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Journal of Atmospheric and Terrestrial Physics, Vol. 48, No. 2, pp. 171–179, 1986.
Printed in Great Britain.

0021–9169/86 $3.00 + .00

The third hop whistler anomaly: possible evidence of d*f*/d*t*-dependent wave amplification

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(*Received in final form* 17 *June* 1985)

Abstract—On occasion the third hop of an echoing magnetospheric whistler exceeds the first hop in intensity over some low range of frequencies. Case studies show that this anomalous behavior can occur over periods ranging from tens of minutes to hours in duration. Most of the five cases studied involved coupling of waves from one ducted magnetospheric path to another (at the point of ionospheric reflection) rather than repeated propagation on the same path. The coupling tended to be from lower to higher latitudes. In two of the five cases, it occurred from paths inside the plasmapause to paths outside. The anomaly is interpreted as the result of d*f*/d*t*-dependent amplification of weak whistler signals by a gyroresonant wave–particle interaction in the magnetosphere. This amplification is facilitated by interpath coupling. Through this process the waves are either able to retain a degree of coherence not achieved by other signals in the same whistler and/or are coupled into a region of relatively large interacting particle fluxes. The anomaly appears to provide a way of looking with some degree of isolation at the factors of spectral purity, d*f*/d*t*, and magnetospheric location (with respect to particle activity) that may affect the amplitication of much larger classes of whistlers.

1. INTRODUCTION

Multi-hop or echoing magnetospheric whistlers observed at a ground station usually exhibit a decrease in peak intensity with increasing hop number. Figure 1a shows such a case; a frequency–time record (lower panel) of a one-hop whistler and echoes recorded at Siple Station, Antarctica ($L \sim 4.3$), is presented beneath a record of amplitude within a narrow band centered at 2.5 kHz. Detailed study shows that the echoing occurred on a path or paths represented by the later part of the one-hop whistler (indicated by arrows). In this case the peak intensity decreased by about 5 dB between the first and seventh hops (first and fourth appearances at Siple). Events of this type sometimes exhibit a damping decrement so small that echoes are observed over periods of many minutes (e.g. HELLIWELL, 1965).

On occasion, the amplitude of a whistler observed in the hemisphere opposite to the source, i.e. a one-hop whistler, shows a maximum strength on the third hop instead of the first. An example of this third-hop anomaly was shown by HELLIWELL (1965), who reported that on rare occasions the first hop of a whistler could be relatively weak or entirely absent over a range of frequencies in which an echo of the whistler is relatively strong. Figure 1b shows such an example from Siple in a format similar to that of Fig. 1a. The first-hop of the whistler exhibits two components, the first and weaker of which is defined at the 2.5 kHz frequency of the amplitude record. The third hop peak intensity is greater than 10 dB above this first hop level, while the fifth hop is down ~ 15 dB with respect to the third.

SMITH and CARPENTER (1982), in discussing the coupling of echoing whistler waves from one magnetospheric path or duct to another at ionospheric heights, reported a case of coupling from inside to outside the plasmapause. The result was the arrival of a third hop whistler component on a path along which no first hop propagation was observed.

Our purpose in this note is to describe major features of the third hop anomaly as determined from several case studies of data from the conjugate stations Siple, Antarctica, and Roberval, Quebec ($L \sim 4.3$), and from Halley, Antarctica ($L \sim 4.2$). The importance of the third hop anomaly is suggested by the fact that it may occur for many hours at a time and by indications that it occurs as the result of wave amplification near the plasmapause.

2. OBSERVATIONS

In the case studies, standard whistler techniques were used to obtain information on whistler occurrence times, on magnetospheric path radius, on equatorial electron density, and on the travel-time relations among the various components observed. The findings, in summary, are as follows.

1. The anomaly was observed over periods ranging from tens of minutes to seven hours in duration. Although we have not derived quantitative occurrence statistics, we roughly estimate that examples could be found on at least 5–10% of the observing days at Siple, Antarctica.

