C-6-3

DUCTED AND NON-DUCTED PROPAGATION OF WHISTLERS AT LOW LATITUDES

Masashi HAYAKAWA and Masaki HASEGAWA
Research Institute of Atmospherics, Nagoya University,
Toyokawa, Aichi, 442, Japan

1. Introduction.

The diurnal variation of the occurrence rate of ground whistlers observed at low-latitude stations of Moshiri(geomag.lat.34.5°N;L=1.59), Sakushima (24°;L=1.39) ans Kagoshima(20°;L=1.22), consists of a sharp peak in the late afternoon(we call this 'daytime whistlers') and a broad maximum at night ('nighttime whistlers'). In their recent review paper, Hayakawa and Tanaka (1978) have suggested, mainly based on the simultaneous measurement of multi-station network(Hayakawa and Ohtsu, 1973) and the in-situ measurement of wave normal directions(Iwai et al., 1974; Hayakawa and Iwai, 1975), that daytime whistlers are likely to have propagated along the field-aligned ducts of enhanced ionization lying in the equatorial anomaly. On the other hand, less definite experimental evidence was obtained to determine the propagation of nighttime whistlers, but Hayakawa and Tanaka(1978) have speculated that the nighttime whistlers are also likely to be entrapped in ducts. Until we clarify whether the whistlers at low latitudes are attributed to the ducted propagation or not, further theoretical and experimental investigations are needed, the former of which is the object of this paper. We first study, by making use of the ray tracing computations, the conditions of trapping whistlers by ducts such as their structure supporting the trapped propagation and the ionospheric conditions. Then we study whether the characteristics of non-ducted propagation can be successful in interpreting the observed data.

2. Trapping conditions at low latitudes

The theory of trapping whistlers in the ducts has been proposed by Smith (1961) to explain the pure gliding tone of whistlers and the presence of echo-train and multiple whistlers. Indirect evidence of ducted propagation has been accumulated at high and middle latitudes(Helliwell, 1965, 1969), and recently convincing in-situ duct observations have been reported by Smith and Angerami(1968), Angerami(1970), and Scarf and Chappell(1973). Smith has estimated the minimum enhancement factor of ducts required for the trapping such that it decreases rapidly with geomagnetic latitude; from 100% at 17° to 10% at 47° and 1% at 77°, approximately. This is resulted from the decreasing the angle between the initial wave normal direction(assumed to be vertical) and the geomagnetic field with increasing latitude.. In his calculations there assumed to be no variation of the background density profile over the width of the duct.

We believe that the effect of any gradient of the background density profile on the duct trapping appears to be more serious at low latitudes rather than at high latitudes treated by Alexander(1971). The geomagnetic field is very inclined to the vertical at low latitudes, hence resulting in the more influential role of the background density profile on the trapping. Secondly the considerable portion of the ray paths of low-latitude whistlers lies in the region below the transition level(~1000km) where we expect a very sharp density gradient. So, the question arises whether the minimum enhancement factor deduced by Smith on the basis of the assumption of no variation of the background density over the width of the duct can be applied to the low-latitude problems.

2.1. Conditions of the duct trapping at low latitudes

Fig.1 illustrates the importance of any gradient of the background density profile on the duct trapping. The duct is assumed to be along the field line passing through the height of 300km at the geomagnetic latitude of 20°, and the figure indicates the cross sections of the profiles along the radial direction which intersects the centre of the column at 400 km. The duct width is varied. The model of the duct superimposed on the background profile of the diffusive equilibrium model, is given by (Yabroff, 1961),

$$1 + c\ \exp\left\{-\frac{(b-b_0)^2}{2\sigma^2}\right\} \quad --(1)$$

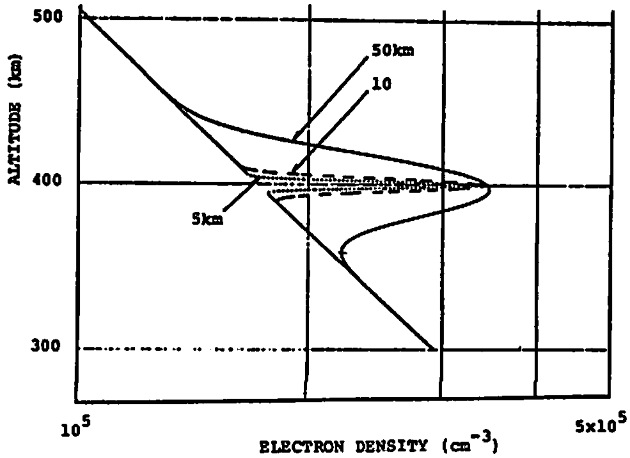

Fig.1

where C is the relative increase of the density at the centre of the column ($b=b_0$) over the background density, and σ is the standard deviation of the column. The figure suggests us an important fact, that is, the duct width is also a factor seriously controlling the trapping, being quite inconsistent with Smith's result in which the trapping can be specified by the fractional density enhancement alone. Thinner ducts having the width of less than 10km are apparently more effective for the trapping than those with the width of $\gtrsim$ 50km.

