

Whistlers with Harmonic Bands Caused by Multiple Stroke Lightning

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Whistlers received with the Injun 5 satellite are frequently observed to have bands of the type shown in Figure 1. The center frequencies of the bands occur at equally spaced frequency intervals. This harmonic relationship is illustrated in Figure 2, which shows the linear relation between the center frequencies of the bands and the band number for the whistler shown in Figure 1. The average frequency difference between adjacent bands was 15.7 Hz in this case. Typically the frequency spacing between adjacent bands is from 10 to 30 Hz. These bands are only observed if the spectrum analyzer filter bandwidth is less than the frequency spacing of the bands. It is considered likely that this band structure was not previously reported because whistler spectrum analysis is frequently performed with filter bandwidths too wide (25 to 50 Hz) to resolve the bands. The spectrum analyzer filter bandwidth that produced the spectrograms used in this study was 2 Hz.

Because the frequency spacing of the bands is comparable to the gyrofrequency of several types of positive ions found in the ionosphere (particularly O^+ or N^+), *Stefant* [1970] initially suggested (followed later by several other investigators) that the bands may be associated with harmonics of an ion gyrofrequency. This suggestion seemed entirely plausible, because cyclotron harmonic resonances are a well-known characteristic of a hot plasma [*Bernstein*, 1958; *Stix*, 1962] and cyclotron harmonic effects have been observed in both laboratory and space plasmas [see *Crawford and Weiss*, 1966; *Gurnett and Mosier*, 1969]. This paper presents an experimental investigation of these bands and discusses an explanation of the observed char-

acteristics that was suggested to us by Dr. R. L. Dowden at the spring 1970 URSI meeting.

CHARACTERISTICS OF WHISTLERS WITH HARMONIC BANDS

Approximately 20 passes of Injun 5 VLF data have been investigated to study the harmonic bands of the type shown in Figure 1. Whistlers with harmonic bands are found to occur on almost every pass that has a significant number of whistlers. Harmonic bands are observed on approximately 15% of all whistlers observed by Injun 5. Bands with comparable frequency spacings have not been observed for any type of ELF radio noise other than whistlers. The occurrence of whistlers with harmonic bands is highly variable. A whistler with very clearly defined harmonic bands may be immediately followed (or preceded) by a whistler with absolutely no evidence of bands (see Figure 1, for example).

To investigate the possibility that the bands are related to harmonics of an ion gyrofrequency, the frequency spacing between adjacent bands was measured for about 70 of the best cases. The measurements show that the frequency spacing varies considerably from event to event and is not proportional to the geomagnetic field strength at the satellite. Figure 3 illustrates the large variations in the frequency spacing of the bands observed during a typical satellite pass. Since the ion gyrofrequency is proportional to the geomagnetic field strength, we conclude that the bands are not related to an ion gyrofrequency at the position of the satellite.

These results, particularly the extreme variability of the band characteristics and the absence of a correlation between the frequency separation of the bands and the ion gyrofrequency, are not consistent with any proposed

