ROCKET OBSERVATION OF VLF RADIO WAVES IN THE IONOSPHERE

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Abstract

The result of radio noise observation with VLF wide band receiver on board the K-9M-26 rocket is discussed. On the flight we observed a large number of short fractional-hop whistlers originating around the launching site. From the altitude dependence of their dispersion the electron density profile of the ionosphere with layer structure is derived. Also the analysis of ordinary whistlers shows that the whistlers which have emerged once above the maximum density region of the ionosphere, echo back and forth between both hemisphereres taking non-ducted propagation, resulting in large dispersion.

1. Introduction

The subject of observation of radio waves in the ionosphere in the frequency range VLF-ELF is well-known whistlers and VLF emissions (Iwai et al., 1965 ; Iwai et al., 1966 ; Hayakawa et al., 1969), recently observed ion cyclotron whistlers (Gurnett et al., 1965) and ion electrostatic waves (Scarf et al., 1965 ; Iwai et al., 1966 ; Hayakawa et al., 1969). Whistlers are the useful means for determination of electron density distribution in the upper atmosphere, and VLF emissions supply to us the information on the motion of charged particles in the magnetosphere. From the estimation of crossover frequency of ion whistlers we can know the ion density distribution. And ion electrostatic waves are expected to be important in that their transporting energy is large, they strongly interact with charged particles, and they reflect the thermal effect of charged particles. However, many important problems on VLF radio waves remain unsolved, for example the penetration characteristics of VLF radio waves through the ionosphere, the energy source and propagation of electrostatic waves etc. In this paper the former problem is discussed carefully using the whistler data observed on board the K-9M-26 rocket launched in August, 1969. The latter problem was examined in some detail by Hayakawa et al. (1969). Ionospheric penetration problem may be essentially inevitable for the propagation of low-latitude whistlers.

2. Measurement items of the K-9M-26 rocket

The K-9M-26 rocket was of exclusive use for the observation of VLF radio waves in the ionosphere, and mother-daughter rocket system was firstly adopted for this rocket. The mother-daughter rocket system is expected to be very effective in the active experiments such as whistler mode propagation experiment proposed by the present authors. The measurement items of the K-9M-26 rocket is as follows ; (1) Observation of radio noise with the wide band VLF receiver on board mother- and daughter-rocket. (2) The effects of rocket bodies on radio wave measurements. (3) Impedance measurement of antennas at the frequencies 740 Hz and 3.5 KHz. For the investigation of item (2), two monopole antennas of different length 0.6m and 1m deployed radially from the side of the rocket and a whip antenna of 0.6m length stretched out from the head in the direction of rocket axis were installed on the mother rocket. On the other hand for the case of daughter rocket the disturbance region is so small that its effect on antenna behavior is expected to be negligible. By making use of antenna impedance measurement, we can estimate the accurate electric fields of radio waves. In what follows, we only discuss the results on wide band VLF receivers on board the mother rocket, especially the result of whistlers, because we couldn't find out the ion electrostatic waves.

3. Observed results and discussions

The experiment was carried out using the K-9M-26 rocket at 17:03 JST on 24 August, 1969. The rocket was launched from Kagoshima Space Center (KSC) with an initial elevation angle of 79°, and with an azimuth of 139° from the north, and the nose cone opened at the altitude of approximately 75 km. It reached the maximum altitude 347 km as shown in Fig. 1. During the flight time of the rocket, a large number of short fractional-hop whistlers originating around Kagoshima area, and ordinary whistlers were successfully observed, which are discussed separately. As the antenna for VLF wide band observation, a whip antenna of 1 m length, a sphere antenna of 9 cm radius, and a loop antenna of approximately 700 cm^2 area were used in time division.

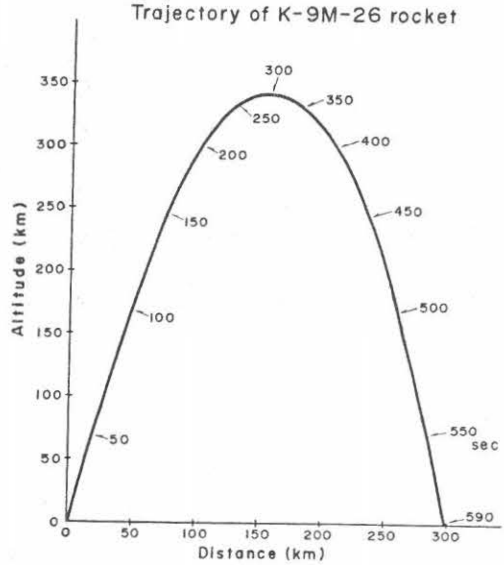

Fig. 1 Trajectory of the K-9M-26 rocket launched on Aug. 24, 1969. It reached maximum altitude of 347 km at 300 sec after firing.

