphere”, as shown in Fig. 6. A Cartesian coordinate system \((x, y, z)\) is used, where the \(y\) direction is chosen to be the geomagnetic north, the \(z\) direction as vertical, and the \(x\) axis is perpendicular to them. The plasma in the ionosphere is assumed to be cold without the thermal motion of electrons, and the inhomogeneous ionosphere is divided into multiple horizontally stratified layers. A down-going whistler mode wave injected into the ionosphere from above is assumed to be a two-dimensional Gaussian beam, which is represented as a superposition of a number of elementary plane waves trapped inside the “trapping cone” of a duct (see Helliwell, 1965, Chapter 3). Then, only the plane waves having their incident angles within the “transmission cone” determined by Snell’s law at the incident height can penetrate the ionosphere down to the Earth (see Helliwell, 1965, Chapter 3 again). The electromagnetic field \(E(x, y, z)\) is represented as follows (see Nagano et al., 1986, Eq. (5))

\[
E(x, y, z) = \frac{1}{(2\pi)^{3/2}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{G(k_x, k_y, z_0) e(k_x, k_y, z)}{E^{R\text{-DOWN}}(k_x, k_y, z_0)} \exp\{-j(k_x x + k_y y)\} \, dk_x \, dk_y,
\]

where \(G(k_x, k_y, z_0)\) is the Fourier component at the spatial frequencies of \(k_x\) and \(k_y\), corresponding to the Gaussian distribution of the whistler beam wave at the incident altitude \(z_0\), \(e(k_x, k_y, z)\) is the spatial Fourier component at \(k_x\) and \(k_y\) of the elementary plane wave at an arbitrary altitude \(z\) obtained from the full-wave solution, which is expressed as an electromagnetic vector \(e = (E_x, -E_y, Z_0 H_x, Z_0 H_y)^T\), where \(Z_0\) is the wave impedance in free space and \(t\) denotes the transpose of the vector (Nagano et al., 1975). Here, we assume that the spatial Gaussian distribution (the inverse Fourier transform of \(G(k_x, k_y, z_0)\)) of the whistler beam wave is equivalent to the amplitude distribution of the \(-E_y\) component of the down-going \(R\) (whistler) mode wave \((E^{R\text{-DOWN}})\) at the incident altitude \(z_0\). Eq. (1) means that the electromagnetic field at any point \((x, y, z)\) can be represented as a synthesis of a large number of elementary plane waves propagating in all directions of the wave normal vector. Here, the elementary plane wave calculated in each stratified layer satisfies the following equation derived from Maxwell’s equation (Nagano et al., 1975)
\[
\frac{de}{dz} = -jk_0 T e, \quad (2)
\]

where \( T \) is a propagation matrix determined by the electron density, the collision frequency between electrons and neutral particles, and the geomagnetic field in each stratified ionospheric layer. All of the elementary plane waves calculated in each layer are connected with those in the adjacent layers by using the proper boundary conditions, where we assume that \( R \) and \( L \) mode waves are propagating upward at the top ionospheric layer, and TM and TE mode waves are propagating downward at the bottom ground layer. TM and TE mode waves are the two independent plane wave modes in the isotropic medium whose magnetic and electric fields, respectively, are perpendicular to the incident plane including the wave normal vectors, in the calculation of elementary plane waves. Thus we can rigorously calculate the propagation of a Gaussian beam of the down-going whistler mode wave, taking into account the Earth-ionosphere waveguide propagation, and the effect of the magnetized ionosphere. The technique to solve Eq. (1) numerically is explained in detail by Nagano et al. (1986).