2. Most events involved coupling from path to path at the point of ionospheric reflection rather than repeated propagation on the same path. The coupling tended to be from lower to higher latitudes. In two of the five cases, it occurred from paths inside the plasmapause to paths outside.

3. In four cases the final, third hop, path was in the immediate vicinity of the plasmapause, which was near $L = 4$. In two of these cases the path was just outside the plasmapause at plasmatrough density levels. In the third case the path was in the region of steep density gradients, while in the fourth it was within the plasmasphere but at $\Delta L < 0.5$ from the boundary. In the fifth case the third hop path was in the outer plasmasphere at $L \sim 4.8$ and the occasion was characterized by propagation of banded hiss and chorus, periodic emissions, and low-decrement whistler echoing.

4. In three of the five cases, a greater intensity was observed, over some low range of frequencies, in the anomalous third hop, than in any of the first hop components of the whistler. In the other two cases the first hop path followed by the waves contributing to the anomaly was strongly excited in the frequency range of the anomaly, but first hop propagation was not observed on the path to which these waves were later coupled and on which they arrived as an anomalous third hop.

Examples

Anomalous whistlers similar to the event of Fig. 1b were recorded at Siple at various times over an approximately 7 h period on 14 January 1981. The whistler travel-time measurements indicated that the first three hops of the waves contributing to the anomaly were restricted to a narrow L range within the region of plasmapause density gradients and propagated at an equatorial density level that was a factor of ~ 2 lower than the nearby plasmasphere level. While the third hop trace varied only slightly, the one-hop traces that could be observed varied widely from whistler to whistler and fluctuated widely in detail with time. None of these one-hop components could be identified as representing the first hop of the waves that eventually appeared as anomalous.

Figure 2 shows events recorded at Halley on 25 June 1982. For this period another study showed the plasmapause to be at $L \leqslant 3.7$ (Smith *et al.*, 1985). Two examples are presented to demonstrate the repeatability of details. Analysis showed that the anomalous third hop, marked A_3 where it crossed the line at 3.79 kHz on the upper spectrogram, was the result of propagation twice over a path inside the plasmasphere and once on a path outside. (The lines and ramps on the spectra represent subionospheric signals from the Siple VLF transmitter.)

Also indicated in Fig. 2 are a 'normal' one-hop 'knee-whistler' component K_1 and its third hop echo K_3. These components propagated at $L \sim 4$ outside the plasmapause on the path on which the anomalous trace is inferred to have arrived. A weak one-hop signal on a path within the plasmasphere is marked B below the second panel. The anomalous trace arriving as A_3 is inferred to have followed the B path on its first two propagation hops.

The trace immediately before K_3 in Fig. 2b is not interpretable as a combination of observed one-hop delays. However, its arrival time is consistent with coupling from within the plasmasphere onto a path outside.

In this and three other cases, the identification of the path on which the third hop trace arrived was supported by echo-period analysis. For example, in Fig. 2 the echoes A_5 (fifth hop) and A_7 exhibited arrival times consistent with repeated propagation of A_3 waves on the K path.

In a third case, from 3 June 1978, coupling from inside the plasmasphere to outside was reported by Smith and Carpenter (1982), but components outside the plasmapause corresponding to K_1 and K_3 in Fig. 2 were not observed, while normal plasmasphere traces corresponding to B were well defined.

A fourth case, from Siple on 20 August 1982, is illustrated in Fig. 3. In this case the anomaly appeared to evolve in time. Figure 3a shows an event near 0840 UT in which the third hop component does not appear unusual in terms of relative intensity. However, by 1130 UT the anomaly was relatively well defined, as the next two panels indicate. Analysis showed that the third hop trace resulted from propagation twice over a path at $L \sim 2.6$, marked X on panel (b), and

