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HEIGHT VARIATIONS OF AURORAL HISS OBSERVED BY S-310JA-11 AND -12 ROCKETS

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Abstract: Electromagnetic waves constructing auroral hiss in the VLF range were observed by the S-310JA-11 and -12 rockets launched into a quiet auroral arc and into a breakup aurora respectively, from Syowa Station in Antarctica. An altitude profile of the electric field intensity, which peaked at an altitude of 90 km was observed by the S-310JA-12 rocket in the frequency range less than 5 kHz. An estimation of the source location of the auroral hiss was made with the altitude profile of the hiss intensity calculated by the full wave analysis so as to agree with those observed especially around the altitude of 90 km. It was found that the auroral hiss is most likely to be generated at an altitude about 700 km or less. On the other hand, the absolute intensity of the auroral hiss at a frequency of 4 kHz observed by the rocket, which was 9.4×10^{-5} V/m/$\sqrt{\text{Hz}}$, was much stronger, by about 50 dB, than that observed at Syowa Station. This means that the *k*-vector direction of the auroral hiss actually observed by the rocket lay outside the transmission cone, so that the auroral hiss could reach Syowa Station with very week intensity.

1. Introduction

VLF hiss associated with an aurora has been observed at Syowa Station during the period of IMS by many sounding rockets (KIMURA *et al.*, 1980, 1981; MATSUO *et al.*, 1979; YAMAGISHI *et al.*, 1981; KAMADA *et al.*, 1981). The characteristics of auroral hiss at the rocket altitudes have been investigated in these rocket experiments from the view points of determining the direction of the ***k***-vector, the wave mode and the Poynting flux. As to the relationship between auroral hiss and energetic electrons, the wave intensity showed a good correlation with the 40–60 keV electron flux in a breakup aurora, but it did not show such a good correlation in a diffused aurora during the quiet condition (KIMURA *et al.*, 1980). The experimental result suggests that the auroral hiss in the breakup aurora is likely to be generated near the rocket altitude. We can also infer the source region from other experimental techniques such as a direction finding on the ground (NISHINO *et al.*, 1982). However, the source region of the auroral hiss has not yet been clarified.

In this paper, we will focus on the altitude profile of the electric field intensity observed by the sweep frequency analyzer onboard the S-310JA-12 rocket and will make a comparison between the observed values and the calculated values by a full wave method (NAGANO *et al.*, 1975, 1980). As a result, the calculated values around an altitude of 90 km tend to show a good agreement with the observed values only if the auroral hiss is emitted from an altitude of 700 km with the wave normal near the resonance cone angle. Then, it can be confirmed that the auroral hiss, which can reach the 90 km altitude, propagates slightly apart toward the pole side from the auroral arc. A comparison is also made between the hiss intensities observed at the rocket altitudes and on the ground during the flight.

2. Experiments

The S-310JA-11 rocket was launched at 0059:53 UT (0359:53 LT) on May 29, 1985 in the direction of the South East in the geomagnetic coordinates and reached an altitude of 222 km at 227 s after launch. The geomagnetic condition was quiet during the flight. The S-310JA-12 rocket was launched at 1935:39 UT (2235:39 LT) on July 12, 1985 in the direction of the geomagnetic field line and reached an altitude of 223 km at 234 s after launch. The second rocket experiment was during a geomagnetic substorm caused by a proton flare, so that a bright auroral arc was present all over the sky. Both the rockets hit auroral arcs during the ascent flights and left