An example of the horizontal distributions of the magnetic field intensity and polarization on the ice is shown in Fig. 7a and b, respectively, which are calculated with the parameters listed in Table 2. The electron density profile is obtained as the one above the observation sites at night from the international reference ionosphere (IRI) model (Bilitza, 2001), and the collision frequency profile is calculated as proportional to the atmospheric pressure (Thrane and Piggott, 1966; Nagano et al., 1982). The magnetic field intensity shown in Fig. 7a indicates that the peak intensity on the ice is shifted by about 20 km southward from the point just below the Gaussian whistler beam injection point (the center of the figure), caused by the geomagnetic field-aligned propagation of the whistler mode wave. On the other hand, the polarization distribution shown in Fig. 7b clearly shows the East–West asymmetry caused by the Earth-ionosphere waveguide propagation (see Budden, 1985, Chapter 10). The right-handed polarization (more than 0.5) is distributed over about 150 km around just below the beam injection point, as the down-going whistler mode wave having a right-handed polarization penetrates the ionosphere down to the ground. As the horizontal distance becomes larger from the injection point, due to the wave reflection at the Earth, the polarization gradually changes to linear and then left-handed. Subsequently, the right-handed polarization re-appears due to further reflection from the lower ionosphere. These results strongly indicate that the effects of both the geomagnetic field and the Earth-ionosphere waveguide are quite important in evaluating the ionospheric exit point, because the magnetic field intensity and polarization distributions on the ice becomes quite complicated, depending on the distance and direction away from the exit point, as shown in Fig. 7a and b.

![Fig. 7](image)

**Table 2.** Parameters for the full-wave analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave frequency</td>
<td>2.0</td>
<td>kHz</td>
</tr>
<tr>
<td>Wave injection altitude</td>
<td>150</td>
<td>km</td>
</tr>
<tr>
<td>Transmission cone angle</td>
<td>12.8</td>
<td>degrees</td>
</tr>
<tr>
<td>Geomagnetic elevation angle</td>
<td>63.6</td>
<td>degrees</td>
</tr>
<tr>
<td>Electron cyclotron frequency</td>
<td>1.208</td>
<td>MHz</td>
</tr>
<tr>
<td>Ionosphere altitude range</td>
<td>60 ~ 150</td>
<td>km</td>
</tr>
<tr>
<td>Ice layer thickness</td>
<td>1</td>
<td>km</td>
</tr>
<tr>
<td>Ice dielectric constant</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Ice conductivity</td>
<td>(3 \times 10^{-6})</td>
<td>S/m</td>
</tr>
<tr>
<td>Ground dielectric constant</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Ground conductivity</td>
<td>(10^{-3})</td>
<td>S/m</td>
</tr>
</tbody>
</table>

![Fig. 7](image)
3.2. Estimation procedure for the VLF ionospheric exit point

In order to estimate the location of the ionospheric exit point, here we define “error functions” for the magnetic field intensity and polarization, when comparing the observed data with the theoretical calculation using the full-wave analysis.

At first, the exit point is assumed to be located at \((x_i, y_j, 100\) km\) in the calculation model shown in Fig. 8, where \(x_i (i = -N, ..., 0, 1, ..., N)\) and \(y_j (j = -M, ..., 0, 1, ..., M)\) represent geomagnetic East–West and North–South distances, respectively, centered at Skallen. The error functions are calculated from a comparison between the observed and calculated values of the intensity and polarization at the three observation sites. On the basis of the “degree of similarity” used in the basic pattern recognition technique (Aoki and Iijima, 1996), the error function for the magnetic field intensity \(E_{\text{int}}\) is defined as follows:

\[
E_{\text{int}}(x_i, y_j) = \frac{I_{\text{obs}} \cdot I_{\text{cal}}(x_i, y_j)}{|I_{\text{obs}}||I_{\text{cal}}(x_i, y_j)|},
\]

where \(I_{\text{obs}}\) is the magnetic field intensity ratio vector obtained from the observed values at the three sites, and \(I_{\text{cal}}(x_i, y_j)\) is also the magnetic field intensity ratio vector obtained by the full-wave calculation also at the three sites for the case of the exit point located at \((x_i, y_j, 100\) km\). These magnetic field intensity ratio vectors are defined as:

\[
I_{\text{obs}} = \left(\frac{|B_{SK}|}{|B_{WO}|}, \frac{|B_{H100}|}{|B_{WO}|}, \frac{|B_{SK}|}{|B_{H100}|}\right),
\]

\[
I_{\text{cal}} = \left(\frac{|b_{SK}|}{|b_{WO}|}, \frac{|b_{H100}|}{|b_{WO}|}, \frac{|b_{SK}|}{|b_{H100}|}\right),
\]

where the vector components, \(B\) and \(b\) are the observed and calculated horizontal magnetic field intensities (the vector magnitudes calculated from the NS and EW magnetic field components), and the suffix represents the observation site: WO, SK, and H100 are West Ongul, Skallen, and H100, respectively. Here, the error function \(E_{\text{int}}\) is calculated as the intensity ratios, because in our observation we have no information on the maximum value of the magnetic field intensity, which is to be observed at just below the actual ionospheric exit point. Since all

