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A Dispersion Anomaly in Whistlers Received on Alouette 1

D. L. CARPENTER AND N. DUNCKEL

Radioscience Laboratory, Stanford University, Stanford, California

INTRODUCTION

Natural whistlers observed in the ionosphere, but not by nearby ground receivers, may exhibit a frequency versus time curve that differs appreciably from the typical curve of whistlers observed at ground level. For wave frequencies well below the minimum value of electron gyrofrequency along the path, the frequency-time curve of most ground-observed whistlers can be approximated within a few per cent by the relation

$$D = tf^{1/2} = \text{constant} \qquad (1)$$

where t represents travel time at frequency f. However, a number of recent Alouette whistler observations at 1000 km show relatively large departures from this relation. The purpose of this note is to describe a particular departure in which the quantity $D(f) = tf^{1/2}$ exhibits an anomalous increase with increasing frequency.

The first known examples of the new type of whistler were found on Alouette 1, which is in a high-inclination, nearly circular orbit at about 1000-km altitude. Through the cooperation of the Canadian Defence Research Telecommunications Establishment, the real-time output of the broadband VLF receiver on Alouette 1 is once weekly telemetered to a ground station at Stanford. The broadband VLF ground-level activity at Stanford and the Alouette transmission are simultaneously recorded on separate tracks of the same tape. Thus far, spectrographic records from about 30 ten-minute runs have been examined. During three of the runs, on March 18, 1963, at about 0010 PST; on April 7, 1963, at about 2125 PST; and on September 26, 1963, at about 2110 PST, well defined examples of the anomalous whistler were recorded. Several other runs exhibited whistlers which may possibly be in the anomalous category. In this report we shall concentrate on the three runs mentioned, and we shall defer a thorough investigation of the statistics of the new phenomenon until a more extensive survey of data can be made.

DESCRIPTION OF THE NEW WHISTLER

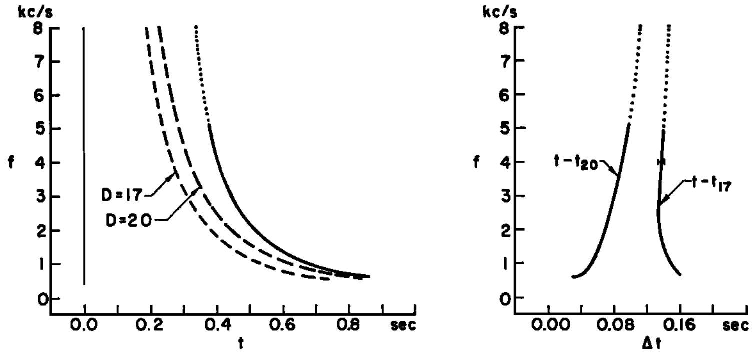
General properties. The solid line in Figure 1*a* shows the measured frequency versus time curve of a whistler component received at 38°N dipole (geomagnetic) latitude during the Alouette run of March 18, 1963. The dotted extension of the solid line represents an estimate of the behavior of the trace above the frequency range in which it is best defined. The presence of an anomaly can be inferred from a comparison of the whistler trace with the two dashed theoretical curves. These constant-dispersion curves represent the relations $D = tf^{1/2} = 17$ sec$^{1/2}$ and $D = 20$ sec$^{1/2}$, the type of behavior that would be expected for quasi-longitudinal propagation on a magnetospheric path in the vicinity of 35° dipole latitude.

The extent of the anomaly becomes clearly evident if we plot as a function of frequency the difference in travel time (Δt) between the observed whistler and the $D = 17$ and $D = 20$ curves. For both curves Δt is roughly constant above about 2 kc/s, tending to increase slightly with increasing frequency. For $D = 17$, Δt is nearly constant over the entire observed frequency range of the whistler.