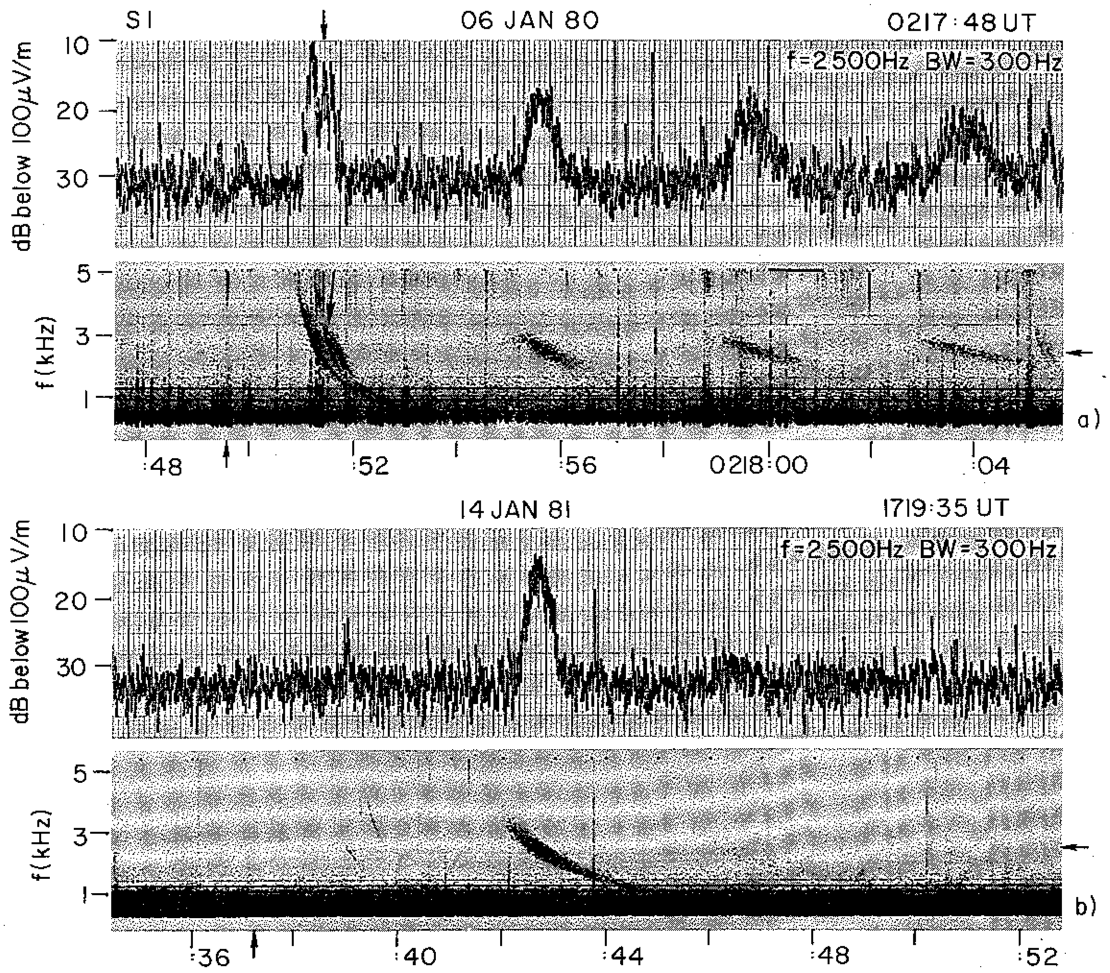

Fig. 1. Whistler records from Siple, Antarctica, showing an example of a normal whistler event with echoes (a), and an event with anomalously high amplitude following the third hop of propagation (b). The upper panels of (a) and (b) show amplitude in a narrow band centered at 2500 Hz; the lower panels of (a) and (b) are frequency–time spectrograms.