Fig. 8. The calculation model and the ionospheric exit point. The location of the exit point is assumed to be the peak location of the magnetic field intensity at the altitude of 100 km calculated by the full-wave analysis. The probability distribution of the exit point is calculated by comparing the observed magnetic field intensity and polarization at the three sites with those calculated.
the vector components for such intensity ratios are positive, the range of $E_{\text{int}}$ becomes 0–1. Larger values of $E_{\text{int}}$ mean that the magnetic field intensity calculated by the full-wave analysis becomes more similar to the observed one. On the other hand, smaller values of $E_{\text{int}}$ mean that the calculated intensity is more different from the observed one. Thus, the error function $E_{\text{int}}$ represents the probable location distribution of the assumed ionospheric exit point, from the viewpoint of VLF wave intensity.

On the other hand, the error function for the polarization $E_{\text{pol}}$ is defined by the least square technique as follows (Ikeda et al., 1988)

$$E_{\text{pol}}(x_i,y_j) = 1 - \frac{\sum_a \{ (P_{a,\text{obs}} - P_{a,\text{cal}}(x_i,y_j))^2 \}}{\max \left[ \sum_a \{ (P_{a,\text{obs}} - P_{a,\text{cal}}(x_i,y_j))^2 \} \right]}, \quad (6)$$

where $a$ means one of the three observation sites: WO, SK, and H100, and $P_{a,\text{obs}}$ and $P_{a,\text{cal}}$ are the observed and calculated polarizations at site $a$, respectively. The polarization value ranges from +1 for the right-handed circular. The second term in the right-hand side of Eq. (6) is normalized by its maximum value in the analysis region to give a value of $E_{\text{pol}}$ that ranges between 0 and 1. Larger values of $E_{\text{pol}}$ mean that the polarization calculated by the full-wave analysis becomes more similar to the observed one, while smaller values of $E_{\text{pol}}$ mean that the calculated polarization is more different from the observed one.

Then, the total error value $E_{\text{total}}$ is calculated by combining both of the error values of $E_{\text{int}}$ and $E_{\text{pol}}$ as follows

$$E_{\text{total}} = E_{\text{int}}E_{\text{pol}}, \quad (7)$$

where the range of value for $E_{\text{total}}$ becomes again 0–1. By calculating $E_{\text{total}}$ for the various locations $(x_i, y_j)$ of the exit point in the full-wave analysis, we can obtain the probable location distribution of the ionospheric exit point. Thus, we can estimate the probability distribution of the ionospheric exit point based on the basic pattern recognition technique, by using the observed and theoretically calculated values of wave intensity and polarization. It must be noted that $E_{\text{total}}$ means the plausible location of the exit point for a whistler beam source.

**4. Estimated results and discussion**

We have estimated the locations of the ionospheric exit point for an auroral hiss event observed between

19:39 and 19:44 UT on 31 March 2006 as shown in Fig. 5. The estimated probability distribution ($E_{\text{total}} \geq 0.9$) of the ionospheric exit point assumed to be at the altitude of 100 km at 19:39:00 UT is shown in Fig. 9. The vertical and horizontal dashed-lines in Fig. 9 are the geographic longitude and latitude lines, respectively. The red-yellow contour represents the $E_{\text{total}}$ value. In this case, the exit point appears about 180–190 km geographically eastward from the three observation sites. The ionospheric exit point was indeed closer to H100, which has the largest magnetic field intensity and the right-handed polarization. In other frequency channels of 1 kHz and 6 kHz, the same auroral hiss was received but with lower signal-to-noise (SN) ratios, where the SN ratios at 1, 2, and 6 kHz were 6 dB, 10 dB, and 4 dB, respectively. The noise levels are defined as the background levels caused by spherics. We tried to estimate the exit regions for the 1 kHz and 6 kHz channels, but the results were not reliable due to the low SN ratios.