3. 1. Short fractional-hop whistlers

After the extension of antennas, the radio waves which were originated from atmospherics on the ground and penetrated the ionosphere, i. e., short fractional-hop whistlers were obsereved in considerable intensity. The reason of detection of many short fractional-hop whistlers would be that the thunder-storm activity is generally high in summer season, and in fact its activity was greatly enhanced especially within

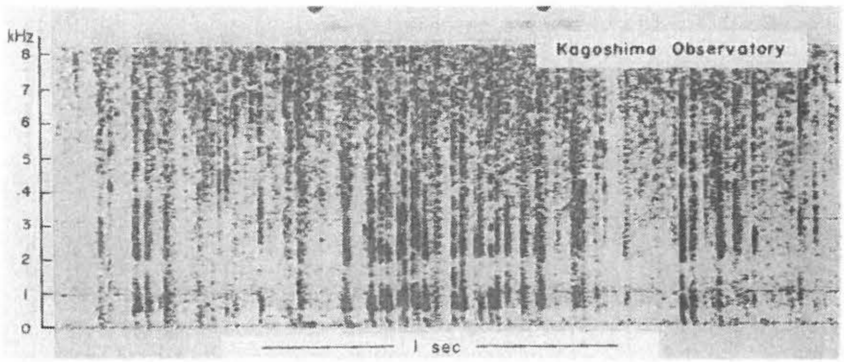

Fig. 2 Simultaneous observation at Kagoshima Observatory, Research Institute of Atmospherics.

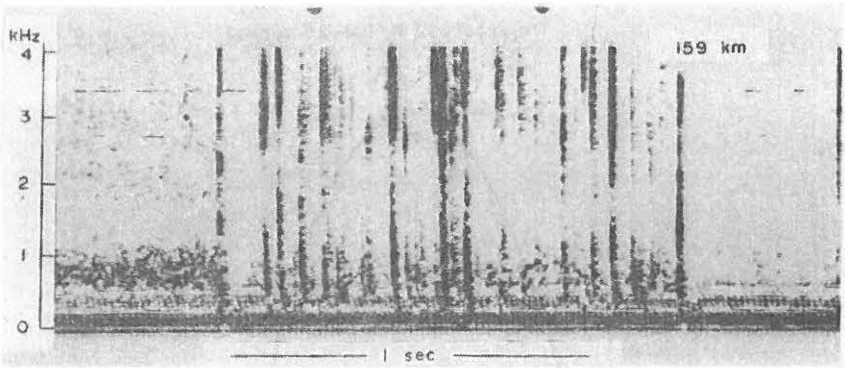

Fig. 3 Short fractional-hop whistlers observed at altitude 159 km.

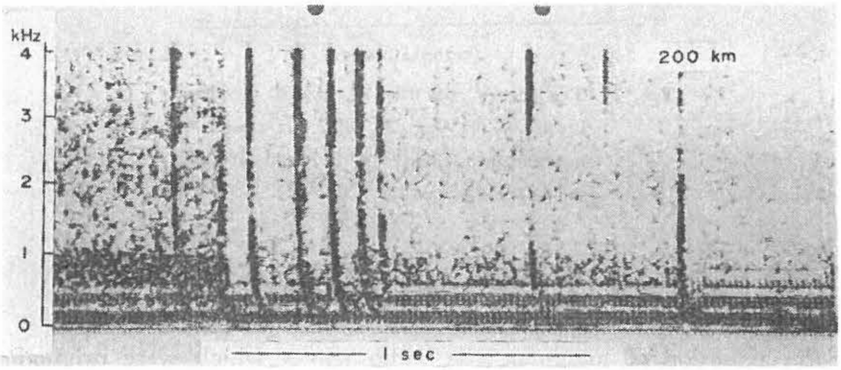

Fig. 4 Short fractional-hop whistlers observed at altitude 200 km.

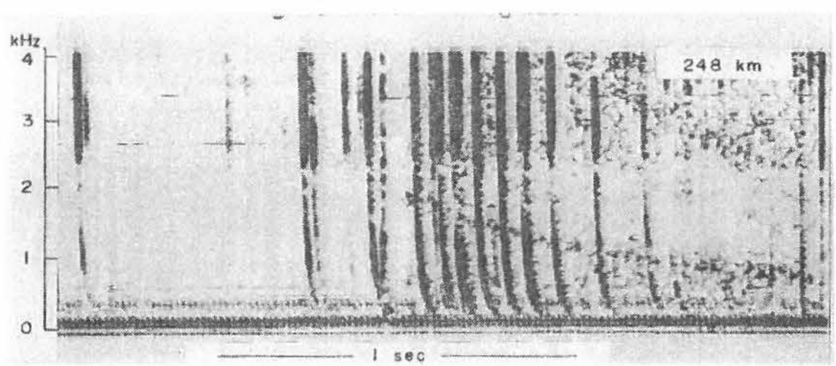

Fig. 5 Short fractional-hop whistlers and an ordinary whistler observed at altitude 248 km.

