Polar Ionospheric Penetration Characteristics of Down-going Whistler Mode Waves by Multipoint Ground-based and Satellite Observations

***Mitsunori Ozaki*[1], *Satoshi Yagitani*[1], *Isamu Nagano*[2], *Yujiro Hata*[1], *Hisao Yamagishi*[3], *Natsuo Sato*[3], *and Akira Kadokura*[3]**

[1]Graduate School of Natural Science and Technology, Kanazawa University,
Kakuma-machi, Kanazawa 920-1192, Japan.
ozaki@reg.is.t.kanazawa-u.ac.jp

[2]Kanazawa University, Kakuma-machi, Kanazawa 920-1192, Japan.

[3]National Institute of Polar Research,
1-9-10 Kaga, Itabashi-ku, Tokyo 173-8515, Japan.

Abstract

The polar ionospheric penetration characteristics of down-going VLF whistler mode waves are discussed. Natural VLF wave observations were conducted at three ground-based unmanned stations around Japanese Syowa station in Antarctica, as well as by Akebono satellite flying over it, during the entire of 2006. The propagation characteristics of the VLF whistler-mode waves coming down from the magnetized ionosphere have rigorously been calculated by using full-wave analysis. From these observations and theoretical calculations, the ionospheric exit point of auroral hiss emission is estimated and found to be clearly related with auroral activity.

Summary

In order to evaluate the ionospheric penetration characteristics of down-going whistler mode waves in the polar region, we conducted simultaneous observations of natural VLF waves by using multipoint ground-based stations in Antarctica and Akebono satellite. In the multipoint ground-based observations, the magnetic field intensity and its polarization in 4 spaced frequency channels (0.5, 1.0, 2.0, and 6.0 kHz) were observed at unmanned three stations around Japanese Syowa station in Antarctica, during the entire year of 2006. The three stations, “West Ongul”, “Skallen”, and “H100” were located at the tips of a triangle of about 80 km on a side. The VLF instruments onboard Akebono satellite have been observing plasma waves in the frequency range from a few Hz to 17.8 kHz [1]. From such ground-based and satellite observations, we have been evaluating the ionospheric exit points of the down-going whistler mode waves.

Figures 1a and 1b show examples of the simultaneous ground and satellite observations of natural VLF waves. The lower panels show the ground-based observation of the magnetic field intensities in the frequency channels of 0.5, 1.0, 2.0, and 6.0 kHz, where 0 dB corresponds to 10^{-33} T^2/Hz. The red, blue, and green lines are the profiles observed at West Ongul, Skallen, and H100, respectively, where the plots have been smoothed with the one-minute average to effectively remove impulsive spherics. The upper contour maps show the dynamic spectra of the electric field intensities observed by a multi channel analyzer onboard Akebono satellite, where the plotted time periods of about 8 min. correspond to the dotted frames in the lower panels of ground observations. “Alt.” means the altitude of Akebono satellite and “Dis.” means the horizontal deviation of the geomagnetic field line crossing Akebono satellite from that crossing the center of three ground-based observation sites. In Figure 1a, on February 3, 2006, Akebono satellite was flying just above the ground-based observation sites, at low altitudes about 700 km, where the strong hiss emissions over all the frequency channels were observed. However, the ground observations showed no specific enhancement of signal levels at any of the frequency channels. Here, it would be considered that the natural VLF waves in the upper-ionosphere were unable to penetrate the lower-ionosphere down to the ground.

On the other hand, in Figure 1b, on March 15, 2006, the electric field observed by Akebono satellite shows the narrow band signals around 1 kHz, which seem to be chorus emissions, while the three ground-based stations also observed the signal enhancement at 1 kHz, where the geomagnetic field line crossing Akebono satellite was about 300 km horizontally away from the center of the ground observation sites. This would indicate that we observed the natural VLF waves which penetrated the lower-ionosphere down to the ground along the geomagnetic field line.

The difference in the ionospheric penetration of VLF waves is determined by the relationship between the "transmission cone angle" and the "trapping cone angle" for the whistler mode waves [2]. To rigorously evaluate the propagation of the down-going whistler mode waves in the ionosphere, we have performed theoretical calculation by using full-wave analysis [3]. The full-wave analysis calculates not only the simple plane wave propagation, but also the whistler beam propagation taking account of the effect of the magnetized ionosphere, and the Earth-ionosphere waveguide.