The anomaly appears to be strongly latitude-dependent. In the observing range of about 1–8 kc/s, the frequency-time curve of the whistler can be approximated by the relation

$$t = (D_0/f^{1/2}) + \tau(l) \qquad (2)$$

where $D_0 \approx 17$ sec$^{1/2}$ = constant, independent of latitude, and τ is a number that varies linearly with dipole latitude at the satellite, l, rising from zero at about 30° to about 0.22 sec at 44°. (In Figure 1, τ (or Δt) for 38°N is about 0.14 sec.) At higher latitudes, the anomalous whistler



(a) (b)

Fig. 1. (*a*) Comparison of the frequency versus time properties of an anomalous whistler trace (solid line) with curves representing the relations $D = tf^{1/2} = 17$ sec$^{1/2}$ and $D = 20$ sec$^{1/2}$. (*b*) Graph of the difference in travel time Δt between the experimental curve in (*a*) and the curves for $D = 17$ and $D = 20$ sec$^{1/2}$. The horizontal flag indicates experimental error, most of which is due to lack of precise knowledge of the time of origin of the whistler.

component is not observed; at latitudes below about 30°, there is no anomaly, i.e. $\tau = 0$. On one occasion, the value of D_0 appeared to decrease with decreasing latitude below 30°, but evidence on this point is fragmentary. There were variations in detail among the three runs studied, but there was substantial similarity in the general features. In particular, the value of D_0 was about 17 sec$^{1/2}$ on all three occasions.

Details of the observations. Spectrographic records of the anomaly illustrated in Figure 1*a* are shown in the upper part of Figure 2. The two left-hand records provide a comparison of Alouette (upper record) and Stanford ground-level activity in the range 0–8 kc/s. The two right-hand records show the same event (as well as a number of closely spaced later events), this time in the frequency range 0–4 kc/s. The whistler was received at a dipole latitude of approximately 38°N when the satellite was a

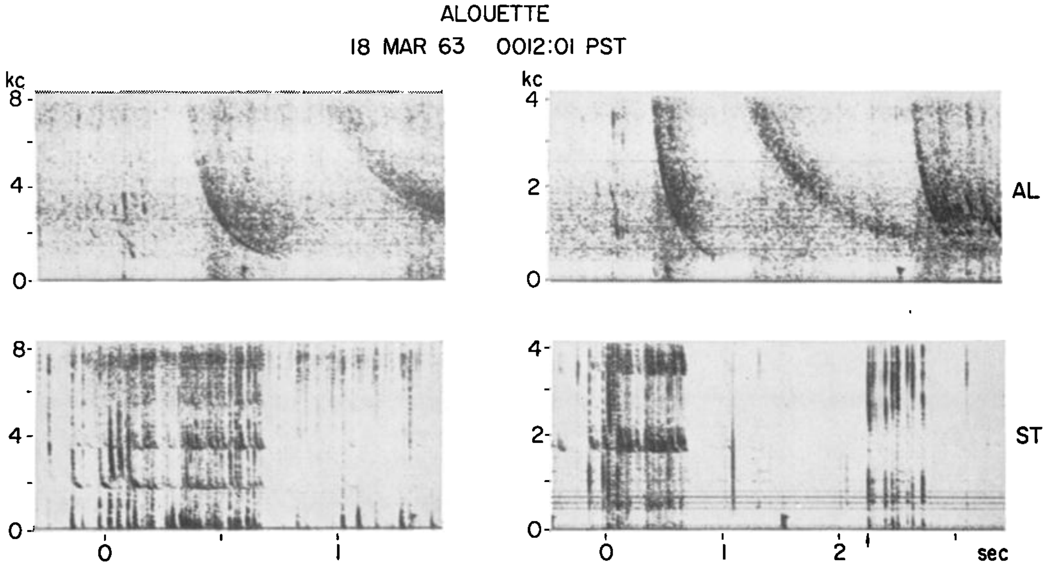


Fig. 2. Spectrographic records comparing a whistler received on Alouette (upper records) with the activity observed simultaneously on the ground at Stanford. The horizontal lines are of instrumental origin.

few hundred kilometers to the west of the Stanford receiver. There are two principal dispersed components, one, the anomalous case, with travel time at 4 kc/s of about 0.4 sec, and the other, a 'normal' trace, with travel time at 4 kc/s of about 1.1 sec. (Alouette whistlers are frequently found to contain both 'normal' and 'unusual' components, as in the subprotonospheric whistler [*Carpenter et al.*, 1964], or as in the present case.) Some of the details of Figure 2 will be discussed in later paragraphs. In the meantime we offer a description of the general sequence of events during the runs of March 18, April 7, and September 26, 1963. The most detailed comments refer to the March 18 run.

The observations began when the satellite was between 60° and 70°N dipole latitude and moving north to south near the meridian of Stanford. Whistlers were received on the higher-latitude segment of the path, but the first event containing an anomalous component was seen at about 45°N, when the satellite was near the latitude of Stanford (44°N). The anomaly was then observed in a succession of whistlers, being most pronounced at first and disappearing gradually as the satellite moved southward to a position of about 30°N. Below about 30° dipole latitude, whistlers with low travel time (≈ 0.2 sec at 5 kc/s) were observed, but they showed no evidence of the anomaly.