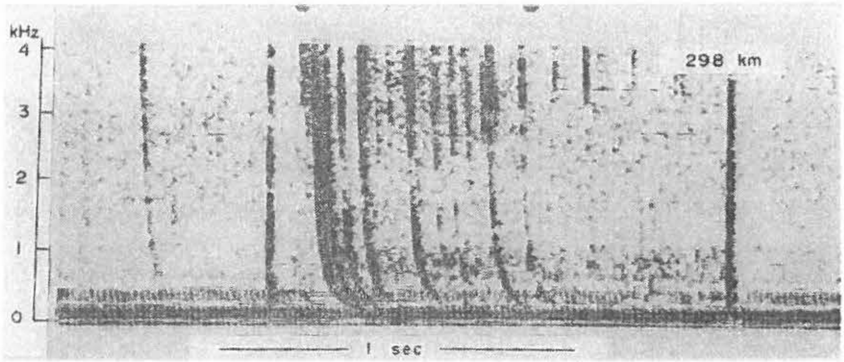

Fig. 6 Short fractional-hop whistlers observed at altitude 298 km, near the height of maximum electron density.

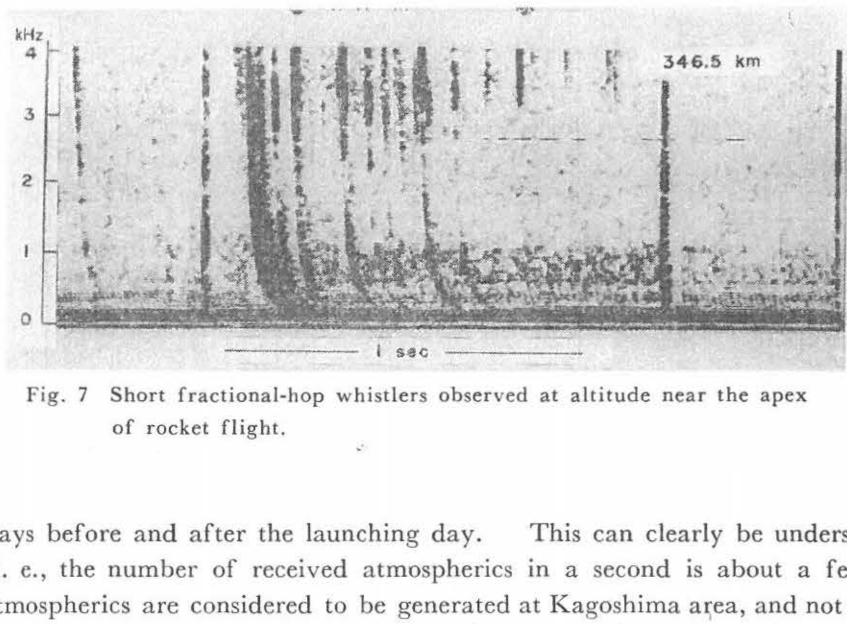

Fig. 7 Short fractional-hop whistlers observed at altitude near the apex of rocket flight.

a few days before and after the launching day. This can clearly be understood in Fig. 2, i. e., the number of received atmospherics in a second is about a few tens. These atmospherics are considered to be generated at Kagoshima area, and not to have propagated from great distances in earth-ionosphere waveguide, because the ionospheric absorption at launching time is considerably high. During the transmission through the ionosphere, the dispersion of short fractional-hop whistlers varies step by step, and this process is shown in Figs. 3-7. In Fig. 3 dispersive effect on short fractional-hop whistlers is not obvious, but this can be understood by the inspection of their low frequency trace. At altitudes 200 and 248 km in Figs. 4 and 5, the electron density is expected to be enhanced, so the dispersive effect is more distinctly in Fig. 5 seen than that in Fig. 4. Figs. 6 and 7 are sonagrams of short fractional-hop whistlers at altitudes 298 km, near the height of maximum density region, and 346 km, around the rocket apogee. It is found that the trace of higher frequency com-

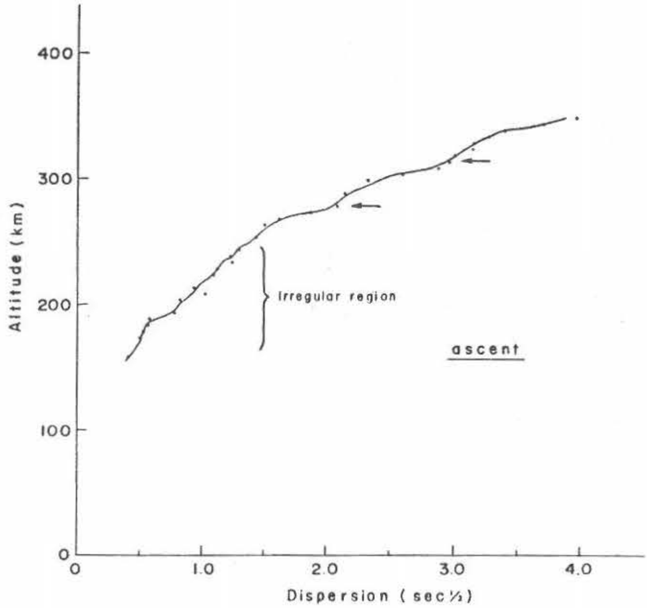

Fig. 8 a Altitude dependence of dispersion of short fractional-hop whistlers during ascending flight.