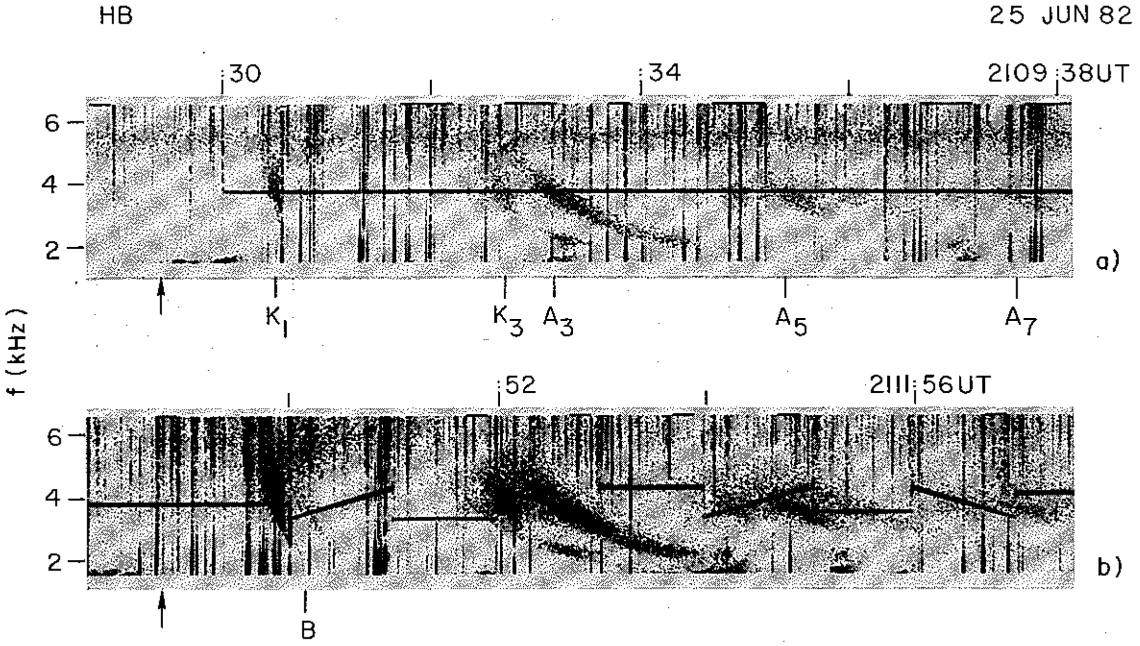

Fig. 2. Whistler records from Halley, Antarctica, showing two anomalous cases in which wave energy coupled from inside the plasmapause to outside. The lines near 4 kHz represent subionospheric signals from the Siple transmitter. See text for further details.

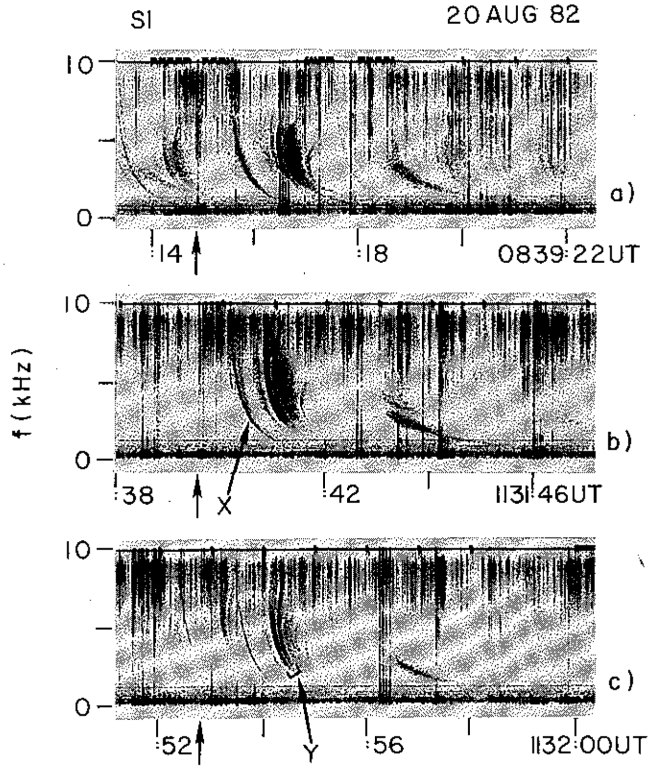

Fig. 3. Spectrograms of Siple whistlers showing an apparently normal event (a), followed 3 h later by events with anomalous third hop intensities (b and c). See text for details.