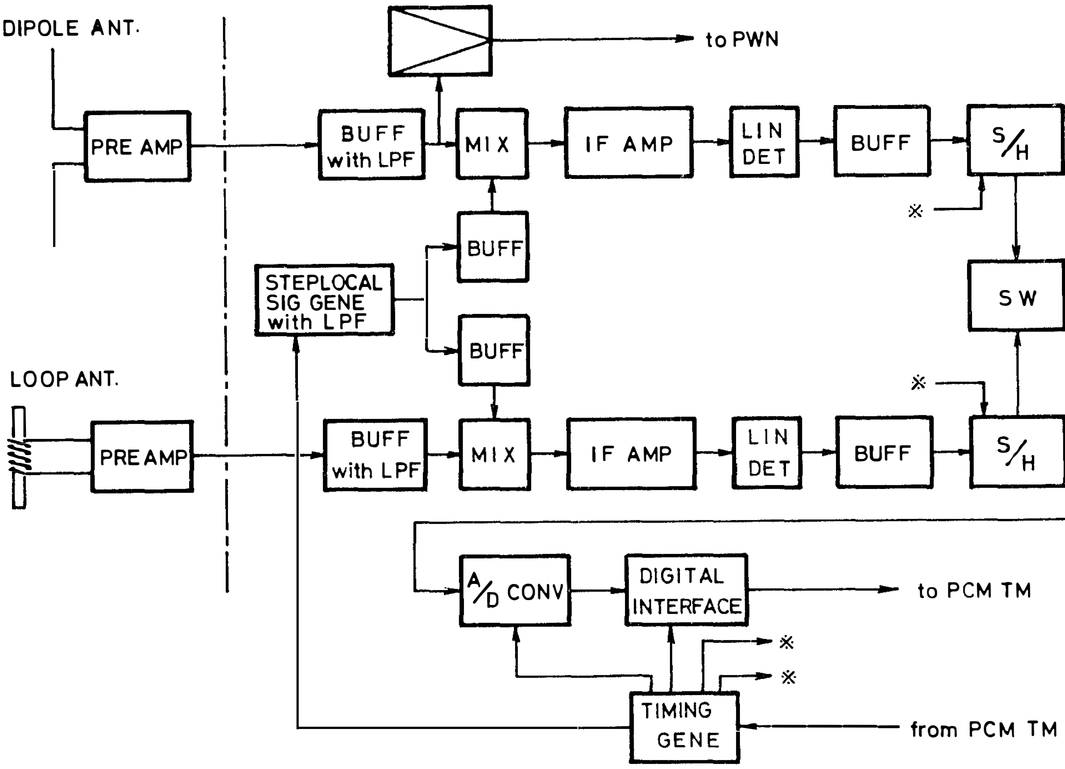

Fig. 1. Block diagram of PWL onboard the S-310JA-11 and -12 rockets.

the arc near the apex, and then hit again auroral arcs during the descent flight.

An identical payload was installed in these two rockets, in order to compare the differences between the wave-particle interaction processes in two types of aurora (Yamagishi and Fukunishi, 1985). The instrument onboard these two rockets to measure plasma waves in the VLF range was called PWL. The block diagram of PWL is shown in Fig. 1. Electric and magnetic field components of plasma waves in the VLF range were measured by a dipole antenna (2.4 m tip to tip) and a search coil sensor (3000 turns on 6×6×250 mm long laminated high permeability core), respectively. The instrument consisted of a two-channel sweep frequency analyzer (SFA) for the simultaneous measurement of electric and magnetic field components, and a single channel wide band receiver for the measurement of electric component. The frequency range, the resolution and the period of the sweep analyzer were 0.2–12.6 kHz, 400 Hz and 160 ms, respectively. The dynamic range of SFA is expanded to 72 dB by using the CODEC method (CODEC is a combined word of *CO*RDER and *DEC*ORDER), of which digital signal consists of chord output (upper 3 bits) and step output (lower 4 bits) for the case of PWI instrument. If *a* and *b* stand for chord