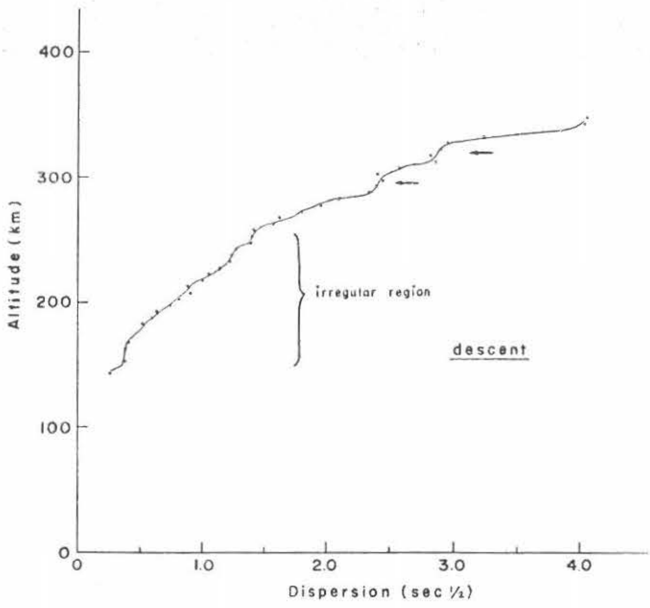

Fig. 8 b Altitude dependence of dispersion of short fractional-hop whistlers during descending flight.

ponents comes to incline and the lower end below 1 KHz is greatly dispersed. In order to estimate the altitude dependence of dispersion, the time scale was expanded by about 10 times using the suitable operation of taperecorder and sonagraph, and the dispersion was measured as the time difference between the two frequencies 2 and 11 KHz, where 2 KHz is chosen to avoid the ion effect on dispersion. Analysis was made by picking up section of the observed record, where are included at least a few short fractional-hop whistlers in a second. Figs. 8 a and b are the results on altitude depedence of dispersion for ascending and descending paths, respectively. Points in Figs. 8 are the averages in every 5 km interval, and curve is drawn using the local average over 10 km interval. Close inspection shows that there exist some sharp variations in dispersion gradient around the altitudes 290 and 310 km for both flying paths. Below the altitude 230 km, the fluctuation in dispersion is found not to be insignificant. In the height regions except those mentioned above, the curve is smoothly connected. Now the arrival time $t(f)$ of each component frequency of whistlers from the initial pulse is given as follows using group-ray refractive index (Storey, 1953).

$$t(f) = D \times f^{-1/2} \tag{1}$$

$$D = \frac{1}{2c} \int \frac{f_0}{\sqrt{f_H}} \left(\frac{\cos \alpha}{\sqrt{\cos \theta}} \right) ds \tag{2}$$

where ds is ray path element, f_0 and f_H, electron plasma, and cyclotron, frequencies respectively. θ and α are wave normal angle and ray angle with respect to the magnetic field. In deriving Eq. (2) the validity of the conditions $f \ll f_H$, $f^2/ff_H \gg 1$ and that

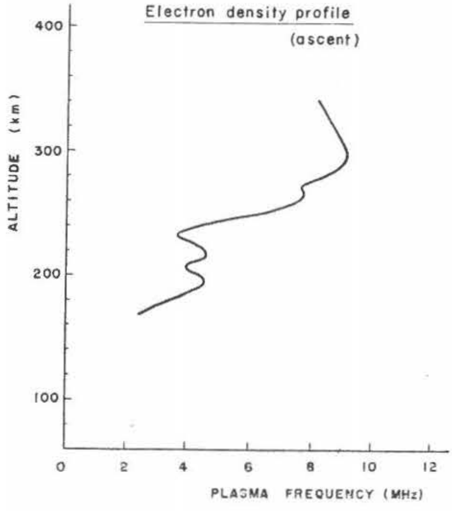

Fig. 9 a Electron density profile in the ascending path.

