RADIO SCIENCE Journal of Research NBS/USNC–URSI
Vol. 69D, No. 8, August 1965

Regular Oscillations Near 1 c/s Observed at Middle and Low Latitudes[1]

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(Received February 3, 1965)

A review is presented of some of the more important properties of Pc 1(0.2–5 c/s) emissions observed at middle and low latitudes. Special attention is given to fine structured regular oscillations referred to by various workers as pearls, type A oscillations, and hydromagnetic (hm) emissions. The following aspects of these oscillations are discussed.

(a) *Signal appearance.* The emissions are considered from both their amplitude-time (waveform) appearance observed on chart records and their frequency-time (*f-t*) characteristics observed on sonagrams. The various types of *f-t* fine structure are discussed (rising and falling frequency elements, fan shaped elements, etc.).

(b) *Simultaniety of occurrence at widely separated locations.* A high degree of similarity is often found in the appearance of *f-t* structural elements of hm emissions recorded simultaneously at widely separated stations. Attention is given to the time-shifts between these elements at stations in the same hemisphere and in opposite hemispheres.

(c) *Time of occurrence.* Correlations are considered between times of occurrence of hm emissions and other geophysical effects such as charged particle events, magnetic storms, and variations of the ionospheric parameter F_0F2.

(d) *Latitude effects.* Various latitude dependent emission characteristics are discussed. These include latitude variations of emission frequency, fine structure repetition period, and signal amplitude.

In addition to the aspects of the Pc 1 emissions outlined above, properties of two other types of emissions are briefly discussed. One of these signals, referred to here as a "continuous emission" also lies in the Pc 1 category. It is often observed continuously throughout the night and is characterized by a slow variation of *f-t* characteristics. The other signal, which might be placed in a Pc 1–Pi 1 transition category, is observed during magnetically disturbed periods. On sonagrams it is characterized by an irregularly spaced rising frequency fine-structure. When monitored aurally on time-compressed magnetic tape (speed-up factor of 1000 to 2000), it is characterized by a sound similar to bubbles blown under water.

1. Introduction

This paper reviews some of the more important properties of signals in the Pc 1 category (regular oscillations in the frequency range 0.2 to 5 c/s). Emphasis is placed on relatively recent results obtained at Lockheed. Recent results obtained by other workers are also included for completeness. For earlier results, the reader is referred to a comprehensive review paper by Jacobs and Watanabe [1963b]. Emphasis is also placed on observations at middle and low latitudes. For high latitude observations, the reader is referred to the accompanying paper by W. H. Campbell [1964].

Most of this paper is concerned with the properties of a type of Pc 1 oscillation which has recently excited considerable scientific interest. Different workers have referred to these signals as "pearls," "type A oscillations," "hydromagnetic (hm) emissions," etc. In addition, brief mention is made of another type of oscillation in the Pc 1 category referred to here by the term "Continuous Emission." Also considered briefly is a third type of event which might be placed in a transition region between the Pc 1 and Pi 1 categories. (The latter term refers to irregular pulsations in the frequency range 0.05 to 1 c/s.)

2. Nomenclature

In investigations of micropulsations in various parts of the world, workers have employed many different types of detection, recording, and analysis equipment. Because of these differences in instrumentation and also because of natural variations in signal characteristics as a function of latitude, studies by different workers have emphasized different aspects of the signals. As a consequence, a number of terms have come into use describing the same (or similar) types of micropulsations. Attempts to standardize nomenclature may sometimes be partially successful but always run the risk of introducing new terms to further confuse the situation. Introduction of the term Pc 1 (IAGA recommendation, [see Jacobs et al., 1964])

[1] Paper presented at the ULF Symposium in Boulder, Colo. 17–20 August 1964.

to describe regular oscillations in the frequency range 0.2 to 5 c/s seems to be a helpful step. However, the signals considered in this paper, which generally fall into this frequency range, are also sometimes observed at slightly higher and lower frequencies so that the frequency limits of the Pc 1 category do not rigidly bracket any type of micropulsation phenomenon.