Provided that the ducts extend down to the F region of the ionosphere, we have found out the relationship between the minimum initial wave normal angle, δi, and the C value. Figs.2(a) and (b) refer to the cases of the width of 10km and 50km, respectively. At the latitude of 35°, corresponding to Moshiri station, the ducts with the C value of $\gtrsim$20% will be able to trap waves in the presence of some mechanism to bend the initial wave normal direction toward the magnetic field by about 20°. Two mechanisms seem to be probable; (1) the ionospheric horizontal gradient, and (2) the scattering by density irre-

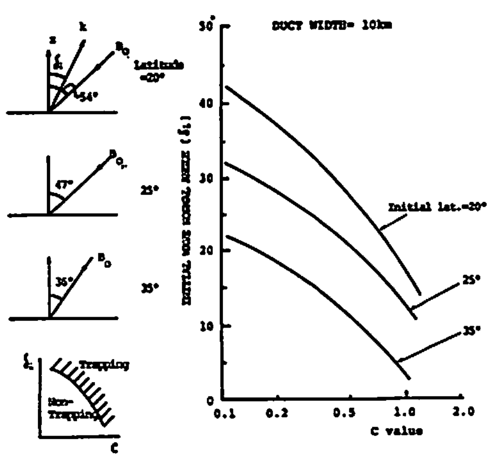

Fig.2(a)

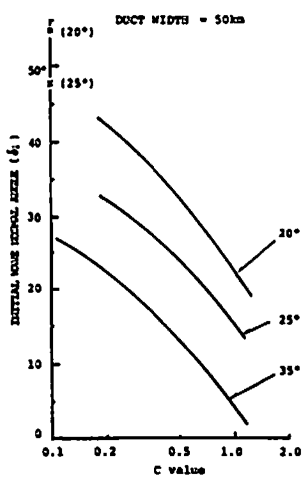

Fig.2(b)

gularities. The rocket measurement of wave normal directions has yielded that the scattering is not likely to be so operative at low latitudes(Iwai et al.,1974;Hayakawa and Iwai,1975). Hence we have to require the horizontal ionospheric gradient of $\gtrsim 20°$,but such a high gradient would not be expected. When the C value is increased to $\gtrsim 50\%$,the minimum δ_i value decreases to $\lesssim 10°$, which would be really observable by the satellites(Aubry,1967;James,1972). Especially the duct having the C value of 100% is found to trap waves with only a very small horizontal ionospheric gradient.

While at much lower latitudes of 25° and 20°,correspondong to Sakushima and Kagoshima observatories,the horizontal ionospheric gradient of > 20° is necessary for the trapping in ducts with the C value less than 50%. However, in the case of C=1.0(or 100%) the minimum δ_i value will be about 15°,possibly realized by the joint influence of the ionospheric gradient and the scattering. One more important point to notice is that the desirable ducts should be additionally "very thin of the order of less than 10km". We expect an extremely small ionospheric gradients for the C values larger than 100%.

Sharply defined high enhancements supporting the duct propagation of low-latitude whistlers predicted by the present paper have some support from the high resolution in-situ density measurements(McClure et al.,1977). McClure et al. have found large amplitude small scale irregularities at night in the equatorial and low latitudes,whose ion concentration changes by up to nearly a factor of 2 over a latitudinal range of less than 5km. While, the equatorial anomaly is known to be well established around sunset,having the enhancement factor in excess of 10(1000%) and the latitudinal extent of more than 10°(Eccles and King,1969), and hence it is quite reasonable to speculate that there exists,in the equatorial anomaly,such large amplitude small scale irregularities as predicted by the present study.