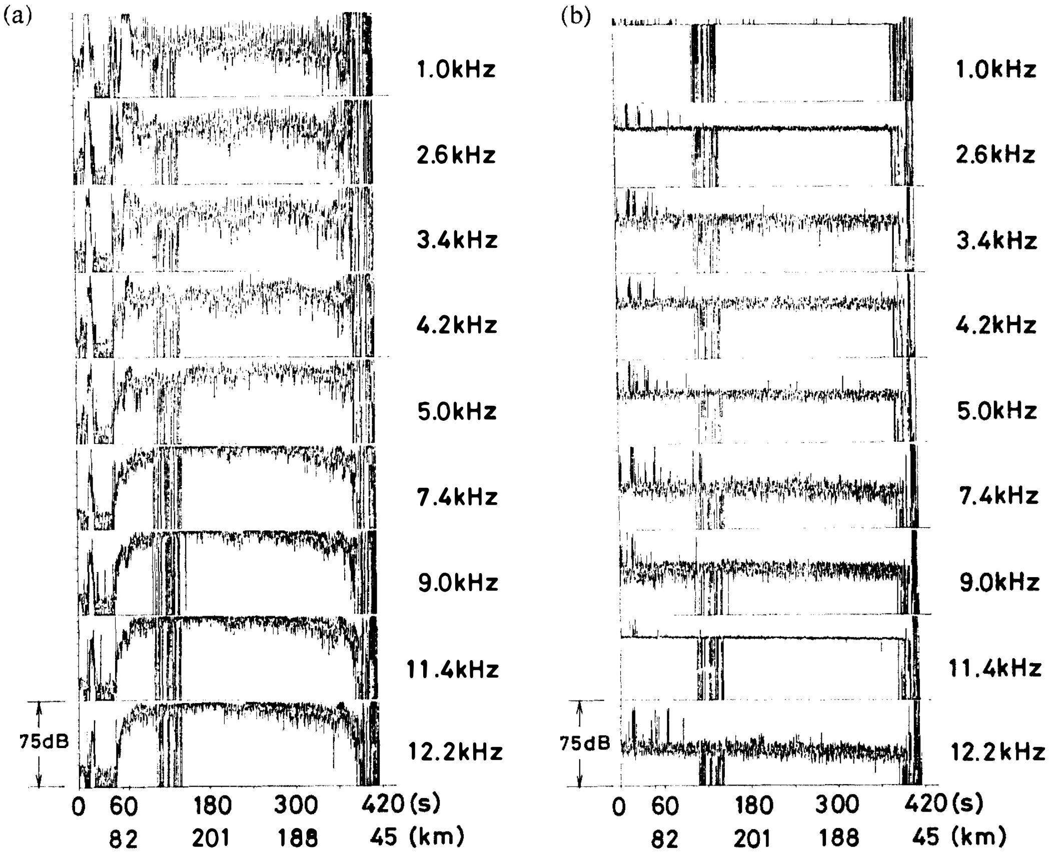

Fig. 2. Electric (a) and magnetic (b) hiss intensities in the frequency range from 1.0 to 12.2 kHz observed by S-310JA-11 rocket. The horizontal axis indicates elapsed time in second after launch and altitude corresponding to the time. The full range from one baseline to the next indicates a 75 dB dynamic range in the vertical axis. The intensity on each baseline is 4.6 × 10^{-4} mV/m for electric component and is 3.8 × 10^{-2} pT for magnetic component. The band width of each frequency channel is 400 Hz.

and step outputs, respectively, an input signal value v is expressed as $v=(2^a \times (b+16) - 16) \times 1.25 - 0.625$ (V). On the other hand, in order to know the absolute electric field strength of auroral hiss, impedance of the dipole antenna was also measured in the frequency range of interest at every 5 s interval by a simple technique of supplying sinusoidal waves to the dipole antenna from a current source with high impedance.

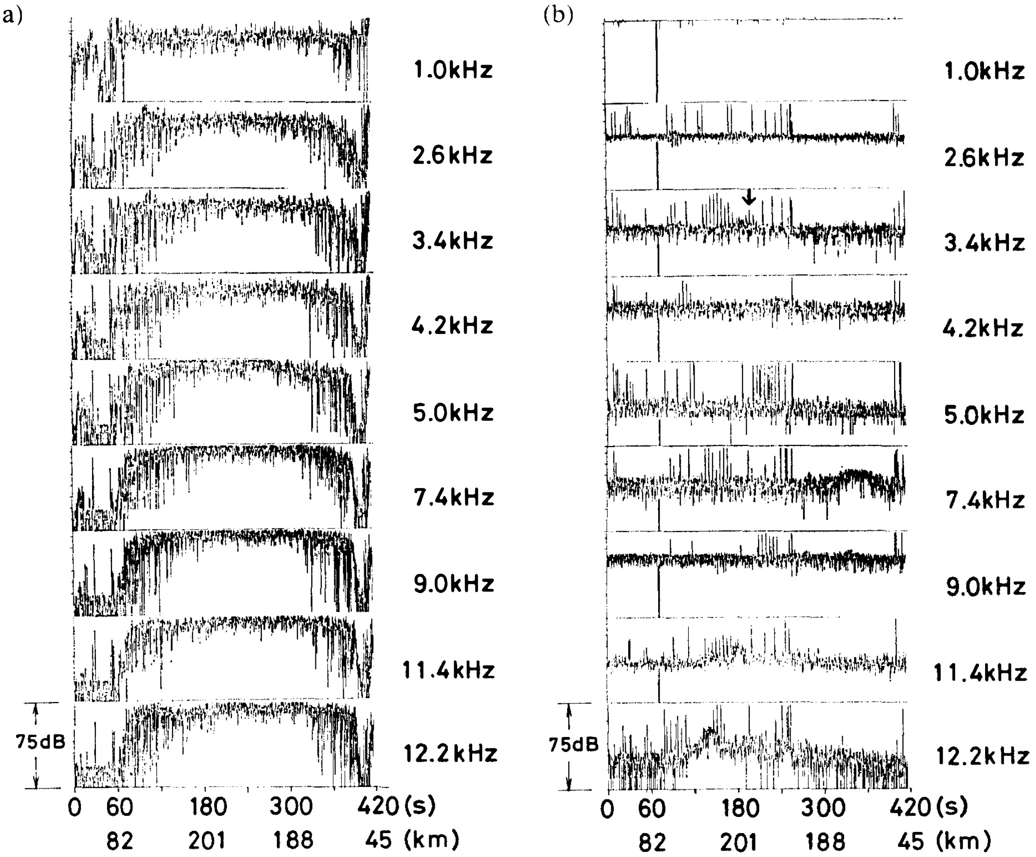

Fig. 3. Electric (a) and magnetic (b) hiss intensities in the frequency range from 1.0 to 12.2 kHz observed by S-310JA-12 rocket. Other explanations are the same as those in Fig. 2.

