Mem. Natl Inst. Polar Res., Spec. Issue, **47**, 109–116, 1987

PHASE AND AMPLITUDE OF VLF OMEGA SIGNALS OBSERVED SIMULTANEOUSLY AT THREE STATIONS IN ICELAND IN ASSOCIATION WITH MAGNETOSPHERIC SUBSTORMS

Takashi ARAKI[1], Natsuo SATO[2], Ryoichi FUJII[2]
and Takashi KIKUCHI[3]

[1]*Faculty of Education, Hirosaki University, 1, Bunkyo-cho, Hirosaki 036*
[2]*National Institute of Polar Research, 9–10, Kaga 1-chome,*
Itabashi-ku, Tokyo 173
[3]*Radio Research Laboratory, 2–1, Nukui-Kitamachi 4-chome,*
Koganei-shi, Tokyo 184

Abstract: The phase and the field strength of 12.1 kHz Omega signals propagating from Aldra, Norway have been continuously recorded at three stations (Tjörnes, Isafjördur and Husafell) in Iceland using a phase locked receiver with a loop antenna parallel to the great circle path between Aldra and each stations.

Sudden phase and amplitude changes associated with magnetic substorms were observed on the VLF signals, for which the phase was advanced and amplitude was increased. From the results of calculation using the full wave method with a sharp density gradient model, it is suggested that these anomalies may be interpreted to be caused by precipitating high energetic electrons. That is, the density gradient in the lower ionosphere becomes steep, and the VLF signal intensity increases due to reflection at the sharp boundary.

It is also suggested from the differences of the onset time of the phase and amplitude anomaly observed at the three stations that the particle precipitation region was restricted in a small area.

1. Introduction

The substorm-associated phase anomalies were observed on the transauroral propagation path for VLF signals, Omega Aldra (12.1 kHz), GBR (16.0 kHz), Omega N. Dakota (13.6 kHz) and NLK (18.6 kHz) received at Inubo, Japan (KIKUCHI, 1981; KIKUCHI *et al.*, 1983; KIKUCHI and EVANS, 1983). They examined that the phase anomalies are caused by the precipitation of energetic electrons into the ionosphere from the magnetosphere. The energy of the precipitating electrons is estimated as >150 keV from the decrease in the reflection height for the VLF waves. KIKUCHI and EVANS (1983) studied quantitative relationships between VLF phase anomaly and the precipitating electron fluxes. They showed that the electrons with $E>30$ keV are predominated in the morning with the flux of one order of magnitude greater than the flux precipitating in the evening, though electrons with $E>300$ keV are precipitated at all local times with a peak in the evening. They also showed that the Cosmic Noise Absorption (CNA) detected with the riometer are affected by relatively low energy ($E>30$ keV) electrons, while VLF phase anomalies are caused by more energetic electrons (300 keV).

BERKEY *et al.* (1974) showed from the ionospheric absorption data that the electron precipitation expands westward from the midnight region as well as eastward. The westward movement of the absorption region does not necessarily mean a westward drift of trapped electrons, but it must be interpreted by means of the movement of the source of injected electrons (HULTQVIST, 1975).

ARAKI *et al.* (1986) showed that the particle precipitation of energetic electrons associated with magnetic substorm is responsible for VLF phase and amplitude anomalies. The precipitating high energy electrons cause a density gradient in the lower ionosphere. The VLF signal intensity increases by the reflection at sharp boundary and the VLF phase advances corresponding to a height decrease of the lower ionosphere.

In this paper, we will demonstrate the significant phase and amplitude anomalies associated with a magnetic substorm observed at three stations in Iceland and show the ionospheric reflection coefficient calculated by full wave method.

