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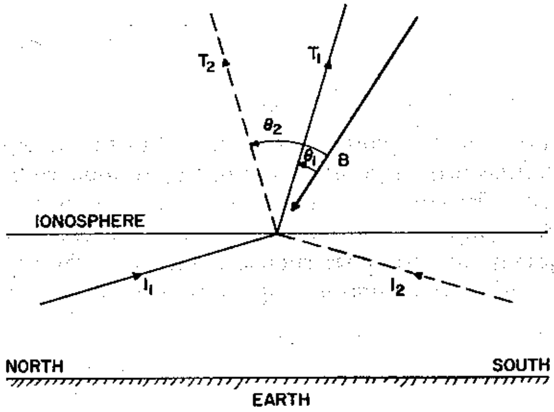

*Fig.* 2. *Transmitted wave normals in the magnetic meridian.*

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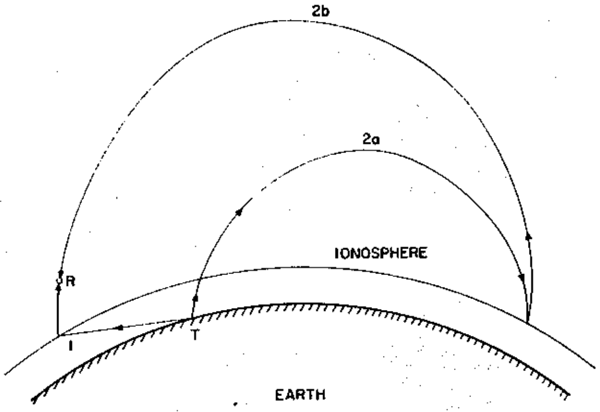

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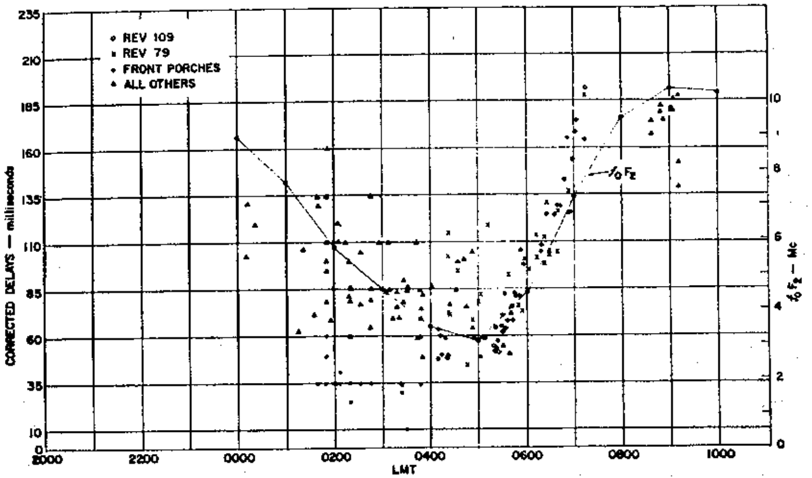

*Fig.* 4. *Group delay and* $f_0F_2$ *vs. LMT.*

Measurements of the Doppler frequency shift of these signals show a scatter of a few cycles per second with zero mean until about local sunrise. At this time the average frequency suddenly decreases by as much as 7 c/s, where it remains until signals are lost. The observed frequency shift is consistent with the value predicted from the rate of change of group delay using the quasi-longitudinal approximation of the magnetoionic theory.