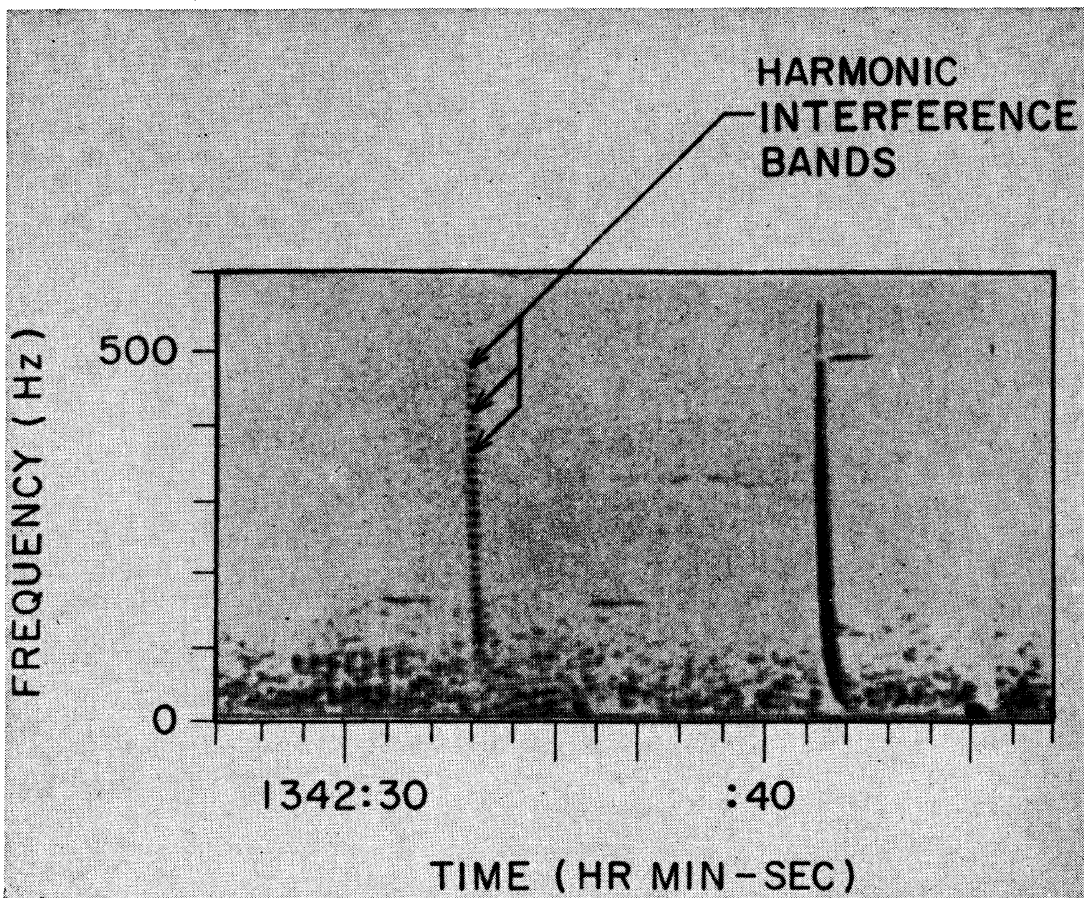


Fig. 1. Harmonic bands observed on a whistler received by the Injun 5 VLF receivers immediately followed by a whistler with no evidence of bands.

propagation effect involving interactions at the harmonics of an ion gyrofrequency.

HARMONIC BANDS CAUSED BY MULTIPLE LIGHTNING STROKES

While an attempt was being made to explain the unusual characteristics of these bands, Dr. R. L. Dowden, at the spring 1970 URSI meeting, noted that similar attenuation effects can be produced by destructive interference between multiple lightning strokes. Subsequent investigations have shown that this process can explain essentially all known characteristics of the harmonic bands observed on whistlers with Injun 5.

This effect can be illustrated by assuming that the lightning impulses consist of two equal amplitude delta functions separated by a time interval Δt

$$V(t) = V_0[\delta(t) + \delta(t - \Delta t)]$$

The frequency spectrum of this double impulse can be easily obtained by Fourier analyzing $V(t)$

$$V(\omega) = \int_{-\infty}^{\infty} V(t)e^{-i\omega t} dt$$

which gives

$$V(\omega) = V_0[1 + e^{-i\omega\Delta t}]$$

The magnitude of the frequency spectrum, which is what is determined by the frequency spectrum analyzer, is given by

$$|V(\omega)| = V_0\sqrt{2} (1 + \cos \omega \Delta t)^{1/2}$$

It is evident from the above equation that the frequency spectrum of this double lightning

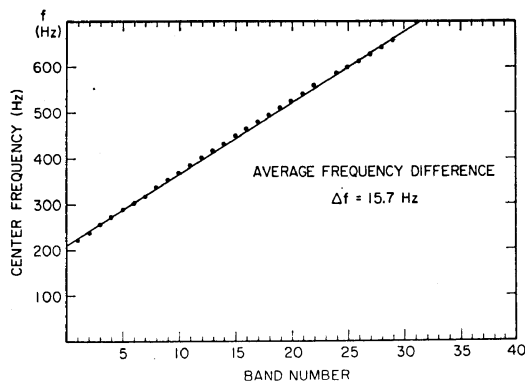


Fig. 2. Plot of the band center frequency as a function of band number for the harmonic bands shown in Figure 1, showing the linear variation of the band center frequency.