2. VLF Wave Propagation

Continuous observations for the phase and the field strength of Omega Aldra

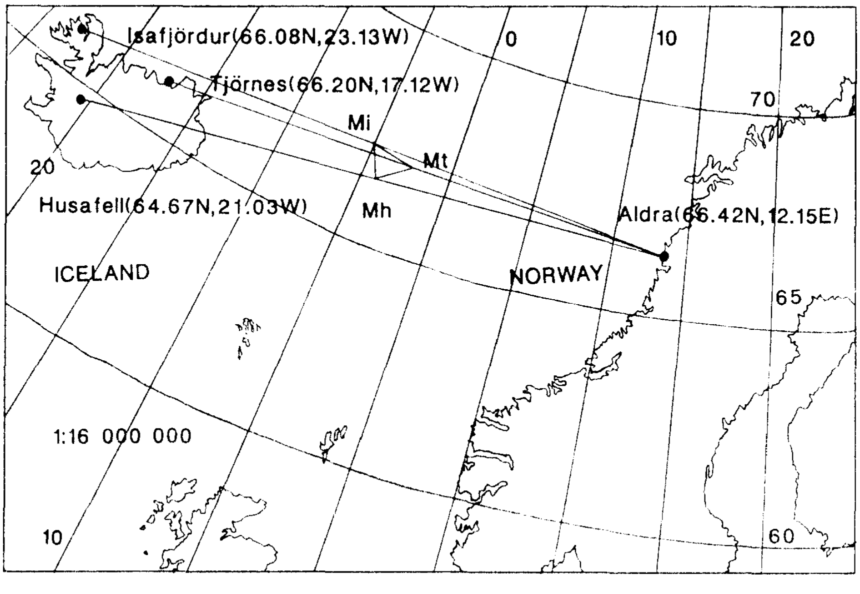

Fig. 1. Propagation paths of VLF signals: Omega Aldra–Tjörnes, Husafell and Isafjördur, Iceland. Mt, Mi and Mh are the middle points of Tjörnes to Aldra, Isafjördur to Aldra and Husafell to Aldra, respectively.

Table 1. Location of VLF receiver sites and distances between the transmitter (Aldra, Norway 66.42°N, 12.15°E) and receivers.

Station	Geographic		Magnetic dipole		Distance	L-Value
	Latitude	Longitude	Latitude	Longitude		
Husafell	64.67N	21.03W	69.90	73.17	1520 km	6.00
Isafjördur	66.08N	23.13W	71.56	72.64	1560 km	6.92
Tjörnes	66.20N	17.12W	70.50	79.52	1290 km	6.45

signals propagating in the earth-ionosphere waveguide were started at Husafell, Isafjördur and Tjörnes, Iceland, from September 1985 by using phase-locked VLF receivers.

Figure 1 is the geographic map with the straight lines connecting the transmitter and receiver sites. The reflection points for one-hop waves are denoted by Mh, Mi and Mt in the center of the figure. The mutual distances between these three points are almost the same and about 100 km. The geographic and geomagnetic coordinates of the three receiver sites are listed in Table 1. Geomagnetic substorms are defined by fluxgate-magnetometer data at these stations.* The observation of CNA as made by a La Jolla Science riometer. This riometer measures cosmic radio noise intensity at 30 MHz with a pair of dipole antennas. The bandwidth and time constant of the receiver are 150 kHz and 0.25 s, respectively.