Strong two-hop whistler mode signals were frequently observed in the northern hemisphere (Fig. 5). The two ray paths which are postulated to explain the signals are shown in Fig. 3. From Figs. 2 and 3 it is seen

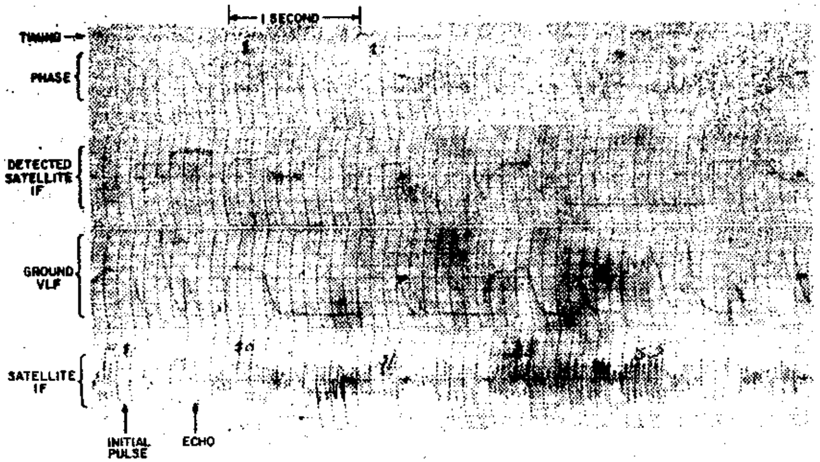

*Fig. 5. Echoes on revolution* 513.

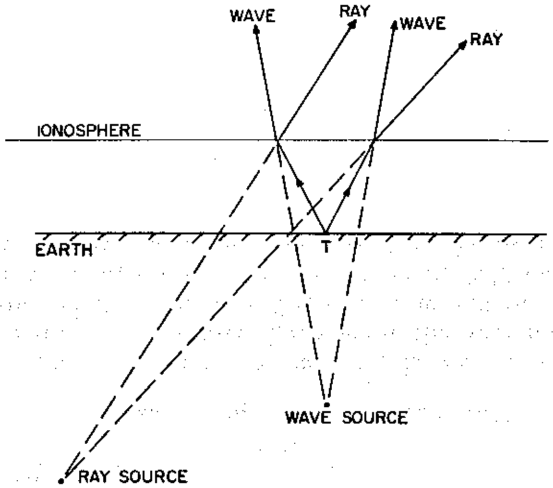

*Fig. 6. Beaming of rays.*

that the direct signal penetrates the ionosphere with an unfavourable wave-normal angle (see the previous section), and therefore suffers relatively more attenuation. To explain the relatively high strength of the echo, it is necessary to postulate that the first segment of the two-hop path begins close by but to the south of the transmitter. Furthermore, as indicated in Fig. 6, the high refractive index and the strong anisotropy of the ionosphere in the whistler mode combine to restrict markedly the divergence of the rays. Using a reasonable model of the ionosphere, the calculated group delay is in good agreement with that measured.

## CONCLUSIONS

(1) The LOFTI–I data clearly show that ducts of enhanced ionization are not required for the propagation of whistler-mode signals to a satellite.

(2) The differential attenuation measurement demonstrates the pronounced effect of the tilt of the earth's magnetic field on attenuation rate. The results are qualitatively in agreement with the predictions of magnetoionic theory. Note that little or no effect would be expected with either a vertical or a horizontal magnetic field.

(3) Two-hop whistler mode propagation to a satellite yields signals that are often comparable in amplitude to the direct signal. The echo strength may even, on occasion, exceed the direct signal in amplitude.

(4) Analysis of the group delay data shows that a scale factor on electron distribution can be obtained from this type of experiment.

## REFERENCES

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## CHAPTER 7

# AN INTERPRETATION OF LOFTI–I V.L.F. OBSERVATIONS*

Louis H. Rorden,†
R. L. Smith and R. A. Helliwell‡

*During February and March of* 1961, *the Naval Research Laboratory LOFTI–I satellite received very low frequency signals transmitted into the ionosphere from U.S. Navy stations NBA in the Canal Zone and NPG in Jim Creek, Washington. The signals were sometimes observed to have been delayed by as much as* 600 *milliseconds.*

*It was possible to deduce the thickness (scale height) of the ionosphere above the height of maximum electron density. The values correspond roughly to those previously found from rocket measurements.*