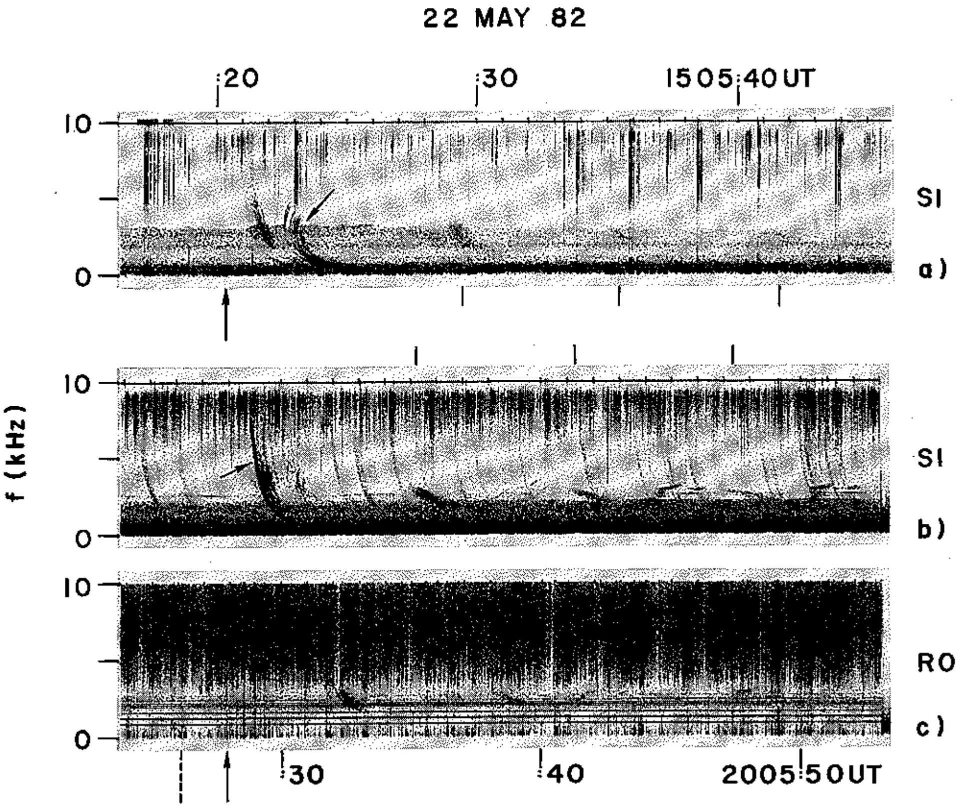

Fig. 4. Spectrograms showing a normal Siple whistler with echoes (a), followed 5 h later by an event with anomalous third hop intensity. Panels (b) and (c) show, respectively, the Siple and Roberval records of the anomalous case. On the Siple record there are numerous weak one-hop whistlers in the background. The echoes of the principal whistler appear to trigger a rising emission which then exhibits dispersion on successive appearances. The Roberval recording was filtered below 2 kHz.

once over one or both of the paths at $L = 3.7$–3.9 marked Y on panel (c). At Roberval, only a weak component corresponding to propagation twice on path X was observed for the whistler in Fig. 3b. All of the paths were within the plasmasphere.

The fifth case, from 22 May 1982, provides another example of coupling between well separated paths. Figure 4a shows a 'normal' Siple whistler recorded at 1505 UT. Several echoes followed the first hop components in the usual way. The first hop component contributing most strongly to the echoing is shown by an arrow on the spectrogram. The time of origin of the whistler is indicated below the record by an arrow, while the approximate times of observation of the echoes at ~2.5 kHz are indicated by tick marks.