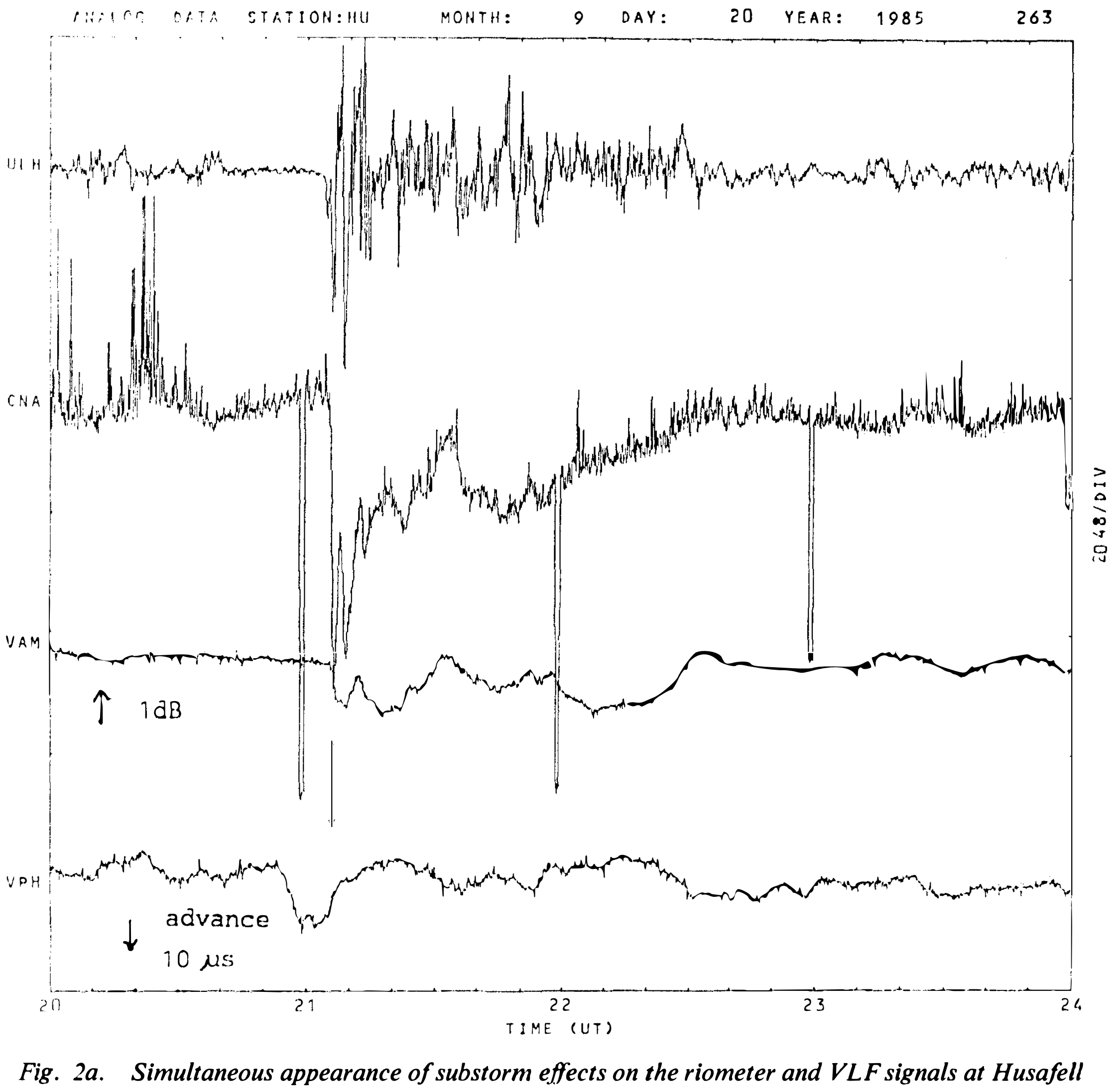

Fig. 2a. Simultaneous appearance of substorm effects on the riometer and VLF signals at Husafell in Iceland. ULH: the H component of induction magnetogram. CNA: cosmic noise absorption. VAM: amplitude of VLF Omega signals. VPH: phase of VLF Omega signals.