*Simultaneous daytime reception of both NPG and NBA showed an interesting difference in attenuation of the signal strengths such that the signal from NBA was more heavily attenuated. The difference can be explained by taking into account the tilt of the earth's magnetic field and the arrival of the NBA signal from the south and the NPG signal from the north.*

*In general, the whistler mode signals observed in LOFTI–I show no evidence of having been trapped in columns of enhanced ionization. This is in contrast to the characteristics of naturally occurring whistlers observed on the ground, which are best explained by assuming that they have been trapped in such columns. The difference may be explained by noting that whistler energy not trapped in columns of enhanced ionization is not observed on the ground, presumably as a result of total internal reflection at the lower boundary of the ionosphere.*

## INTRODUCTION

During February and March 1961, the Naval Research Laboratory satellite LOFTI–I received very low frequency (v.l.f.) signals transmitted into the ionosphere from U.S. Navy stations NBA in the Canal Zone and NPG in Jim Creek, Washington.[1] These signals were received in the satellite with a small loop antenna and narrow band receiver (25 cycle bandwidth). Signals were strong at night and generally weak during the daytime, but were observed over every region of the satellite orbit within the range of telemetry recording stations.

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NBA signals were observed out to a ground range of over 16,000 km from the transmitter. Signals were observed to fade randomly and to show group delays ranging from a few milliseconds to as high as 600 msec. The longer delays were attributed to echoes, which were observed in a region centred to the north of NBA. Random Doppler shifts of a few cycles per second were observed consistently. On some occasions, the average Doppler shift was as high as 7 c/s.

## PATHS OF PROPAGATION

Analysis of ground-based whistler observations strongly suggests that the signals are trapped in ducts of enhanced ionization aligned with the earth's magnetic field. This hypothesis has been advanced to explain the multipath character of whistlers, the similarity of different whistlers within an hour or so, and the integrally related time intervals of echoing components.

Very low frequency signals were observed over a wide area at the satellite. These signals, moreover, were often observed continuously over distances greater than the average spacing between the postulated ducts (estimated from the ground-based results). No evidence of ducted propagation was found. On the other hand, evidence was found that propagation—under certain conditions at least—takes place along paths not aligned with the earth's magnetic field. A consistent interpretation of the data was made without requiring the ducts. Even if the satellite had been in a whistler duct, any characteristic changes in wave-normal direction and field intensity might well have gone undetected.

One explanation for the difference in the interpretation of whistler characteristics and the LOFTI results appears to be that whistler energy trapped in ducts is readily transmitted across the lower boundary of the ionosphere, whereas the energy not so trapped suffers total internal reflection at the boundary. The non-ducted mode is nevertheless guided to a large extent by the earth's magnetic field as discussed by Storey,[2] and by Yabroff.[3]

## DIFFERENTIAL ATTENUATION

An interesting result was the simultaneous observation of signals from stations NPG and NBA in a region generally north of NBA and south-east of NPG. The cumulative amplitude distributions of the two signals for both day and night are shown in Fig. 1. In the daytime, the signals from NPG were consistently stronger than those from NBA, even thought the satellite was near a ground receiver at which the field strengths from these two stations were about the same. Under night-time conditions, on the other hand, the intensities of NBA and NPG signals were about the same at the satellite.

The greatest attentuation of the v.l.f. signals in the daytime occurs in the $D$-region, where the refractive index is relatively low (about 2·5). The angle of wave-normal refraction with respect to the magnetic field will be much larger for signals propagating from south to north than from north to south for medium latitudes in the northern hemisphere. Figure 2 shows the general nature of the wave-normals for the two cases. It is to be expected that the attenuation of v.l.f. waves will increase markedly as the angle between the wave normal and the earth's field is increased, and hence the difference in attenuation is qualitatively explained. Attenuation calculations were made for a slab model of the lower ionosphere ($f_0 = 285$ kc/s, $f_H = 100$ kc/s, $\nu = 2 \times 10^6$/sec, tilt of magnetic field = 45 angles), including the effects of the inhomogeneous wave structure.[4] The results give an attenuation rate of 1·6 dB/km for NPG and 3·0 dB/km for NBA. The measured difference is about 10 dB, which corresponds to an effective absorbing path length of 7 km, assuming a constant value of differential absorption as computed above. Since the effective thickness of the absorbing region—based on total absorption—is closer to 25 km, it appears that the calculated differential absorption is not actually realized.