In order to investigate the relationship between the auroral activity and the location of the ionospheric exit point, we have compared the auroral images taken by an all-sky camera installed at Syowa station, with the estimated ionospheric exit points in Fig. 10, where each panel uses the geomagnetic coordinate and is represented in polar coordinates as seen from above: the radial distance and the rotational direction

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For interpretation of the references to color in this text, the reader is referred to the web version of this article.
represent the zenith and azimuth angles, respectively. The probable locations of the ionospheric exit point are plotted with the red-yellow contours over the black and white all-sky snapshots of the aurora in 30-s time intervals from 19:39:00 to 19:44:30 UT.

We can clearly see that the ionospheric exit points were located toward the regions of the brighter aurora. During this time period, a bright auroral band gradually expanded from East to West. The ionospheric exit point also moves westwards in accordance with the auroral movement. First, a brighter aurora region was seen southeast from 19:39:00 to 19:39:30 UT, when the estimated exit region also distributed toward southeast. Then the brighter aurora region began to gradually move westwards from 19:40:00 UT and an East–West bright auroral band was dynamically formed from 19:42:00 UT. The estimated exit region gradually expanded in accordance with such an auroral

Fig. 10. Comparison of all-sky aurora snapshots with the estimated locations of the ionospheric exit point at 30-s intervals from 19:39:00 to 19:44:30 UT, 31 March 2006.
expansion from 19:40:30 UT. Especially, the estimated exit region at 19:42:30 UT is quite consistent with the bright auroral region. These results suggest that the azimuth angle of the ionospheric exit point of auroral hiss is clearly correlated with the auroral activity.

On the other hand, the estimated ionospheric exit regions of auroral hiss appear to be located about a few hundred kilometers toward low latitudes of the associated auroral arcs. The zenith angles of the estimated exit regions varied around 50°–70°. The zenith angles of the exit region at 19:40:00 UT were 64°–68°, while those of the auroral precipitation were over 75°. These zenith angles correspond to the horizontal distance between them of about 130 km based on the assumed projection altitude of 100 km. On the other hand, the zenith angles of the exit region at 19:44:00 UT became 54°–66 degrees, while those of the stable auroral arc were about 80°, which indicates that the horizontal distance between them was about 200 km at the same projection altitude.

These differences in the distance between them would be caused by the difference between the directions of the ray path of the down-going whistler mode wave and those of auroral particle precipitation along the geomagnetic field line (Makita, 1979). From simultaneous observations of the auroral hiss by ISIS 2 satellite (a circular polar orbit with an inclination of 88.18°, an apogee altitude of 1424 km and a perigee altitude of 1354 km) and the ground auroral imager at Syowa station, Makita (1979) showed that the auroral hiss did not propagate down to the satellite altitude along the geomagnetic field line of auroral particle precipitation. In a sounding rocket experiment flying through a diffuse aura, a dark region, and an auroral arc, the intensity of auroral hiss in the dark region was stronger than that within the auroral arc located at the higher latitude (Bering et al., 1987).

Tanaka and Nishino (1988) presented that the ionospheric exit point was located at the lower latitude (by the horizontal distance over 200 km) from an auroral arc, by using the previously conducted direction-finding measurements around Syowa station in Antarctica (Nishino et al., 1981). They also found that the altitudes where the geomagnetic field line of the auroral precipitation and the 8 kHz ray trajectory intersected were equivalent to the duct termination altitude of the auroral hiss, which was several to ten thousands of kilometers. As suggested by Tanaka and Nishino (1988), auroral hiss with weak geomagnetic disturbance (variations of the geomagnetic north component (ΔH) ~ 50 nT) would propagate down to the lower ionosphere in a non-ducted propagation from the duct termination altitude at several thousands of kilometers. As a result, the ionospheric exit point should be located at the lower latitude relative to the associated aurora. They also showed that the ionospheric exit points of the auroral hiss related to a quite active auroral movement during a geomagnetic disturbance (ΔH ~ 200 nT) were localized near the related aurora, which suggests the ducted propagation. The schematic illustration, originally by Makita (1979), of the relationship between the propagation of auroral hiss and the related geomagnetic field line of auroral precipitation is shown in Fig. 11.

In our present case study event from 19:39:00 to 19:44:30 UT on 31 March 2006, the horizontal distances between the exit region and the related auroral particle precipitation were about 130–200 km. These distances are similar to the ones presented by Tanaka and Nishino (1988). The maximum variation of the geomagnetic north component by the fluxgate magnetometer at Syowa station was less than 60 nT from 18:00 to 21:00 UT and the K-index was 2. Therefore, in our case study, the ionospheric exit regions are seen toward lower latitudes from the related aurorae, which suggest non-ducted propagation of auroral hiss in accordance with the previous works.