The intensities of the electric and magnetic field components at sampled frequencies during the flight of S-310JA-11 are shown in Figs. 2a and 2b, and those of S-310JA-12 are shown in Figs. 3a and 3b, respectively. In these figures, the vertical axis at each frequency denotes the intensity of the field with logarithmic scale of 75 dB and the base lines of the electric and magnetic fields correspond to 0.024 μV/m/$\sqrt{\text{Hz}}$ and 1.9×10^{-3} pT/$\sqrt{\text{Hz}}$, respectively. The electric field intensities were estimated by taking account of the antenna impedance simultaneously observed, under the assumption that the effective height of the antenna was half of its real length. The data during the time interval from 110 to 140 s and after 360 s in Figs. 2a and 2b involve the bit-errors caused by a lock-off of the PCM telemetry. Similarly, the data at 75 s in Figs. 3a and 3b are not reliable. As can be seen in those figures, the electric field of the auroral hiss wave increased abruptly soon after the dipole antenna was developed at 47 s and it varied severely with the spinning period of the rocket. On the other hand, the data of the hiss magnetic field did not show any effect of the rocket spinning. The almost constant level of the observed magnetic field may be attributed to an interference amounting to about 10 pT from other payload instruments onboard the rocket.

In this paper, we will pay special attention to the electric field, especially a characteristic peak at an altitude of 90 km in a frequency range from 1 to 5 kHz as shown in Fig. 4. This height profile with a striking peak was observed only during the ascending flight of the S-310JA-12 rocket. The observed electric field for 3.4 kHz can be identified to be associated with whistler mode wave because the accompanying magnetic field for the same frequency was observed near the apex, as is seen with an arrow in Fig. 3b. Therefore, we will compare these observed height profiles with those calculated by the full wave method, and finally estimate the source region of the auroral hiss.

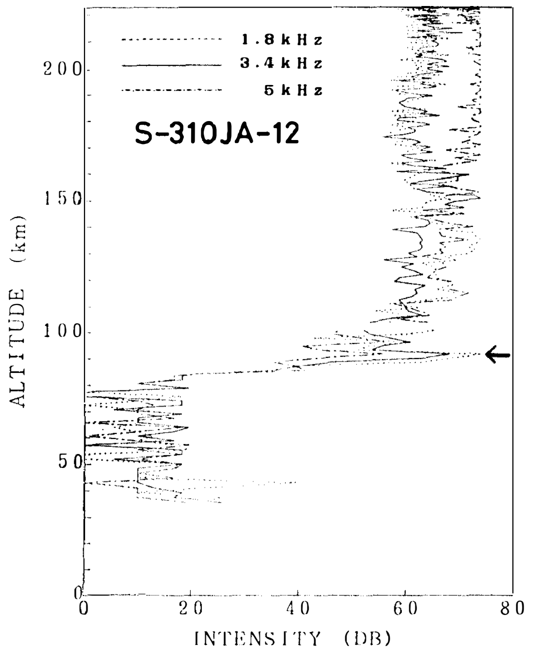

Fig. 4. Height variations of electric field for three frequencies of 1.8, 3.4 and 5.0 kHz observed by S-310JA-12 rocket during the ascending flight. An arrow indicates the characteristic peak at an altitude of 90 km. 0 dB is 0.024 $\mu V/m/\sqrt{Hz}$.

3. Ionospheric Model

We can calculate a height variation of the whistler mode wave above the ionosphere taking account of the ground effect, in the VLF range in the full wave method (Nagano *et al.*, 1975), if both electron density and collision frequency profiles are assumed in the interested region. An electron density profile was obtained by a gyro-plasma probe for the altitude range from 95 to 225 km (apex), but it is necessary to know the profile up to an altitude of 1000 km to calculate the auroral hiss intensity as well as the ray path of the wave. Therefore for altitudes less than 95 km, the electron density was estimated from DC probe current data simultaneously observed by "PWN" onboard the same rocket, under an assumption that this current is proportional to the electron density. For altitudes above the rocket apex the electron density was calculated using a value of the scale height in winter, which was estimated from the electron density measured by ISIS-2 satellite (Matsuura, 1979). On the other hand, the collision frequency profile was estimated from an atmospheric pressure profile.