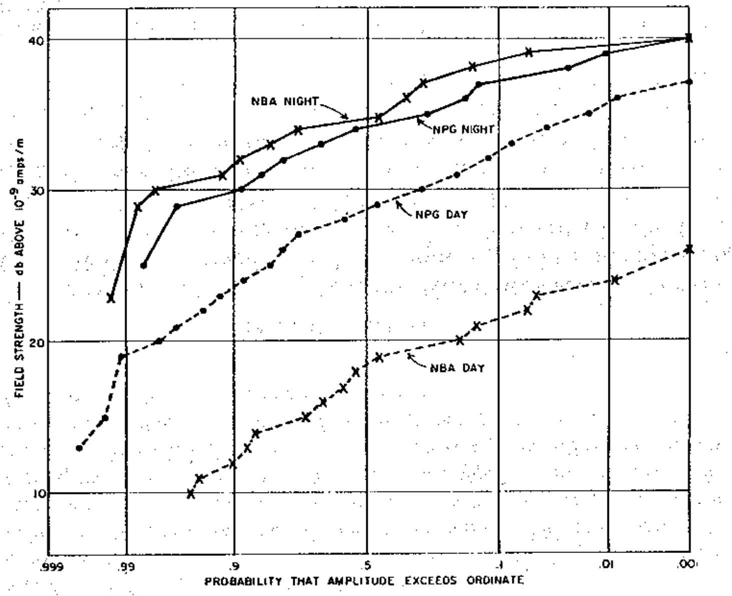
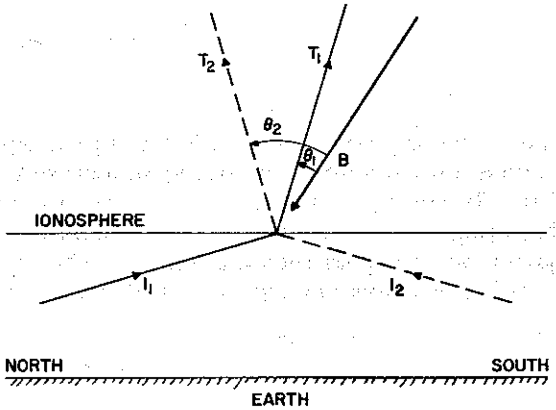


*Fig. 1. Differential attenuation.*

One possible source of this discrepancy is the assumed value of refractive index at the altitude of maximum absorption, which could be in error because of inaccurate knowledge of the parameters of the $D$-region. In addition, the variation of refractive index with altitude, which is large in the $D$-region, has been neglected for the purpose of calculation. It is possible that a full-wave analysis or a short-interval ray tracing approach would give significantly different results.



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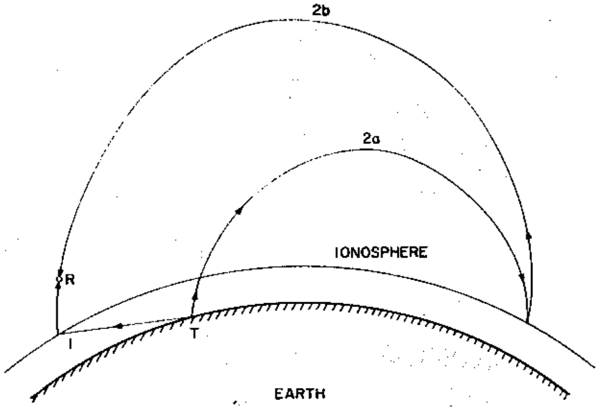