We have estimated the VLF ionospheric exit point of an auroral hiss emission by comparing the ground-based observation and full-wave calculation. Figure 2 shows another example of 24-hour plot of the magnetic field intensity observed at West Ongul on March 31, 2006. Figure 3 shows the magnetic field intensity and its polarization profiles at the 2.0 kHz channel at three stations between 19:30 and 20:00 UT (the period indicated with a dotted frame in Figure 2), where the polarization 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, and the red, green, and blue lines show the profiles observed at West Ongul, Skallen and H100, respectively. The possible wave observed here is an auroral hiss emission. The intensity at H100 was the strongest, Skallen was the medium, and West Ongul was the weakest. As for the polarization, West Ongul showed almost left-handed, while at Skallen and H100 the polarization changed unsteadily between right-handed and linear. Around 19:39 UT, when the intensities were over 35 dB at all the three stations, the polarization at H100 indicated right-handed, Skallen was linear, while West Ongul became left-handed. Such an interesting difference in wave intensity and polarization would give an important information on the locations of their ionospheric exit point. We try to estimate the exit point of this auroral hiss emission by evaluating the propagation characteristics of down-going whistler mode waves calculated by using the full-wave analysis. Our estimation method is based on the template matching analysis in the basic pattern recognition technique, where the wave intensity and polarization profiles calculated by the full-wave analysis are used as a template to be matched with the actual multipoint ground-based observation results.

Figure 4 shows the estimation results of VLF ionospheric exit point for the auroral hiss emission overplotted on the auroral images taken by an all-sky camera in the duration from 19:39:00 to 19:44:30 UT every 30 sec. on the same day. The red-yellow contours indicate the plausible locations of the exit point estimated by comparing the full-wave calculations with the observation results, and the auroral images are depicted as the black and white snapshots. We can clearly see that the estimated regions of the exit point were located toward the bright auroral regions, where the exit point gradually expanded in accordance with the auroral expansion. Such an estimation result suggests that the direction of the exit point of auroral hiss emission is clearly correlated with the auroral activity. However, the exit point was located around a few hundreds of km toward lower latitude side. This would suggest that the ray paths for the auroral hiss could be slightly different from the directions of the geomagnetic field lines for auroral precipitation particles [4].

In the presentation, we will discuss quantitatively ionospheric penetration characteristics of the VLF whistler mode waves in the polar region.

References

1. I. Kimura, K. Hashimoto, I. Nagano, T. Okada, M. Yamamoto, T. Yoshino, H. Matsumoto, M. Ejiri, K. Hayashi, "VLF Observations By the Akebono (EXOS-D) Satellite," *Journal of Geomagnetism and Geoelectricity*, 42, 1990, pp. 459–478.

2. R. A. Helliwell, "Whistlers and Related Ionospheric Phenomena," Stanford Univ. Press, Stanford, California, 1965.

3. I. Nagano, M. Mambo, T. Shimbo, and I. Kimura, "Intensity and Polarization Characteristics Along the Earth's Surface For the ELF-VLF Waves Emitted From a Transmission Cone in the High Latitude," *Memories of National Institute of Polar Research, Special Issue*, 42, 1986, pp. 34–44.

4. K. Makita, "VLF-LF Hiss Emissions Associated with Aurora," *Memories of National Institute of Polar Research,* A 16, 1979, pp. 1–126.