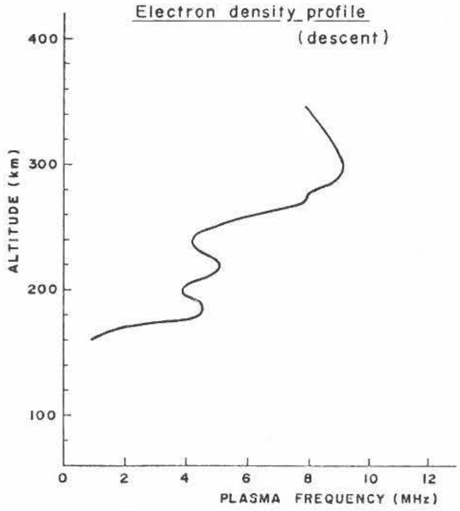

Fig. 9 b Electron density profile in the descending path.

of QL approximation in the height region in question was confirmed. As the refractive indices of whistler modes in the atmosphere and in the ionosphere are extremely different from each other, the wave normal direction of short fractional-hop whistlers in the ionosphere seems to be directed vertically upward, and so $\theta \simeq 45°$ at the launching site. For this θ value, the term in parenthesis can be approximated as unity.

However, as the ray paths are unknown, we consider that the ray direction is parallel to the magnetic field. Under this assumption, the electron density distribution using the dispersion variation, locally averaged over 30 km, was derived as shown in Figs. 9 a and b. Now the question we must notice is whether the sharp change

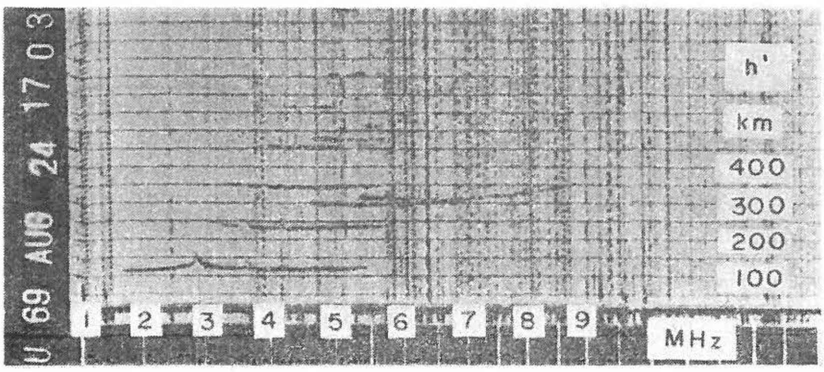

Fig. 10 The ionogram obtained at KSC during rocket flight.

in dispersion is due to the variety of whistler paths, or not. If the change is assumed to be due to the effect of various paths, it will be difficult to explain the smooth variation in other regions. So it will be appropriate to think that the variation in dispersion reflects the layer structure of the ionosphere. From Figs. 9a and b, the ionosphere below the region of altitude 230 km at this time is found to be consisted of two layers, and also the small valley extended over about 10 km around 290 km corresponds to the sharp change of dispersion gradient plotted with arrows in Figs. 8a and b. And electron density distributions for ascending and descending flights are different to some extent. Moreover the f_0 F2 evaluated from the ionogram at KSC shown in Fig. 10 agrees with our result. Finally the unsolved problem concerning short fractional-hop whistlers is the comparison between the height distribution of the observed intensity and that of the calculated field intensity in assuming a realistic model ionosphere, and this is under investigation.

3. 2. Ordinary whistlers

About 50 ordinary whistlers hopping in the magnetosphere were observed during the flight time. However, very intense short fractional-hop whistlers made an obstacle in the analysis of ordinary whistlers. The noticeable point is that we could not find the corresponding whistlers in simultaneous observations made at Kagoshima Observatory. Several sonagrams of the observed whistlers are shown in Figs. 11–16. In Fig. 11 a very diffused whistler with such large dispersion as 90 sec$^{1/2}$ was received at altitude of 180 km. A whistler illustrated in Fig. 13 is obtained near the maximum electron density region. Whistlers in Figs. 14–16 were detected during the rocket flight near apogee. Whistlers with dispersion 25, and 30 sec$^{1/2}$ respectively in Figs. 12 and 14 are estimated to be short whistlers from southern hemisphere of low thunder activity. Dependence of whistler dispersion on altitude is plotted in Fig. 17 for both flights. At a glance, the following facts can easily be derived. (1) Plots of

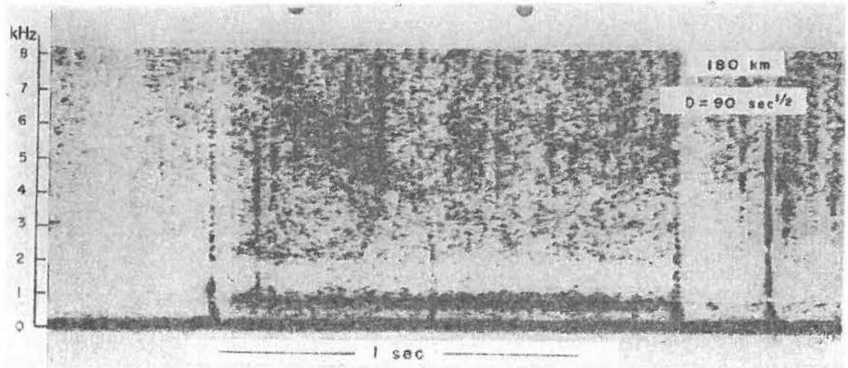

Fig. 11 A whistler with large dispersion observed at altitude of 180 km.