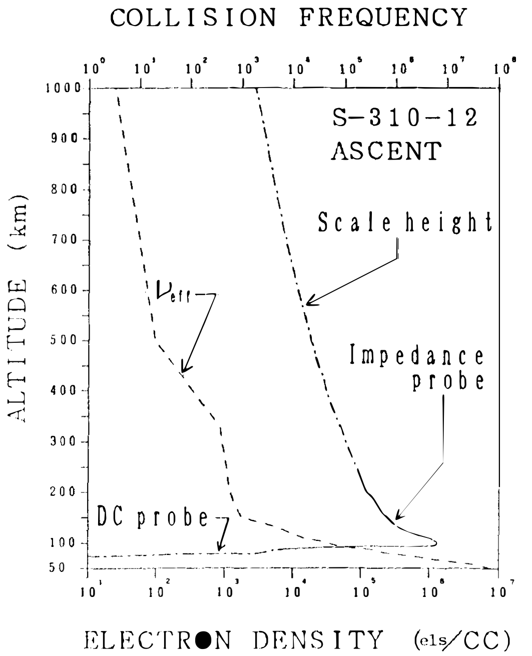

Fig. 5. Ionospheric model which is used in the full wave calculation. The electron density profiles at lower than 220 km were simultaneously observed by S-310JA-11 rocket during its ascent flight. The rest profile for electron density was estimated from the value of the scale height. The collision profile was calculated from an atmospheric pressure model.

We can thus obtain the ionospheric model shown in Fig. 5 for the S-310JA-12 rocket experiment. Similarly, we calculated the ionospheric model for the S-310JA-11 rocket experiment, though not shown here.

4. Full Wave Analyses and Discussions

In order to interpret quantitatively the height variation of electric field observed by the rocket, we calculated the field intensity and polarization characteristics using the full wave method when a plane wave is incident onto the ionosphere from above. The parameters used in the full wave calculations are shown in Table 1.

Figures 6a and 6b represent the height variations of the up-going (dotted line), down-going (dot-dashed line) and resultant (solid line) field intensities of the horizontal electric field for a vertically downward incidence at an altitude of 220 km under the ionospheric models corresponding to the S-310JA-11 and -12 experiments, respectively.

The horizontal axis denotes the absolute magnitude of the electric field when the z-component of Poynting flux of the incident whistler mode wave is assumed to be

Table 1. Parameters used in the numerical calculations.

Incident conditions		Variables: angle and altitude (close to resonance condition)
Geomagnetic dip angle	dip	65 degrees
Electron gyrofrequency	f_H	1.26 MHz
Wave frequency	f	3.4 kHz
Azimuth angle		0° (N-S propagation) 135° (Eastward from M.N)
The conductivity and dielectric constant of earth		10^{-3} (S/m) and 10

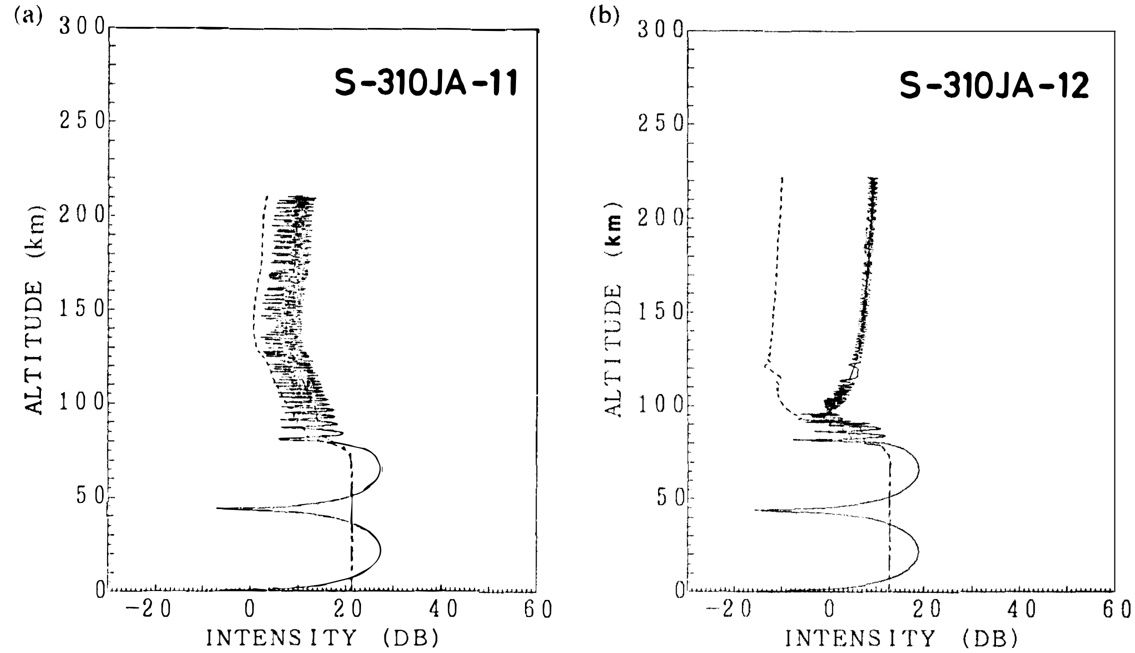

Fig. 6. Height variation of the horizontal electric field of waves with a vertical downward incidence at an altitude of 220 km and for the ionospheric models at the time of the S-310JA-11 (a) and the S-310JA-12 (b) rocket experiments (see Fig. 5). The dotted, dot-dashed and solid lines indicate up-going, down-going and resultant waves, respectively. A wave frequency of 3.4 kHz is used. 0 dB is taken as 1 μV/m when Poynting flux of the down-going whistler mode wave is 1 pW/m² at the incident altitude.