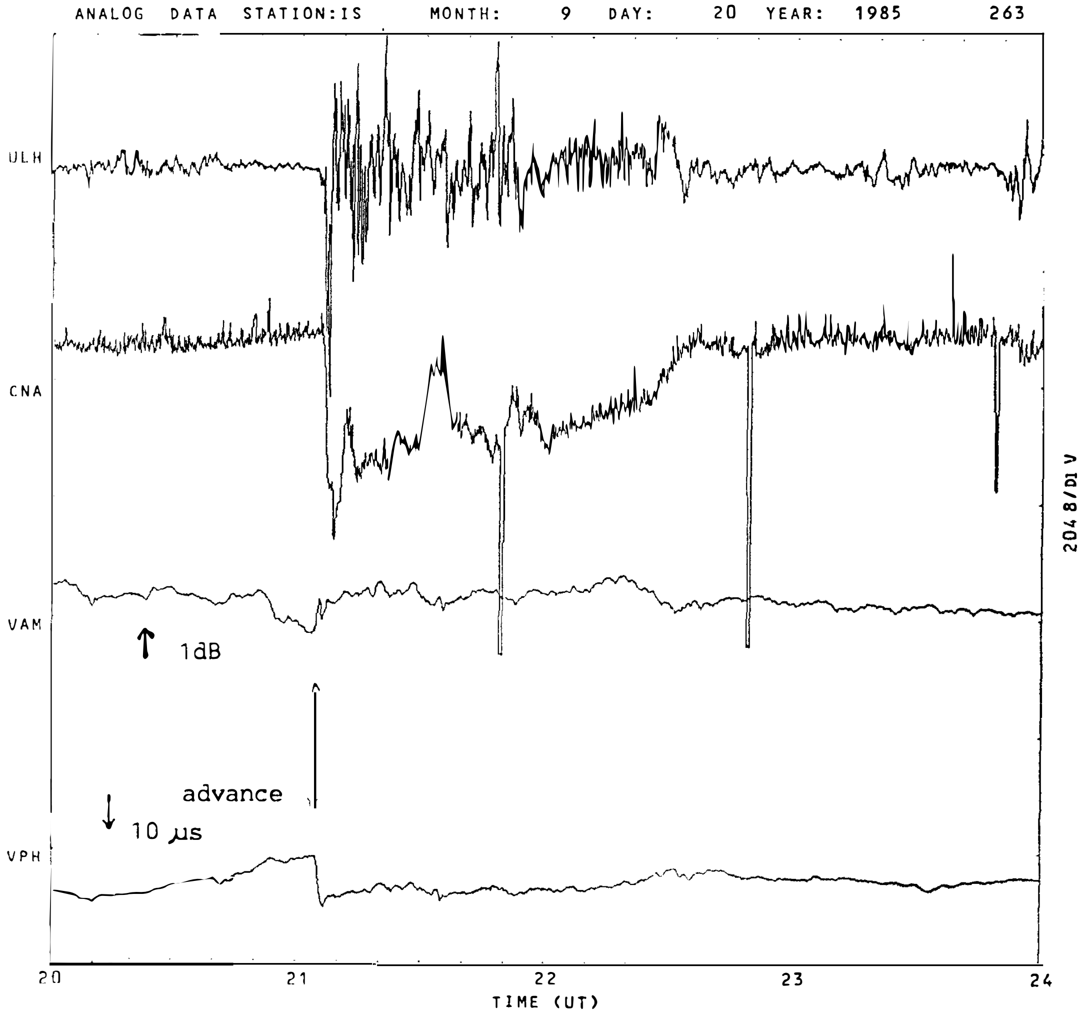

Fig. 2b. Same as Fig. 2a but for Isafjördur.