The anomaly then developed, as shown in panels (b) and (c) below the Siple and Roberval records from 2005 UT, 5 h later. The time of origin of the whistler of interest is marked by an arrow below the Roberval record, while the observations of echoes at Siple at ~2.5 kHz are marked by tick marks above the Siple panel. On the two Siple records [(a) and (b)] the echo periods and echo frequencies are approximately the same, but in the anomalous case the echo arrivals are shifted to earlier times by ~1.7 s. This is attributed to initial propagation of the echoing waves on the lower latitude path of relatively short travel time marked in panel (b) by an arrow. The energy then coupled (in the southern hemisphere near Siple) to a path at $L \sim 4.8$ with propagation characteristics similar to the one involved in the normal echoing at 1505 UT [panel (a)]. The output of this path was first detected at Roberval, and then at Siple on the third hop. On the Siple record of panel (b), a one-hop path associated with the echoing energy was not detected or was at least very poorly defined. Note that if the two-hop echo periods on the Siple and Roberval records had been used to estimate the time of the causative spheric by simple extrapolation, an incorrect time estimate, shown by the dashed line below the Roberval record, would have been made.

Northern hemisphere records from Roberval and St. Anthony, Newfoundland (conjugate to Halley), were found helpful for purposes of identifying the times of causative atmospherics, but in only two of the five cases provided limited information on the development of the anomaly. In the other cases either no whistlers were detected, or propagation was detected on paths not involved in the anomalous propagation. The lack of two-hop information from the northern stations is not well understood. However, at least three of the cases involved interduct coupling in the north, and the density structure favoring that process may have tended to inhibit transmission to the ground. Also, as noted below, the amplification process may in most cases have occurred preferentially within the time of third hop propagation.

3. DISCUSSION AND CONCLUDING REMARKS

We suggest that the anomaly results from the cooperative action of passive propagation effects and of wave amplification. Among the important propagation effects are ones that inhibit penetration of the ionosphere by downgoing or upgoing waves. For example, the case of Fig. 1b comes to attention because essentially no first hop components are detectable on the records. Also important is the process of interpath coupling, which provides a means of illuminating a higher latitude path with signals whose spectral purity and df/dt characteristics meet the requirements for amplification along that path. Such coupling, as a propagation process, appears to be a fundamental feature of magnetospheric whistler mode propagation. Coupling between ducts, originally noted by Morgan *et al.* (1959), and recently discussed by Smith and Carpenter (1982), appears to be only one aspect of the 'scattering' process involving the transformation of downgoing to upgoing whistler mode energy at ionospheric heights.

The spectral purity of the upgoing wave energy entering a magnetospheric path or duct following the arrival at the ionosphere of a multi-path whistler depends strongly upon the arrival times and intensities of the reflected contributions from the path itself and from neighboring paths. The contributions from the nearest ducts or from hyperfine structure within the duct should cause mixing of signals with very similar travel times, and thus should lead to an increase in the diffuseness of the upgoing signal. If, on the other hand, there is coupling from a single path with much shorter travel time, as in the 22 May and 20 August 1982 cases reported above, or from a path within the plasmasphere (to one outside), the coupled signal would tend to be isolated in time as it entered the path of further propagation, and thus would not exhibit significant spectral broadening.

Since coupling over large interduct distances of order 1000 km within the plasmasphere, or over shorter distances across the plasmapause, probably involves significant attenuation, the spectral purity of the signal entering the path of subsequent propagation would seem to be of particular importance. This is borne out in active VLF experiments, which have revealed a type of amplitude limiting when the spectrally broadened echo of a previously transmitted wave mingles with a newly injected signal (Raghuram *et al.*, 1977), or when multiple frequencies are transmitted within what is known as the 'coherence bandwidth' (CHANG and HELLIWELL, 1979). The coherence bandwidth is nominally about 50 Hz for frequencies in the 2–5 kHz range at $L \sim 4$, with maximum suppression occurring for $\delta f \approx$ 20–30 Hz (HELLIWELL, 1983). In such cases the nominal 30 dB of growth frequently observed may be reduced by ~20 dB (RAGHURAM *et al.*, 1977; HELLIWELL 1983).

Regarding the frequency–time slope of the whistler, and the observations of anomalous trace energy at ~2–3 kHz, work by YOSHIDA *et al.* (1983) on the interaction times of gyroresonant electrons with whistlers supports the idea of a preferred range of frequencies for whistler amplification below the whistler nose frequency. These authors suggest that near the whistler nose, the interactions become relatively short (compared to the particle bunching time) because of the rapid frequency variation of the whistler, while at the much lower frequencies, the bunching times become too long for the interaction to be effective.