A convenient measure of the anomaly is the ratio of dispersion at 4 kc/s to dispersion at 1 kc/s, $D(4)/D(1)$. For typical ground observations at relatively low latitudes, this ratio is about 1.03. During the Alouette pass of March 18, the ratio was approximately 1.3 at about 45°N and decreased roughly linearly with the position of the satellite as it moved southward to about 30°N. (The whistler illustrated in Figures 1*a* and 2 was recorded at 38°N, in the middle of the range of anomalous observations. Figure 1*a* shows that its ratio of $D(4)/D(1)$ is about $25/21 = 1.2$.) Near 30°N, the ratio $D(4)/D(1)$ became less than 1.05 and the value of D became about 17 $\text{sec}^{1/2}$.

The frequency-time curve of the second, or normal, trace in Figure 2 shows general agreement with the properties of middle-latitude whistlers observed on the ground. It follows the relation $D = 76\ \text{sec}^{1/2}$ within about 1% over the range 2–4 kc/s. Over the latitude range of about 45°N to 35°N it showed no significant variations in dispersion properties, and simply disappeared as the satellite moved out of its 'effective area.'

The upper cutoff frequency of the anomalous components was not clearly defined. In a number of cases during each of the three passes, the upper part of the anomalous trace extended above 10 kc/s, the approximate upper limit of the receiver passband. In a single case on April 8, 1963, the anomalous trace was observed to extend above 13 kc/s and appeared at this point to be approaching a 'nose,' or point where the variation of travel time with frequency is zero. This aspect of the trace is not clear, however.

The question of propagation transverse to the static magnetic field may arise in considering an explanation of the dispersion anomaly, and it is therefore of interest to report on the presence or absence on the records of the lower hybrid resonance (LHR) band. (This noise band, which has a well-defined lower cutoff frequency, has been observed on many broadband Alouette records [*Barrington and Belrose*, 1963; *Barrington et al.*, 1965]. The lower cutoff frequency of this band is believed to represent the hybrid resonance for propagation transverse to the earth's field [*Brice and Smith*, 1964, 1965; *Barrington et al.*, 1965].) The LHR band was not observed when the whistler anomaly reported here was present. On the September 26 run, the band was well defined in the early part of the run but became faint and appeared to rise above the receiver passband about 1000 km north of the first observation of an anomalous trace. Fragmentary evidence of the LHR band appeared in the first minute of the April 8 run, and no clear evidence of the band was seen on March 18.

Broadband VLF recordings at ground level during the runs of March 18, April 7, and September 26 revealed no whistler activity (see Figure 2). This is a relatively common feature of satellite-ground or rocket-ground comparisons. It has recently been discussed by *Cartwright* [1964] and, as a theoretical point, by *Helliwell* [1963].

ANALYSIS OF PROPAGATION GEOMETRY

The following discussion is intended both to clarify the nature of the anomalous whistler and to illustrate a comparative study of ground and satellite records.

During the course of the investigation it was concluded that each anomalous whistler component had propagated over some magnetospheric path from a point of origin in the southern hemisphere. This aspect of the propagation geometry can be clarified through further reference to Figure 2.

The anomalous whistler trace on the Alouette records is preceded by a very low dispersion ($D \sim 3$ sec$^{1/2}$) fractional-hop whistler [see *Barrington and Belrose,* 1963]. This low-dispersion whistler appears about 70 msec after the origin of the time scale. Faint segments of it can be seen on the Alouette records at about 1 kc/s and about 3.5 kc/s. The fractional-hop whistler is assumed to have propagated on a short path through the ionosphere to the satellite, and it was observed at ground level in the form of a 'causative' atmospheric. This atmospheric is shown on the Stanford record just after the origin of the time scale. It is followed closely by one or two similar signals that may have contributed to the formation of the diffuse trailing part of the whistler components. The upper and lower records were aligned so that the time between the observation of the causative atmospheric on the ground and the observation of the fractional-hop whistler on the Alouette would correspond to the travel time through the ionosphere of the fractional hop whistler wave (as deduced from its dispersion properties). On the lower records, the separation of 15 msec between the origin of the time scale and the causative atmospheric was made to allow for the approximate time of propagation of the causative atmospheric from a point in the southern hemisphere some 5000 to 10,000 km from the receiver. (The matter of a southern hemisphere origin will be discussed in detail in a later paragraph.)