3. Event Studies on Substorm-Associated Phase Anomaly

In this section we study the relationships among the magnetic substorm, CNA, Omega signal intensity and the phase anomaly. Figures 2a, 2b and 2c show examples of the *H* component of induction magnetogram, CNA, Omega Aldra signal intensity and the relative phase variations during 20–24 UT on September 20, 1985, observed at Husafell, Isafjördur and Tjörnes, respectively. From the induction magnetogram and CNA data in these figures, a magnetic substorm started around 2105 UT. It is very interesting to study the relationships among the magnetic substorm, Omega signal intensity and the relative signal phase variations observed simultaneously at three stations. The intensity of Omega Aldra signal at Husafell started to decrease at 2104 UT associated with the onset of the magnetic substorm as shown in Fig. 2a. The VLF phase at Husafell started to advance from 2050 UT and the advancement become maximum during 2058–2103 UT, then, the phase gradually recovered to the normal level. It is noticeable that the phase was not apparently affected by the substorm. The characteristics of VLF signal intensity and phase observed at Isafjördur were dif-

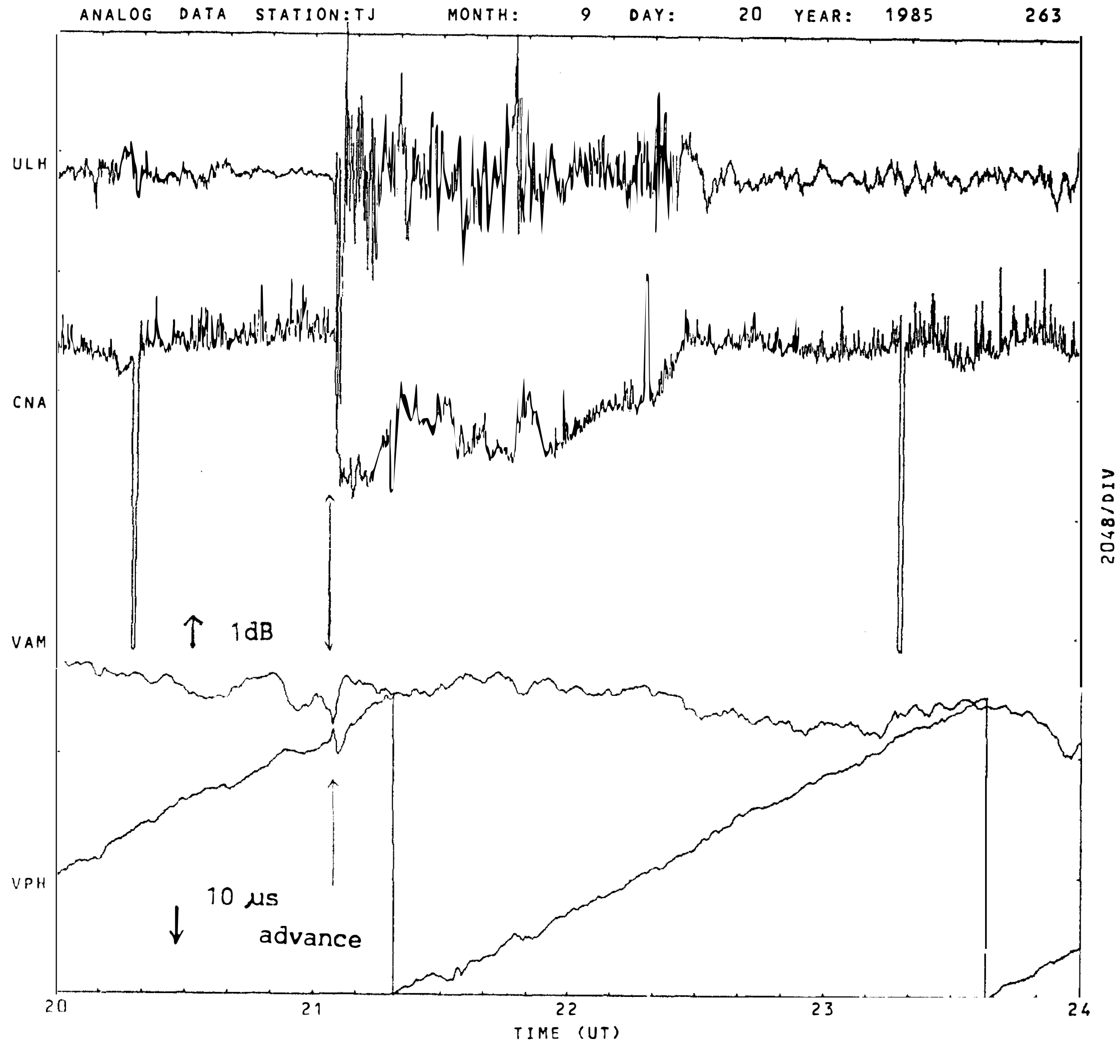

Fig. 2c. Same as Fig. 2a but for Tjörnes.