1 pW/m^2. The level of 0 dB is taken as 1 μV/m.

As can be seen in these two figures, the down going whistler mode waves penetrate the lower ionosphere without much attenuation, and reach the ground so that standing waves appear in free space between the ground and the bottom of the inosphere. These height variations of the electric field do not agree with the observed one at the frequency of 3.4 kHz shown in Figs. 2 and 3.

On the other hand, as it has been thought that the auroral hiss waves are generated by Cerenkov type of radiation (JØRGENSEN, 1968; LIM and LAASPERE, 1972; JAMES, 1973), we modify the initial condition of the wave normal direction; we then assume that the incident direction at an altitude of 220 km satisfies the resonance condition. Figures 7a and 7b show the electric field thus calculated for the S-310JA-11 and -12 experiments, respectively. The electric field intensities in both figures decrease abruptly at the bottom of the lower ionosphere. This is due to the fact that waves become evanescent below a certain altitude in the bottom ionosphere. In particular, a small peak appears at an altitude of 90 km only in Fig. 7b and the field profile is very similar to that for a frequency of 3.4 kHz observed by the S-310JA-12 rocket shown in Fig. 4. It is interesting to note that in case of S-310JA-11 such a peak in the intensity does not appear at the bottom ionosphere both the calculated and observed values. The appearance of such a peak in intensity may be due to a propagation effect, which is dependent on the electron density profile. Therefore, we investigate how the peak intensity in the height variation changes with altitudes of the wave incidence. Figure

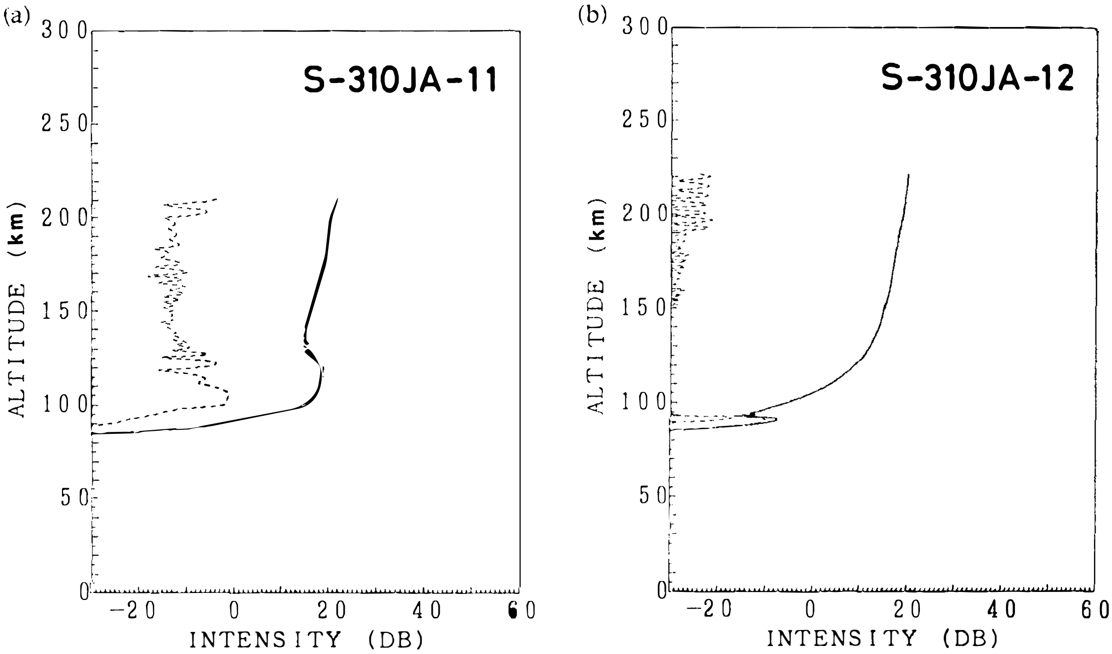

Fig. 7. Height variations of the horizontal electric field of waves for the ionospheric models of S-310JA-11 (a) and S-310JA-12 (b), under the assumption that the initial wave normal direction satisfies the resonance conditions. Other parameters are the same as those in Fig. 6. Note that there is a peak at an altitude of 90 km in (b).