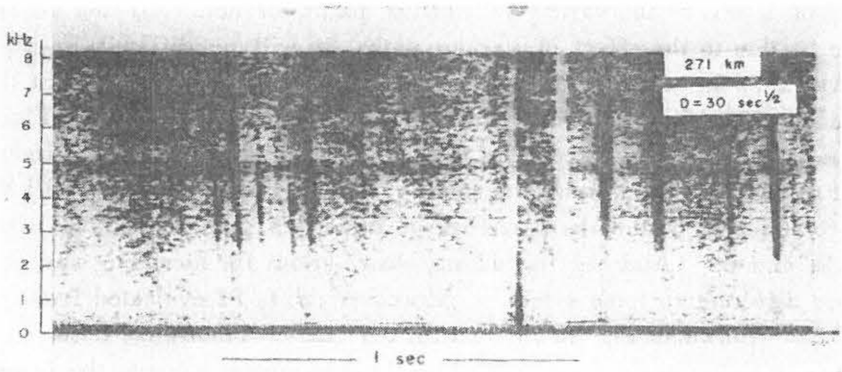

Fig. 12 A whistler observed at altitude of 271 km.

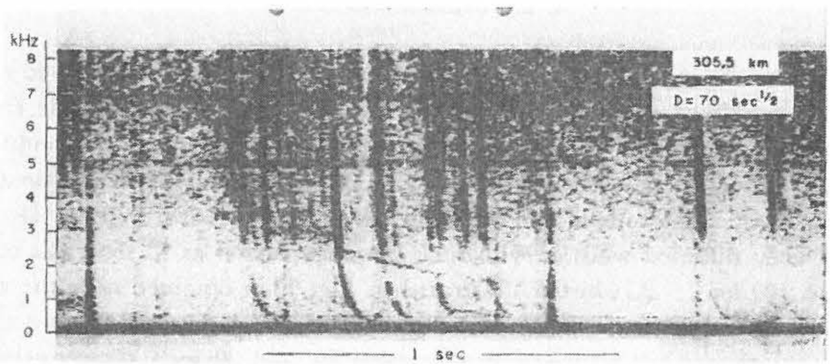

Fig. 13 A whistler observed around the altitude of maximum electron density.

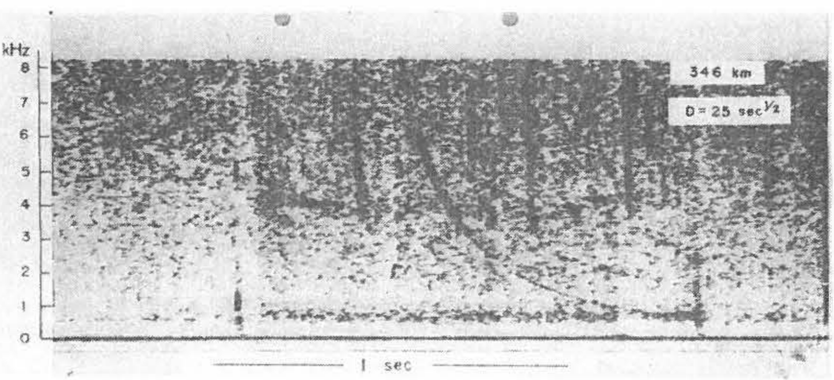

Fig. 14 A whistler observed during the flight near apogee.

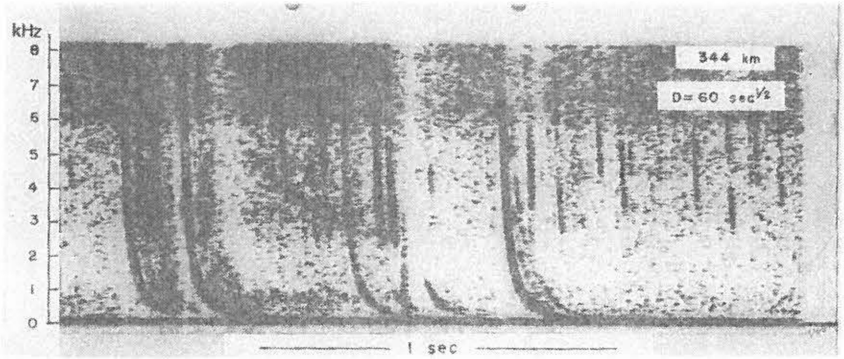

Fig. 15 A whistler observed during the flight near apogee.