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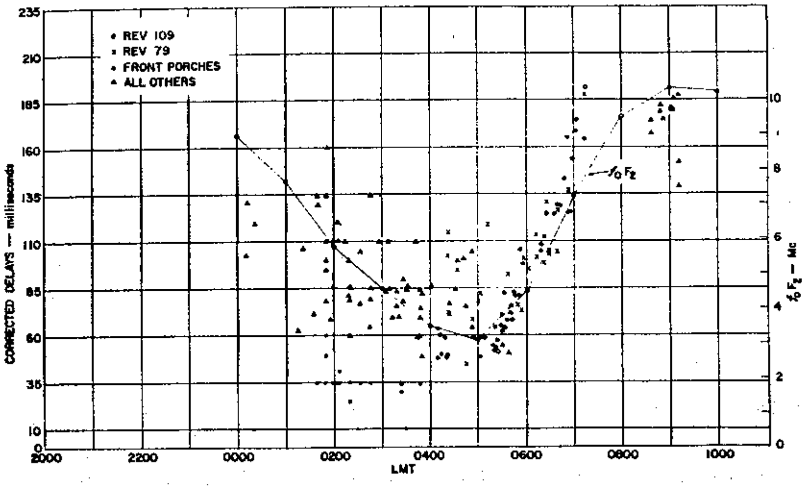

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Measurements of the Doppler frequency shift of these signals show a scatter of a few cycles per second with zero mean until about local sunrise. At this time the average frequency suddenly decreases by as much as 7 c/s, where it remains until signals are lost. The observed frequency shift is consistent with the value predicted from the rate of change of group delay using the quasi-longitudinal approximation of the magnetoionic theory.

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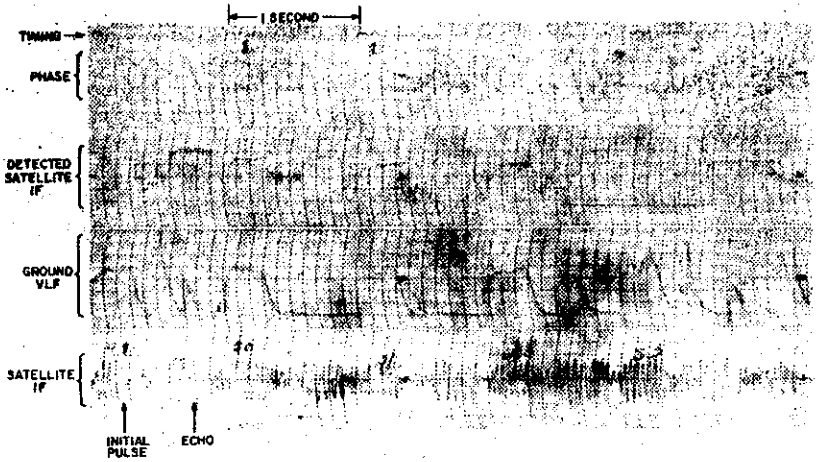

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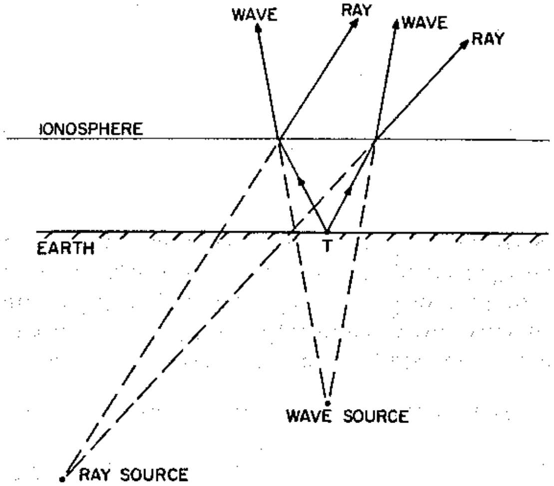

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