ferent from those observed at Husafell as compared in Figs. 2a and 2b. The intensity of Aldra signal observed at Isafjördur started to decrease gradually and became minimum at 2103 UT, then the intensity impulsively increased about 2 dB at 2105 UT associated with the substorm. On the other hand, the VLF phase variations were quiet before 2104 UT, completely in contrast to the data at Husafell, and that steeply advanced about 14 μs at 2105 UT at the substorm onset. From Fig. 2c the intensity of Omega Aldra signal observed at Tjörnes started to decrease gradually from 2050 UT and it decreased rapidly at 2104 UT associated with the substorm, then the intensity suddenly started to increase about 2 dB at 2106 UT. The VLF phase gradually advanced from 2054 UT, then recovered to normal level at 2104 UT when the signal intensity became minimum. It is interesting that the phase suddenly advanced about 6 μs at 2105 UT associated with the substorm and the increase of signal intensity.

From a simplified calculation (Davies, 1965), the 6 μs phase advance corresponds to the decrease of 3 km in the reflection height of the lower ionosphere, which is located normally at a height of 80 km.

4. Reflection Coefficient of VLF Waves by Full Wave Method

For studying a rapid phase advance and intensity increase, we estimate the reflection coefficient of VLF signals in the lower ionosphere by full wave method (SCARABUCCI, 1969). In this case the wave equations are integrated directly by introducing an orthogonalizing procedure which stabilizes the numerical technique of integration. Suppose that there is an electromagnetic plane wave propagating in free space. The wave incidents upon a planely stratified ionosphere, where the electron density varies only in the vertical Z-direction. The Y-axis is in the magnetic meridian (plane Y-Z) where the positive direction points northward. DIP means the dip-angle of the magnetic field. The wave-normal of the incident wave makes an angle I with the Z-axis (angle of incidence) and an angle χ with the magnetic meridian (azimuthal angle). The parameters used in the present calculation are shown in Fig. 3.

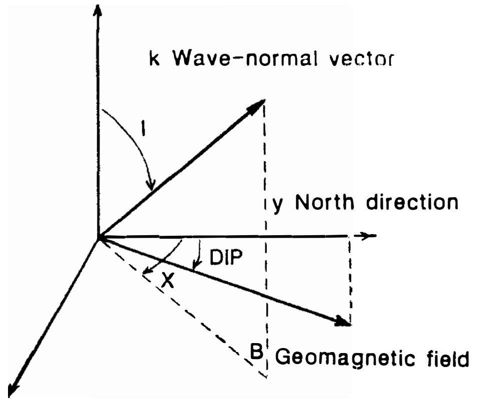

Fig. 3. The assumed geometry. Planes of constant stratification are parallel to the (x-y) plane. DIP is the angle between the geomagnetic field B and the y-axis. B lines in the (y-z) plane. I is the angle between the vertical and the wave-normal vector k. The azimuthal for k is χ.
$I=83^\circ$: Incident angle of VLF wave.
$=270^\circ$: Azimuthal angle for wave normal vector.
DIP$=75^\circ$: Magnetic dip angle.
$f=12.1$ kHz: VLF wave frequency.
$f=1$ MHz: Electron gyrofrequency.
HSTART$=100$ km: The height where the integration start.
HEND$=78$ km: The height below the ionosphere where the integration is to be stopped.
STEP$=.05$ km: The initial step size.
HLASTX$=78$ km: The height below which the plasma frequency is assumed to be zero.