Figures

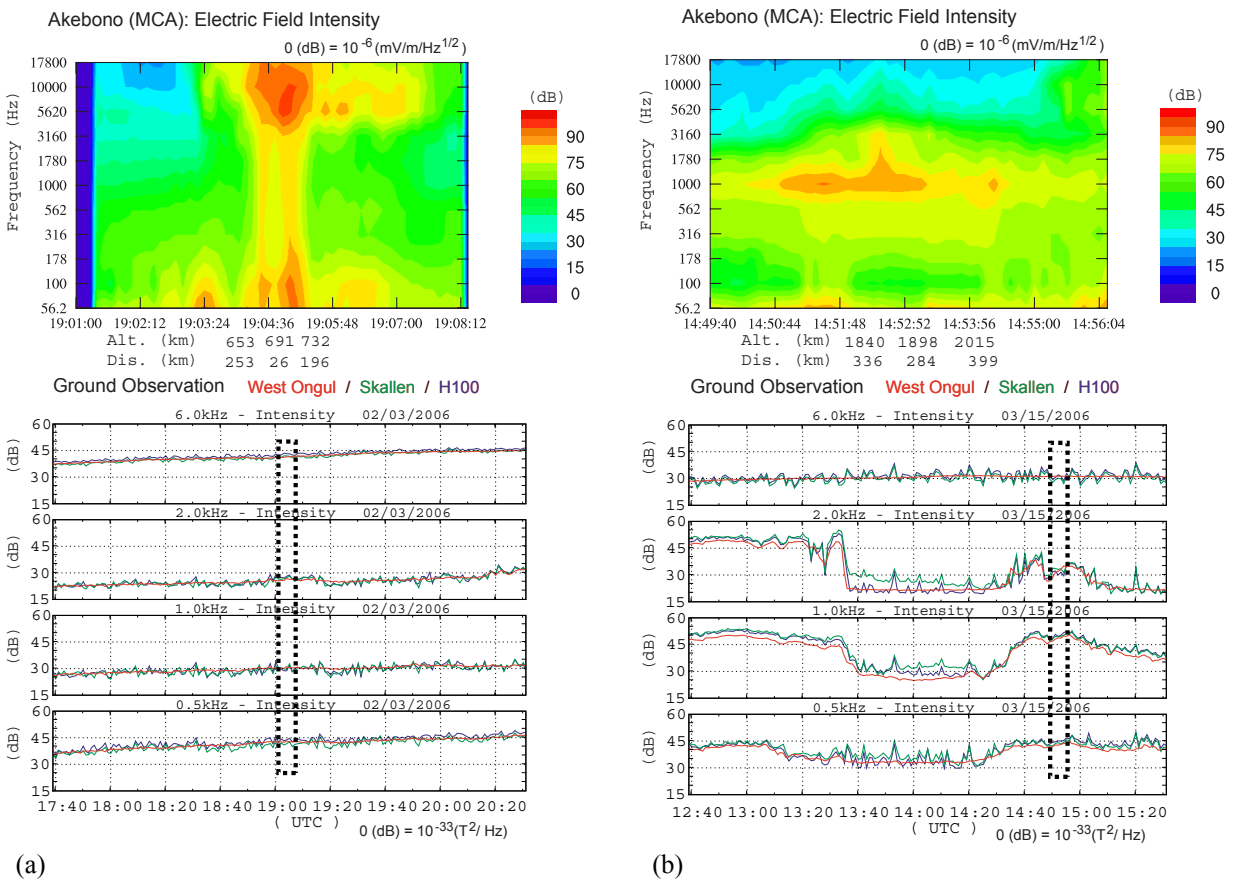

Figure 1. Examples of the simultaneous observations of natural VLF waves, by multipoint ground-based stations around Syowa station and Akebono satellite on February 3, 2006 (a), and on March 15, 2006 (b).

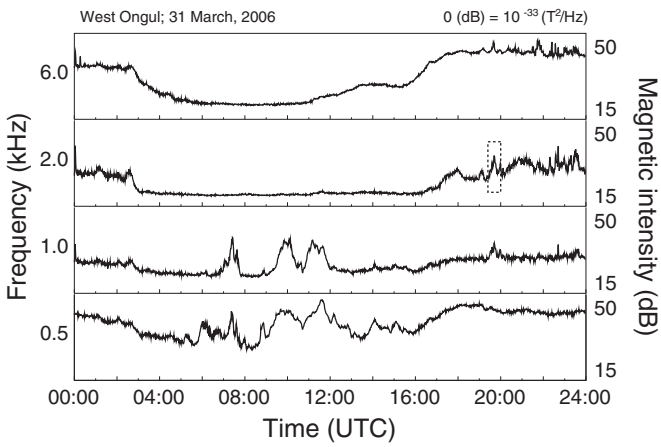

Figure 2. The 24-hour plots of VLF magnetic field intensities observed at West Ongul in Antarctica, on March 31, 2006.

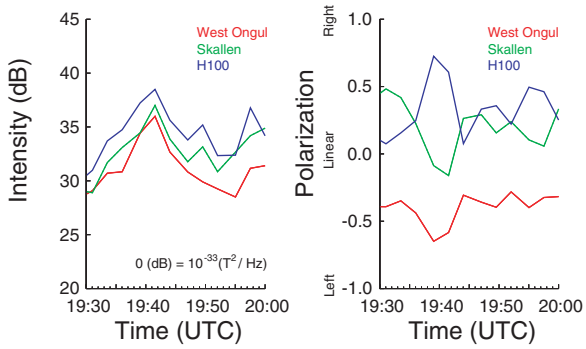

Figure 3. VLF magnetic field profiles at 2 kHz observed at the three ground-based stations in Antarctica, on March 31, 2006.