A number of causative atmospherics can be seen following the arrow in the lower right-hand record. These and the few near the origin of the time scale differ in several ways from the 700-msec-long burst of background atmospherics on the left-hand side of the Stanford record. The causative atmospherics appear to be relatively strong in the range from 2.5 to 5 kc/s, whereas the background atmospherics show relatively great strength just above the tweek cutoff frequency of about 1700 cps. The background atmospherics also show pronounced evidence of a cutoff at about 3400 cps. The differences between the two types of atmospherics may be attributable to particular amplitude versus frequency properties of the whistler-producing atmospherics and to the variation in the attenuation versus frequency characteristic of waveguide modes as a function of distance from source to receiver.

A number of arguments support the belief that the lightning source of the Alouette whistler was in the southern hemisphere. These arguments are based both on the spectrographic records of Figure 2 and on a large number of records representing other events in the passes of March 18, April 7, and September 26.

1. The fractional hop whistler is relatively faint in comparison to the other two components. Had the lightning source been located in the vicinity of the satellite and thus given rise to either two-hop (long) whistlers or to a transequatorially excited hybrid trace, the fractional-hop trace would probably have exhibited an intensity at least as great as that of the major whistler components.
2. The travel times of the whistler components, in particular that of the anomalous trace, are substantially less than what would be expected in the case of two-hop northern hemisphere excitation.
3. The causative atmospherics, when examined carefully, reveal substantially greater dispersion near the tweek cutoff frequency than do the background atmospherics. This suggests a substantially greater source-receiver separation in the case of the causative events.
4. The spectral characteristics of the causative atmospherics resemble closely those of thousands of similar one-hop (short) whistler sources previously identified on IGY records by comparisons of data from both hemispheres [e.g., *Helliwell and Carpenter,* 1961].

DISCUSSION

It may be wondered if the whistler illustrated in Figures 1*a* and 2 is not simply the lower part of a nose whistler with unusually low travel time. This possibility can be ruled out for several reasons. First of all, the dispersion curve of the anomalous whistler departs by at least several per cent from the curve of the conventional nose whistler. Secondly, the frequency-time characteristics of the anomalous trace change relatively rapidly with satellite position, while the characteristics of the higher dispersion trace do not. This suggests that the early trace is in fact propagating at low latitudes where nose frequencies are well above 30 kc/s and thus tends to rule out the possibility of explaining the anomalous trace as simply evidence of the nose effect. Still another argument concerns the 'knee' phenomenon. If the anomalous trace is a nose whistler of low travel time, the composite event of Figure 1 must be a knee whistler [*Carpenter,* 1963]. However, the observations do not agree with the known dispersion characteristics and latitudes of observation of the knee whistler. Thus, we conclude that the anomalous whistler is in fact a new phenomenon.

Whistlers observed at ground level have long been believed to propagate along field-aligned ducts of enhanced (or depressed) ionization, a situation that has led to considerable theoretical and experimental interest in ducted propagation. By contrast, nonducted propagation received early attention from *Storey* [1953], *Yabroff* [1961], and others, but only recently, as the result of observations in the ionosphere, has it attracted renewed interest. An explanation of the dispersion properties of the new whistler will probably require consideration of several aspects of nonducted propagation, including the possibility of propagation transverse to the magnetic field. A preliminary study of this kind has recently been conducted by *Kimura et al.* [1965].

SUMMARY

Whistlers observed by Alouette 1 at 1000-km altitude, but not detected at a nearby ground station, have on several occasions shown an anomalous increase in 'dispersion' $D = tf^{1/2}$ with frequency. The anomaly was most pronounced at midlatitudes and gradually diminished in extent as the receiver moved equatorward. The frequency-time properties of the anomalous whistler over the range of observations of about 1–8 kc/s can be approximated by adding a constant travel time τ to a curve $t = Df^{-1/2}$, where $D = \text{constant} \approx 17\ \text{sec}^{1/2}$, and τ varies roughly linearly with dipole latitude at the satellite, ranging from zero at about 30° to 0.22 sec at about 44°. The upper cutoff frequency of the observed anomalous whistlers was frequently above 10 kc/s. The examples found thus far were recorded at night. It is believed that the observed whistlers propagated from a source in the hemisphere opposite that of the receiver.

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