3.Non-ducted propagation

It is known that there exists the equatorial anomaly with a high density modulation and with a large latitudinal extent during the daytime at low latitudes(Eccles and King,1969), and Hayakawa and Tanaka(1978) have pointed out its important influence on the propagation of daytime whistlers. In the following ray tracings the centre of the anomaly is assumed to be along the field line passing through the height of 300km at the geomagnetic latitude of 20°. The modulation factor factor is taken as 5.0(500%) and the widths of the inner and outer edges of the anomaly are assumed to be 1500 and 4000km,respectively. Also,the modulation factor is a function of altitude such that it decreases with height. This is likely to be a very satisfactory model for the actually observed equatorial anomaly. We have made the computations of non-ducted whistler ray paths in the magnetospheric plasma including the effect of the anomaly and the initial wave normal direction is taken as vertical. One of the most important results is the finding of the "whispering gallery type" guiding along the anomaly, which may be relevant to

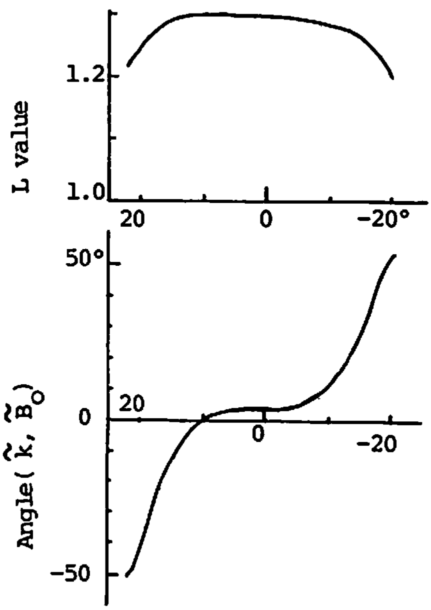

Fig.3

the daytime whistlers. Fig.3 illustrates the variations of the L value and the wave normal direction of the ray starting at 22°. It is seen from the figure that the ray path is restricted within a small range in L value, and also the angle between the wave normal direction and the geomagnetic field decreases with decreasing latitude in the input hemisphere,and it is nearly zero around the equator,followed by the increase of the inward directed wave normal angle with increasing latitude. The final wave normal is found to be nearly downward directed,enabling the wave to be transmitted onto the ground. This propagation mode is identified to be possible over a limited range in latitude, 20° to 22°. This kind of guiding,although non-ducted, is another possibility of the interpretation of the sharp enhancement of daytime whistlers in terms of non-ducted propagation.

4.Comparison between the theoretical predictions and the experiments of direction finding

In order to interprete the ground-based whistler data,or to obtain the definite evidence of the propagation mode,we have to carry out the extensive comparisons between the theoretical predictions as those made in the present paper and the experiments,especially,of the direction findings to locate the exit points of whistlers from the ionosphere(Hayakawa et al., 1978;Okada and Iwai,1978). The study in this direction is being done by our group. The results are under preparation.

References

1) Alexander,P.D.(1971). Computations of ray paths for very low frequency waves propagating through the magnetospheric plasma. Ph.D.Thesis, Univ.of Southampton,U.K.
2) Angerami,J.J.(1970). J.Geophys.Res., 75, 6115.
3) Aubry,M.P.(1967). Ann.Geophys., 23, 467.
4) Eccles,D. and King,J.W.(1969). Proc.IEEE, 57, 1012.
5) Hayakawa,M. and Ohtsu,J.(1973). J.Atmos.Terr.Phys. 35, 1685.
6) Hayakawa,M. and Iwai,A.(1975). J.Atmos.Terr.Phys. 37, 1211.
7) Hayakawa,M. and Tanaka,Y.(1978). Rev.Geophys.Space Phys. in press,May.
8) Hayakawa,M.,Tanaka,Y.,Okada,T. and Iwai,A.(1978). To be presented at URSI Helsinki meeting.
9) Helliwell,R.A.(1965). Whistlers and related ionospheric phenomena,Stanford Univ.Press, Stanford,Calif.
10) Helliwell,R.A.(1969). Rev.Geophys.Space Phys. 7,281.
11) Iwai,A.,Okada,T. and Hayakawa,M.(1974). J.Geophys.Res., 79,3870.
12) James,H.G.(1972). Ann.Geophys., 28, 3ol.
13) McClure,J.P.,Hanson,W.B. and Hoffman,J.H.(1977). J.Geophys.Res.,78, 7431.
14) Okada,T. and Iwai,A.(1978). To be presented at URSI Helsinki meeting.
15) Scarf,F.L. and Chappell,C.R.(1973). J.Geophys.Res., 78, 597.
16) Smith,R.L.(1961). J.Geophys.Res., 66, 3699.
17) Smith,R.L. and Angerami,J.J.(1968). J.Geophys.Res., 73, 1.