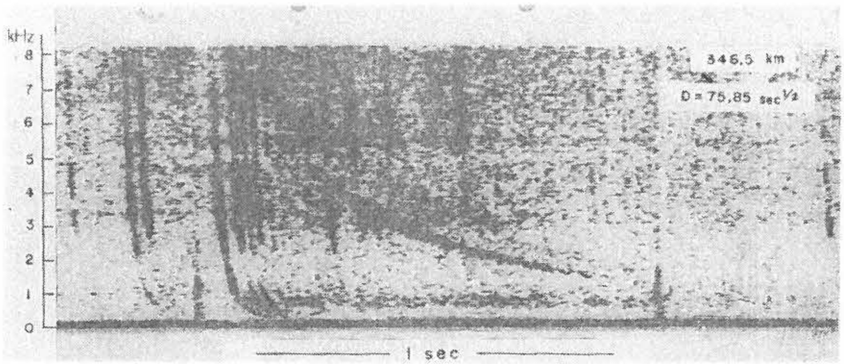

Fig. 16 A whistler observed during the flight near apogee.

dispersion are very scattered, especially the number of plots of larger dispersion is large. (2) Number of the observed whistlers is extremely concentrated above approximately 290 km. From the careful study of whistler sonagrams, another interesting feature is found, i. e., (3) Most whistlers show pure tone below about 300 km, while the number of pure and diffused whistlers is nearly equal above the altitude of 300 km. These facts are considered to be essentially important in low-latitude whistlers. Fact (1) is not understandable, if we assume the ray direction of whistlers being parallel to the magnetic field as in the case of ducted propagation. The reason is that if they are ducted, the distribution of dispersion must be fairly concentrated in a small region in dispersion, above the altitude of ~300 km, separated by an amount that corresponds to the two-hop paths in the magnetosphere, and echo train whistlers are expected to be observed for this propagation condition, which are the expectations now generally being proved to be correct. So this suggests that observed whistlers are to be attribute to non-ducted propagation. In order to examine the non-ducted propagation, we use ray tracing methods under the following plasma density distribution.

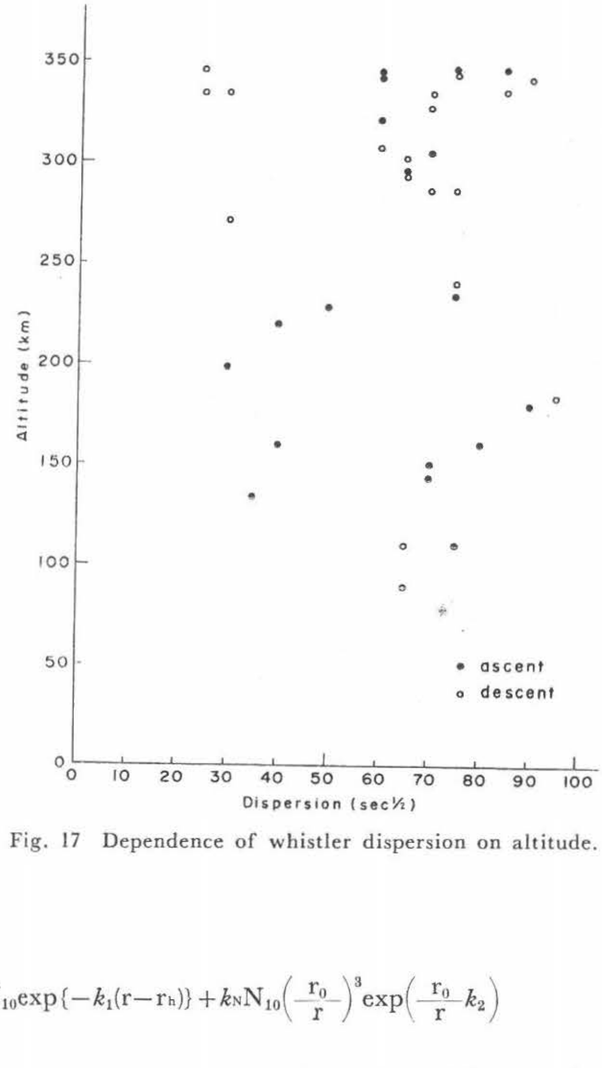

Fig. 17 Dependence of whistler dispersion on altitude.

$$N = N_{10}\exp\{-k_1(r-r_h)\} + k_N N_{10}\left(\frac{r_0}{r}\right)^3 \exp\left(\frac{r_0}{r}k_2\right) \qquad (3)$$

where $r_0=6370$ km, $r_h=6670$ km, $k_N=2.5\times10^{-3}$ and $k_2=3.0$. N_{10} is maximum electron density, approximately $10^6/cm^3$. These values are determined from dispersion value. In Eq. (3) electron density is taken to be the sum of densities of oxigen ions and protons. The first term represents the contribution from oxigen ions, and the second term that from protons. The first term decreases sharply with altitude, and plays an important role on low-latitude whistler propagation, so k_1 is taken as a parameter. Ray tracings were concerned with the region above 300 km, and the initial wave normal direction is assumed to be vertically upward. Fig. 18 is the numerical result on the relationship between the intial, and the final, latitudes, and shows the validity of polar creep propagation. From this figure, short whistlers observed at latitudes about 20° such as Kagoshima are found to be originated from atmospherics at latitude $\sim$10° in the opposite hemisphere. Then we must estimate the penetration conditions