impulse goes to zero whenever

$$\omega = \frac{2\pi(n + 1/2)}{\Delta t}, \quad n = 0, 1, 2, \dots$$

or

$$f = \frac{1}{\Delta t} (n + 1/2)$$

Thus, the frequency spectrum of the radiated fields has nulls at equally spaced frequency intervals of $\Delta f = 1/\Delta t$. At these frequencies, the fields radiated by the two impulses interfere destructively. Similar destructive interference

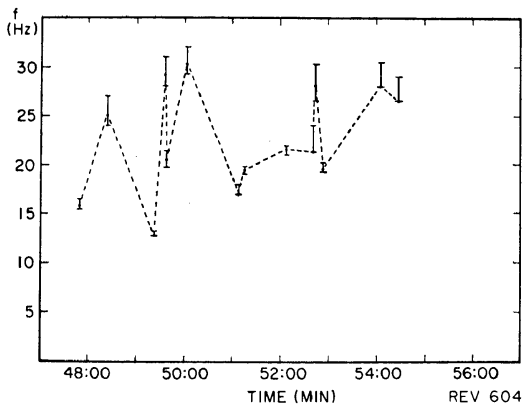


Fig. 3. Plot of the average frequency interval for 14 bands observed on one continuous satellite pass as a function of time during the pass. The points do not show any continuous variation, which suggests that the frequency interval is not dependent on any satellite orbit parameters.

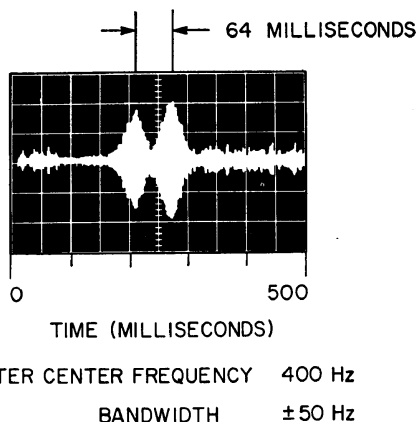


Fig. 4. The whistler signal shown in Figure 1 viewed through a filter with a bandwidth sufficiently wide to show the separate whistler impulses. The inverse of the time interval between impulses is 15.6 Hz, which agrees well with the average frequency interval of 15.7 Hz measured in Figure 2.

effects can occur for any number of equally spaced lightning discharges.

To determine if the harmonic bands observed by Injun 5 were produced in this manner, the received whistler signals were reanalyzed by using a filter of sufficient bandwidth (± 50 Hz) to resolve the individual lightning impulses, if present. This analysis was performed for a total of 70 cases with the following results.

In every case where the bands were as clear and sharply defined as those shown in Figure 1, two or more distinct lightning impulses separated by the same time interval could be resolved. Figure 4, for example, shows the output signal from the wide band (± 50 Hz) filter for the first whistler in Figure 1. This signal shows that the whistler originated from two distinct lightning impulses separated by about 64 msec. The inverse of the time separation between the lightning impulses, $1/64 \text{ msec} = 15.6 \text{ Hz}$, corresponds well to the frequency interval between the interference bands (15.7 Hz) observed for this whistler (see Figure 2). In all cases where the time interval between the lightning impulses could be accurately determined, the inverse of the time interval between the impulses was in agreement with the average frequency interval between adjacent bands. In no case did we find a whistler with bands that was clearly due to a single lightning impulse.

Multiple-stroke lightning has, on the average, three to four strokes per flash. The average time interval between strokes is 40 msec [Uman, 1969]. The inverse of the average time interval between strokes is 25 Hz, which corresponds well to the typical frequency spacing observed for the harmonic bands.

The evidence obtained in this study indicates that the bands observed on whistlers with Injun 5 are produced by multiple lightning discharges. While it is apparent that these results do not eliminate the possibility of the production of harmonic effects due to the presence of ion harmonic resonances, this study does show the necessity for extreme care in observing such bands. Any investigation into the occurrence of ion cyclotron harmonics in whistlers must eliminate the possibility that the bands are actually interference bands produced by multiple stroke lightning.

Acknowledgments. This research was supported in part by the National Aeronautics and Space

Administration under contracts NAS5-10625, NAS1-8141, NAS1-8144(f), NAS1-8150(f), and NGR-16-001-043; and by the Office of Naval Research under contract N00014-68-A-0196-003.

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(Received October 30, 1970;
 accepted December 11, 1970.)

Communicated by D. L. Carpenter.