In Fig. 4, five model cases of electron density distribution are shown, which are used to calculate the reflection coefficient by full wave method. The models used here are the normal electron density profile (model 1), a slightly enhanced ionization in the lower ionosphere (model 2), the bottom edge of ionosphere is lowered from 80 to 77 km as discussed in Section 3 and this change corresponds to the 6 μs phase advance in VLF data (model 3), the lower ionosphere becomes more ionized (model 4 and 5), respectively. The calculated reflection coefficients R (model 1, 2, 3, 4 and 5) are 0.8195, 0.8532, 0.8012, 0.8597 and 0.9544, respectively. From Fig. 4 and these calculations, the electron distribution seems to be most effective in the intensity of reflected waves, for example, the VLF signal intensity decrease and phase advance occurred by the distribution change from model 2 to 3 resulted in a decrease of reflection coefficient. Amplitude increase and phase advance occurred by the distribution change of electron density from model 1 to 5 resulted in an increase of reflection coefficient.

As mentioned above, the sudden phase advance (6 μs) and intensity increase (2 dB)

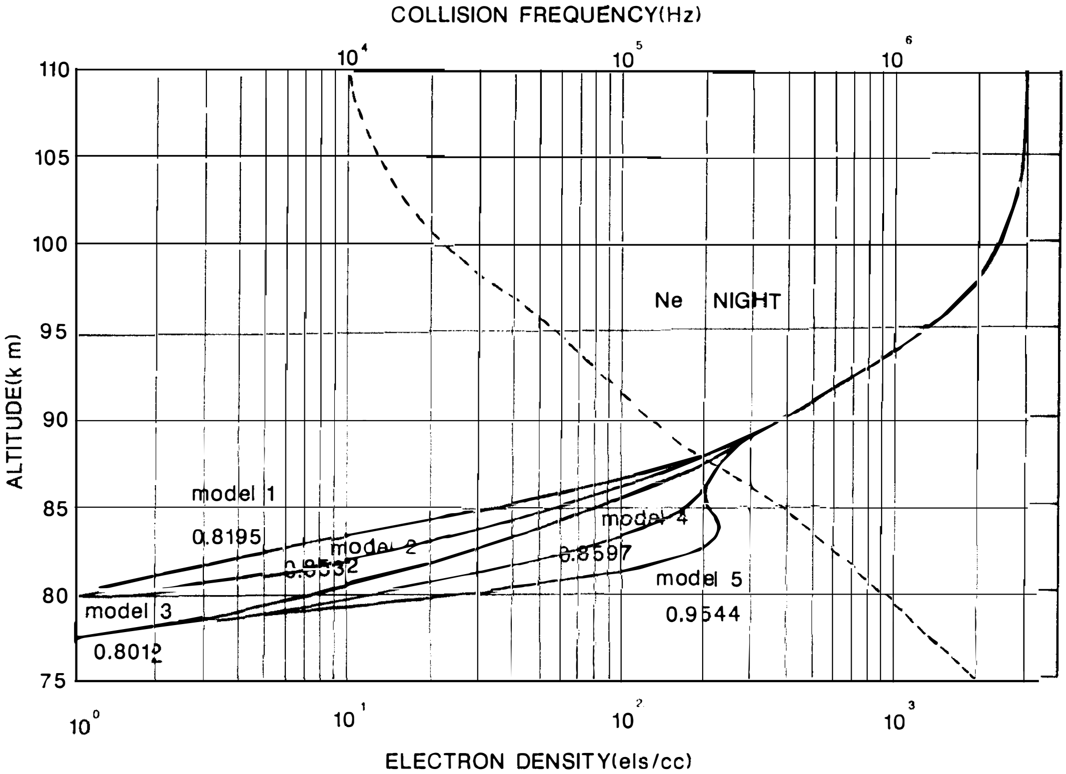

Fig. 4. Reflection coefficient computed by full wave method. The distribution of the collision frequency is shown by the broken line and the electron density distributions are shown by solid lines.

associated with the magnetic substorm will be interpreted by the change of density profile from model 1 to 5.