Our estimated results are basically similar to those reported in the previous works on the ionospheric exit point. Makita (1979) showed that the arrival direction of auroral hiss detected from the NPE method is related to the bright aurora region. Particularly, it suggests that the auroral hiss propagates not along the geomagnetic field, but along a non-ducted path (see Fig. 11 and Makita (1979), Fig. 90). Also, Nishino

[Diagram: Schematic illustration of the ray trajectory of auroral hiss and corresponding geomagnetic field line of auroral precipitation (redrawn from Makita (1979), Fig. 90).]
et al. (1981) showed that the directions of the ionospheric exit point for the auroral hiss change in accordance with the auroral movements, which are estimated by the measurement of the time-of-arrival differences in the incoming waves observed at three sites around Syowa station. These previous studies for the exit point of auroral hiss assumed the plane wave approximation, so that they obtained just “point” sources as the exit point. Our estimation method can evaluate the most plausible locational regions of VLF exit points, by comparing the multipoint observation with rigorously calculated VLF waves, and taking into account the effect of the down-going whistler mode beam propagation through the magnetized ionosphere into the Earth-ionosphere waveguide.

5. Summary

We conducted the ground-based observation of the natural VLF emissions at three unmanned sites: West Ongul, Skallen, and H100 around manned Syowa station, to study the dynamic structure of the ionospheric exit points of the VLF emissions. We developed the three sets of autonomous observation systems of natural VLF magnetic field. The observed data at each site showed the difference in wave intensity as well as polarization due to the propagation of whistler mode waves down through the ionosphere. The locations of the ionospheric exit point were estimated from the multipoint ground-based observation and the theoretical calculation by the full-wave analysis for down-going whistler mode beam propagation. In this study we were able to estimate the exit points more rigorously than the previous studies. First, we calculated the rigorous electromagnetic field distributions covering the three observation sites. Second, the full-wave calculation takes account of the effect of the magnetized ionosphere. Third, the calculation includes the effect of the Earth–ionosphere waveguide propagation of a whistler beam. Also, we have calculated the probability distribution of the ionospheric exit point based on the pattern recognition technique by using the observed and theoretically calculated wave magnetic fields. The estimated ionospheric exit regions for the auroral hiss observed during 19:39–19:44 UT on 31 March 2006 showed that the azimuth angles of the exit regions are toward the brighter aurora, but its zenith angle appears to be toward lower latitudes, which could be caused by the difference between the directions of the ray path of the auroral hiss and those of the auroral particle precipitation (Makita, 1979).

In this study, we have assumed a single ionospheric exit point for a down-going whistler beam. Even in more complicated (but possible) situations such as two or more simultaneous emissions with different locations and comparable intensities in the ionosphere, our method would be applicable in principle. Our full-wave analysis described in Section 3.1 can be extended to include the wave propagation for the injections of multiple whistler beams, by just changing the Gaussian distribution of a whistler beam, \( G(k_x, k_y, z_0) \) in Eq. (1), into that of multiple whistler beams. Here we do not discuss this possibility further, as the actual estimation of the multiple sources will require more complicated searches for the unknown parameters such as the intensities, locations, and spatial extents of multiple Gaussian beams, which is beyond the scope of the present paper. As other future studies, we will analyze the magnetospheric source regions of auroral hiss by comparing the zenith angle of the exit point with ray tracing calculations (Kimura, 1985). Since the comparison with the all-sky camera images of aurora is restricted by the meteorological conditions such as clouds, moonlight, and sunlight, we will also analyze the cosmic noise absorption measured by an imaging riometer (Yamagishi et al., 1992), which has been continuously operating at Syowa station under any meteorological conditions, and gives us the horizontal distribution of the ionospheric absorption of HF electromagnetic waves. Furthermore, by analyzing the electromagnetic wave data observed by the polar orbiting scientific spacecraft such as Akebono (Kimura et al., 1990), we will comprehensively analyze the 3-D propagation of VLF emissions in detail.

Acknowledgements

We wish to thank the 47th Japanese Antarctic Research Expedition, who supported our multipoint ground-based observation of natural VLF emissions in Antarctica.

References