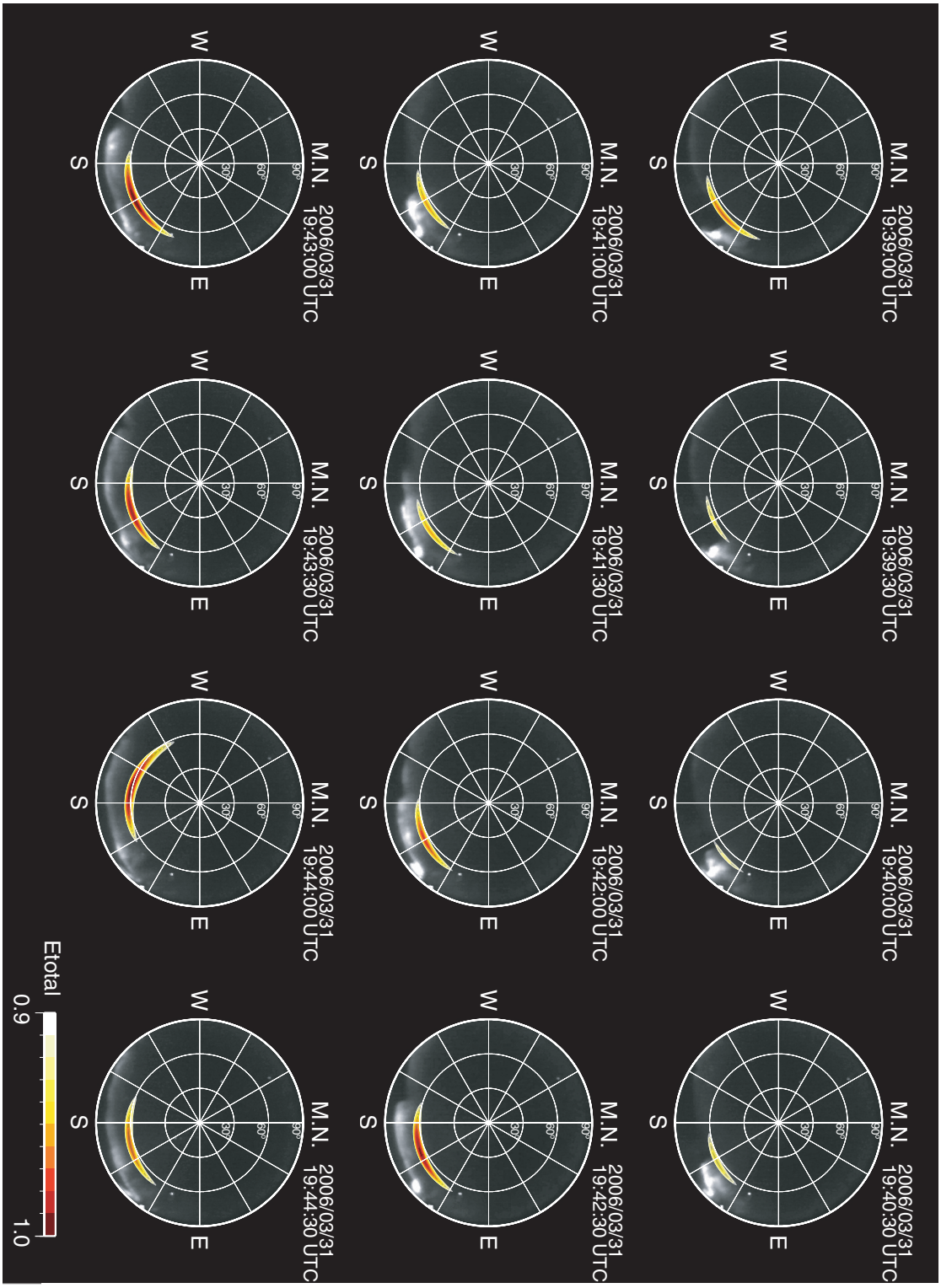

Figure 4. Estimation results of VLF ionospheric exit point of auroral hiss emission with all-sky aurora snapshots every 30 sec. from 19:39:00 to 19:44:30 UT, on March 31, 2006.