5. Summary

The data analysis of VLF signals and the estimation of reflection coefficient of VLF wave by full wave method were performed, and the results are summarized as follow.

(1) A rapid phase advance (6 μs) and a rapid increase in the intensity (2 dB) of the VLF signals were observed in association with magnetic substorms at two stations (Isafjördur and Tjörnes).

(2) The sudden phase advance (6 μs) and the amplitude increase (2 dB) may be interpreted by a wave reflection in the sharply ionized layer in the ionosphere.

(3) The characteristics of VLF signal intensity and phase observed at Husafell were very different from those observed at other stations (Isafjördur and Tjörnes). It is also suggested from the differences of the phase and amplitude anomaly observed at the three stations that the particle precipitation region will be restricted to a small-scale area.

Further theoretical and experimental studies are desirable and more precise computer calculation will be necessary, including multi-hop reflected waves and other method such as mode theory.

Acknowledgments

The authors wish to express their heartfelt thanks to Prof. T. SAEMUNDSSON, Iceland University for his kind advice and excellent arrangement in Iceland. The authors also thank Dr. I. NAGANO of Kanazawa University for his helpful discussions. We are also grateful to Messrs. A. EGILLSON, J. MARVINSSON and S. JOHANESSON for their support at Tjörnes, Isafjördur and Husafell respectively. This research was done using ACOS-850 computer facilities at the Hirosaki University. The project in Iceland was supported by Grant-in-Aid for Overseas Scientific Survey 60041085, Ministry of Education, Science and Culture, Japan.

References

ARAKI, T., SATO, T., FUJII, R., KIKUCHI, T. and KOKUBUN, S. (1986): A case study of VLF phase and amplitude variation at 12.1 kHz (Aldra) in Iceland. Mem. Natl Inst. Polar Res., Spec. Issue, **42**, 45–51.

BERKEY, F. T., DRIATSKY, V. M., HENRIKSEN, K., HULTQVIST, B., JELLY, D. H., SHCHUKA, T. I., THEANDER, A. and YLINIEMI, J. (1974): A synoptic investigation of particle precipitation dynamics for 60 substorms in IQSY (1964–1965) and IASY (1969). Planet. Space Sci., **22**, 255–307.

DAVIES, K. (1965): Ionospheric Radio Propagation. New York, Dover Publ., 394–395.

DRIATSKY, V. M. and SHUMILOV, O. I. (1972): Ionospheric substorms. Planet. Space Sci., **20**, 1375–1389.

HULTQVIST, B. (1975): The aurora. The Magnetospheres of the Earth and Jupiter, ed. by V. FORMISANO. Dordrecht, D. Reidel, 77–111.

KIKUCHI, T. (1981): VLF phase anomalies associated with substorm. Mem. Natl Inst. Polar Res., Spec. Issue, **18**, 3–22.

KIKUCHI, T. and EVANS, D. (1983): Quantitative study of substorm-associated VLF phase anomalies and precipitating energetic electrons on November 13, 1979. J. Geophys. Res., **88**, 871–880.

KIKUCHI, T., NOZAKI, K. and OHTANI, A. (1983): Simultaneous observation of anomalies at Syowa Station, Antarctica in association with magnetospheric substorms. Mem. Natl Inst. Polar Res., Spec. Issue, **26**, 113–123.

SCARABUCCI, R. R. (1969): Analytical and numerical treatment of wave-propagation in the lower ionosphere. Tech. Rep. No. 3412-11, Radioscience Laboratory, Stanford Electronics Laboratories, Stanford University, 95 p.

(Received August 11, 1986; Revised manuscript received January 22, 1987)