8 shows the electric field profile calculated for various incident altitudes, where the resonance condition is satisfied. When the wave is incident at higher altitude, the peak intensity of the electric field increases and conversely the intensity at altitudes higher than 120 km decreases. The calculated value of the peak for the incident altitude of 700 km is almost the same as that of around 150 km altitude. We can see such a tendency for the observed values of a frequency of 3.4 kHz shown in Fig. 4. These results will suggest that the auroral hiss observed by the S-310JA-12 rocket is likely to be generated around an altitude of 700 km.

The polarization of the horizontal component of whistler mode wave can also be calculated by the full wave method. The height variation of the wave polarization, which is represented by the ratio of minor to major axes, is shown in Fig. 9 when the wave is incident to the direction of 135° toward the magnetic east from the north at an altitude of 700 km. We can estimate the polarization characteristics from the data of the spin modulation of the electric field intensity observed by a dipole antenna. Since the direction of the rocket axis of the S-310JA-12 was almost constant, only 10° from the vertical during the ascent flight, the observed electric field component could be regarded as the horizontal component. Figure 10 shows both the calculated and observed values of the electric field at a frequency of 3.4 kHz for S-310JA-12. The maximum and minimum values of the observed field due to the rocket spinning indicate the degree of polarization. It is found that the electric field has an elliptical polarization with an axial ratio of 0.3 for altitudes higher than 160 km, an almost linear polarization for the altitude range from 160 to 100 km and an approximately circular polarization at an altitude of 90 km. The observed values are in fairly good

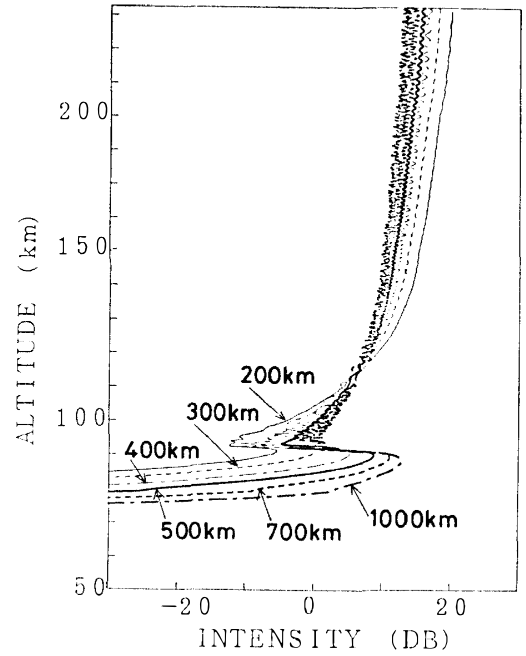

Fig. 8. Height variations of the horizontal electric field of waves or the incident altitudes of 200, 300, 400, 500, 700 and 1000 km. Their incident azimuthal angle is 135 degrees geomagnetic east from north.

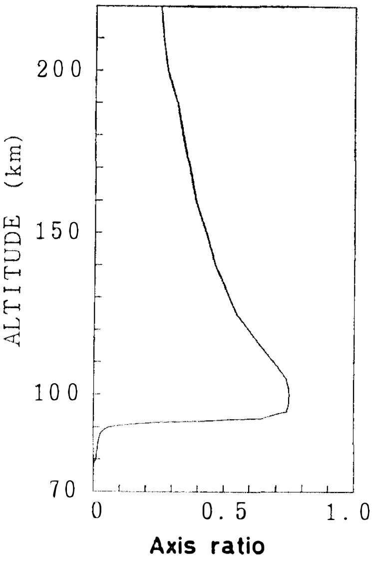

Fig. 9. Height variation in polarization of waves incident at 700 km altitude. The horizontal axis indicates the ratio of minor to major axes. The ratio of unity represents the circularly polarized wave.

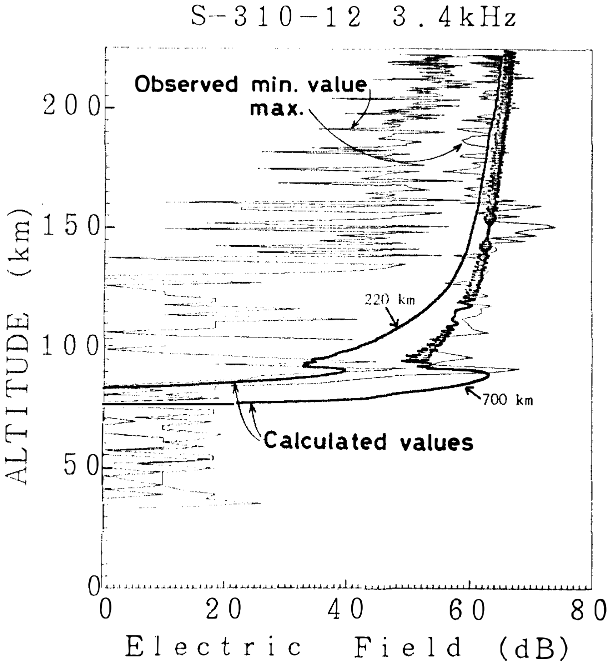

Fig. 10. Comparison between the observed value (thin) and the calculated value (thick) of the wave electric field for the ascending flight of S-310JA-12 rocket. The maximum and minimum values due to the rocket spinning are examined to investigate the wave polarization. The calculated lines are shown for wave incident altitudes of 220 and 700 km.