Studies with the Siple transmitter have shown that the magnetospheric response to the injection of frequency ramps in the outer plasmasphere is highly ramp-slope dependent. In a well documented case, CARLSON *et al.* (1985) found that positive and negative ramps in the ~2–5 kHz range with slope magnitudes greater than 3.5 kHz s^{-1} showed significantly less overall growth, by ~10 dB or more, than ramps with lesser slopes. In the present study, characteristic values of $|df/dt|$ near 2.5 kHz for the first hop paths of the anomalous traces were measured to be greater than 3 kHz s^{-1}, while typical values in the anomalous trace itself were ~1 kHz s^{-1}, a value found to be characteristic of both strong Siple transmitter signal wave growth and of the slope of triggered rising emissions.

Regarding particle fluxes, three of the cases involved coupling onto a path within or just beyond the plasmapause density gradients, where relatively large fluxes of interacting particles should be available. In the fourth case, there was evidence from VLF subionospheric signal perturbations of burst scattering within the plasmasphere of electrons with energies ~100 keV. In the fifth case there was evidence of echoing, banded noise and discrete VLF emissions, all propagating on the final path.

The fact that the anomaly tends to occur on the third hop and not the fifth, seventh, etc., suggests that once the final path of propagation is reached, after one or two hop propagation on other paths, normal propagation losses and the above-mentioned 'self' suppression effects associated with re-entering a path cause there to be no further single hop gains in intensity.

We do not suggest that the process of whistler amplification is limited to the unusual cases described here. The cases simply provide a way of looking with some degree of isolation at the factors of spectral purity, df/dt, and magnetospheric location (with respect to particle activity) that may affect that amplification.

In anomalous cases, such as that of Fig. 1b, it might be speculated that the anomaly is simply a propagation effect, such that at the end of the first hop the downcoming waves have unfavorable wave normal angles for ionospheric penetration, while after the third hop the wave normals are within the cone of penetration or transmission cone.

We have reviewed details of all the cases, and find that in order to explain them entirely in terms of passive propagation effects, it is necessary to postulate that the path of third hop propagation is only weakly excited in the 2–4 kHz range by the original lightning flash, while at the same time, paths at some distance from the third hop path are very strongly excited in the 2–4 kHz range. There must be highly efficient coupling at ionospheric heights between a strongly excited path and the weakly excited one, and this coupling must be frequency selective so as to favor the 2–4 kHz range. Explanations along these lines cannot be ruled out, but the various factors discussed above persuade us that magnetospheric amplification is required in order to explain the third hop spectra observed. Passive propagation effects probably dominate the first hop structure of the whistler, and thus help to provide the various conditions under which the third hop anomaly is recognized.

To conclude, the anomaly appears as unusual because: (i) a third hop component is more intense in some low frequency range than is any corresponding first hop signal; and/or (ii) a third hop component appears on a path that does not transmit an observable first hop signal. We believe that the third hop anomaly involves df/dt-dependent amplification of weak whistler signals by a gyroresonant wave–particle interaction in the magnetosphere. Through the particular combination of paths followed by the waves as they undergo interpath coupling, they are either able to retain a degree of coherence not achieved by other signals in the same whistler and/or are coupled into a region of relatively large interacting particle fluxes.

Acknowledgements—Portions of this work were completed during a visit by one of us (D.S.) to the STAR Laboratory at Stanford. We are grateful to staff and student colleagues for comments on the research, to the field personnel at Siple, Halley and Roberval for conduct of the field observations, to J. YARBROUGH for preparation of the spectrographic records, to P. PECEN for assistance in data presentation, and to N. LEGER for preparation of the typescript. The research at Stanford was supported by the Division of Polar Programs of the National Science Foundation under grants for work at Siple and Roberval stations. The VLF project at Halley is supported by the Science and Engineering Council.

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