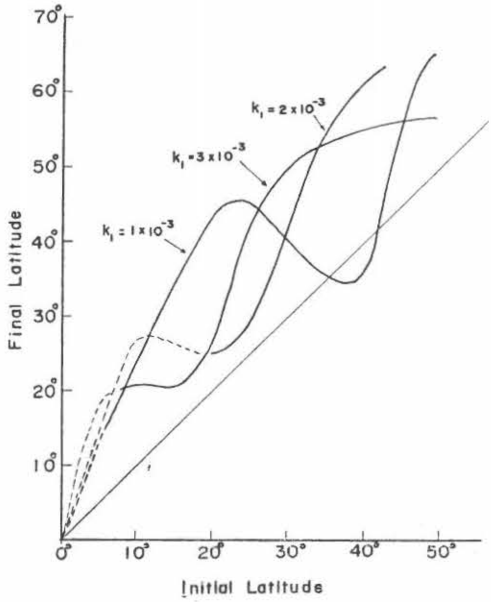

Fig. 18 Relationship between initial and final latitudes of whistlers with k_1 a parameter. f=4kHz.

at altitude of 300 km at final latitude. The calculated result is shown in Fig. 19 with k_1 a parameter, in which the final wave normal direction measured from vertical upward of one-hop whistlers at the final latitude is given. So when the final wave normal angle takes nearly 180°, whistlers can penetrate the maximum density region, while its deviation from 180° makes it difficult for whistlers to be transmitted to the ground, and the reflection of whistlers may occur.

The values $k_1=10^{-3}$, 3×10^{-3} correspond approximately to the conditions for daytime and nighttime, respectively. The larger value of k_1 leads to the shifting of final latitude to lower value, while the deviation of wave normal angle from 180° grows gradually as k_1 increases. These two effects have quite opposite influence to each other. Maeda and Oya (1963) made numerical calculations of energy penetration of VLF radio waves under the assumption of sharply bounded homogeneous ionosphere, and showed that only waves with wave normal lying in a narrow angle band ± 2° near the boundary normal can penetrate down to the ground. As the deviation angle from 180° in our result is found to be a few degrees, being around the boundary between penetration and reflection, considerable number of whistlers are reflected, and return to the same hemispere, then repeat echoing propagation. This result can explain the facts (1) and (2). Similar arguments on whistler echoes were made by Laaspere et al. (1965). And the scattered nature in Fig. 17 above

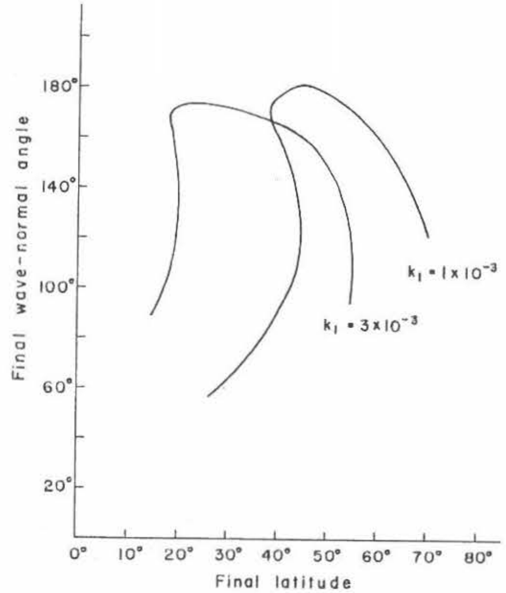

Fig. 19 Wave normal direction when reached at the final latitude with k_1 a parameter.

altitude of 300 km may be attributed to the difference of the initial wave normal direction after ionospheric reflection from the direction used in the computation, i. e., deformation of ray paths due to the change in initial wave normal direction. Also whistlers observed below 300 km have penetrated the maximum density layer because of favorable transmission condition, so that their energy are absorped at the lower collisional region. The diffused nature given in the fact (3) may partly be the effect of energy spread in reflection. In conclusion theoretical investigation on whistler penetration characteristics must be made for the more genaral case than was discussed by Hayakawa (1969).

4. Conclusion

A large number of short-fractional-hop whistlers and about 50 ordinary whistlers were detected with the VLF wide band observation on board the K-9M-26 rocket. Altitude dependence of dispersion of short fractional-hop whistlers yielded the electron density profile of the ionosphere, thus the layer structure of the ionosphere was deduced. Judging from the study of short fractional-hop whistlers, it is considerably easy for whistlers to penetrate into the ionosphere from free space even at law latitude such as 20°. As it is derived from the detailed numerical study on the height distribution of whistler dispersion, once the whistlers have emerged above the maximum density layer of the ionosphere, they cannot penetrate down to the ground due to hard transmission condition, and they echo back and forth between both hemispheres.

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