agreement with the calculated values (shown in Fig. 9) in the altitude range except from 150 to 100 km. This disagreement in the altitude range from 150 to 100 km may be due to a presence of strong electrostatic wave that might have been generated in the auroral arc. It is thought that the observed electric field at an altitude of 90 km consists only of whistler mode waves propagating downward through the ionosphere, where the flux of energetic electron associated with aurora decreases enough to generate electrostatic waves. Although an instrument for measuring the flux of energetic electrons was onboard the same rocket, we could not confirm the above hypothesis because the measurement was started from 120 km altitude. The height variation of the electric field calculated for the two incident altitudes of 220 and 700 km are also shown in Fig. 10. As stated above, the calculated values for the incident altitude of 700 km fairly agree with the observed values. Judging from these calculations, we can conclude that the auroral hiss observed at an altitude of 90 km is most likely to be generated around an altitude of 700 km rather than at the altitude of the rocket altitude. This result is consistent with the source region estimated from the wave normal direction of the auroral hiss observed by S-310JA-5 rocket (KIMURA and MATSUO, 1982).

VLF observations were simultaneously carried out on the ground at Syowa Station during the flights of these two rockets. The average value of Poynting flux on the ground over the flight of the S-310JA-12 rocket was 5×10^{-16} W/m^2/Hz at the frequency of 4 kHz. The intensity of the auroral hiss in altitudes higher than 100 km was much stronger, by about 50 dB, than that observed on the ground. On the other hand, as we can guess from Figure 3b, the calculated intensity at an altitude of 200 km is much stronger, by as large as a few hundred dB, than that on the ground. This discrepancy may be due first to a simple horizontally stratified layer model of the ionosphere for calculation, and second to an assumed narrow angle range of incident wave normal direction, which lies outside the transmission cone. Fortunately, since the S-320JA-12 rocket was launched along the geomagnetic field, we can estimate the wave normal direction using the spin modulation method reported by NISHINO and TANAKA (1987). For example, the ratio of $E_{\min}$ to $E_{\max}$ in the spin modulation at an altitude of 200 km of Fig. 10 is about 0.2, the elevation angle of the rocket is about 80° and dip angle of the geomagnetic field is 65°, and these values lead to the wave normal angle toward the vertical axis as about 50°. On the other hand, the transmission cone angle is about 1.5° for the frequency of 3.4 kHz at the altitude of 200 km. Therefore, this second assumption can be confirmed by this estimation of the wave normal direction. Actually, however, the ionosphere may have inhomogeneities when auroral electrons precipitate into the lower ionosphere and the auroral hiss emissions may have a spatially confined amplitude distribution. Then the incident wave normal directions for a certain portion of the waves lie within the transmission cone, so that the attenuation through the lower ionosphere cannot be so large (NAGANO *et al.*, 1987). Hence, the hiss waves seem to be propagated on the ground from some source regions far apart from Syowa Station.

5. Conclusion

The electromagnetic waves in the VLF range observed by the S-310JA-11 and -12 rockets were investigated in detail using the full wave calculation. A height variation of the electric field with a distinct peak at an altitude of about 90 km was observed only by the S-310JA-12 rocket. As the amplitude of this peak depended on both the source altitude and the initial wave normal angle, the source location of the auroral hiss observed by the rocket can be estimated in such a way that the calculated values should agree with the observed values, in particular taking account of the observed peak around an altitude of 90 km. It was found from this method that the auroral hiss observed by the S-310JA-12 rocket was most likely to be generated at an altitude of about 700 km, at least at altitudes higher than the apex (220 km) of the rocket trajectory and propagated nearly along the geomagnetic field line down to the lower ionosphere. As to the intensities of simultaneously observed auroral hiss on the ground at the frequency of 4 kHz, it was very weak by about 50 dB in comparison with the wave intensity observed by the rocket. The minimum absorption of a whistler mode wave through the lower ionosphere is about 10 dB according to calculation for an incident direction within the transmission cone. This means that the wave normal direction of the auroral hiss around the rocket altitude seems to be well outside the transmission cone *i.e.*, not to be vertical to the ionosphere.

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