The classification problem is further complicated by the fact that there may be a number of different types of events in any given frequency range, and regardless of how many subcategories are defined, the possibility always exists of finding hybrid signals between these subcategories. Classification schemes are often based on the properties of the signals on some type of data display (frequently used methods are amplitude-time displays, frequency-time displays, and aural monitoring of time-compressed magnetic tape records). The writer has found that, regardless of the type of display employed, transitions between categories appear to be continuous. In other words, hybrid signals are likely to be found between hybrid signals. This does not necessarily imply that the signal generation processes also vary continuously, but it does suggest that these processes may be extremely complex. Despite the apparently continuous nature of transitions between different types of events, it is often useful for analysis purposes to define discrete signal categories, but the categories defined by different workers do not always coincide, and even workers in the field may have difficulty in associating their own categories with the categories of others. The writer believes that further attempts at standardization of nomenclature are likely to be of little value and are not worth the effort, and that the situation will ultimately become clarified when the phenomenology of the signals is better understood. In the interim period, it would probably be helpful to the reader for workers to include in their publications a short summary of nomenclature used by other workers to refer to the (presumably) same type of signal.

Table 1 includes a number of terms used by various workers to describe signals in the Pc 1 category. The terms are placed in three subcategories which (presumably) describe the same type of signal. The subcategories—referred to as fine-structured regular, nonstructured regular, and fine-structured semiregular—are based on the appearance of the signal on *f-t* displays (sonagrams). The meanings of the terms employed should become clear in later sections of this paper. Hybrid signals may of course appear between the three subcategories. Also since terms used by other workers do not always apply to exactly the same type of signal, the table cannot be guaranteed for accuracy.

TABLE 1. *Geomagnetic fluctuations in IAGA category Pc 1 (0.2 to 5 c/s)*

A. Fine-structured regular oscillations:
  1. Pearls (PP) [Sucksdorff, 1936; Troitskaya, 1961].
  2. Type A and B oscillations [Benioff, 1960].
  3. Hydromagnetic emissions [Tepley and Wentworth, 1962b].
  4. CpSp, CpLp [Yanagihara, 1963].
  5. Hydromagnetic whistlers [Obayashi, 1964; Jacobs and Watanabe, 1964b].

B. Nonstructured regular oscillations (< 1 c/s):
  1. Type B oscillations [Benioff, 1960].
  2. CpLp [Yanagihara, 1963].
  3. Continuous emissions [Tepley and Amundsen, 1964b].

C. Fine-structured semiregular oscillations:
  1. IPDP [Troitskaya, 1961].
  2. SIP [Troitskaya, 1961].
  3. Storm-time emissions (gurglers) [Tepley and Amundsen, 1964a].

In the following sections, the writer will use the term "Hydromagnetic (hm) emission" to describe signals in the subcategory of fine-structured regular oscillations. The term "Pearl" is also used occasionally to describe the same type of signal when referring to results by other workers and also when referring to fine-structured regular oscillations of the narrow-band variety.

3. Properties of Hydromagnetic Emissions

3.1. Comparison of Frequency-Time (*f-t*) and Waveform Signal Characteristics

An *f–t* display (sonagram) is essentially a three-dimensional plot of the following quantities:

Time t.
Signal frequency f.
Signal amplitude.

Time and frequency are plotted in the horizontal and vertical directions, respectively. The signal amplitude in any given frequency-time interval is indicated qualitatively by the darkness of the record.

On a sonagram, an hm emission is represented by a band of frequencies that is sometimes observed continuously for many hours, during which time the bandwidth Δf, and center frequency, f_c, may vary over several octaves. The emission bandwidth is sometimes extremely narrow ($\Delta f/f_c \lesssim 1/10$). A number of such narrow-band emissions are sometimes observed simultaneously at slightly different center frequencies. The emissions may merge to form a single band and then may separate (see fig. 1). Frequently the emission bandwidth is relatively broad (typically $\Delta f/f_c \approx 1/2$).

Of particular interest is the fine structure within the emission band. In broadband emissions, the fine structure can usually be interpreted as a series (or several successive series) of repetitive overlapping wave trains of rapidly rising frequency. Typically

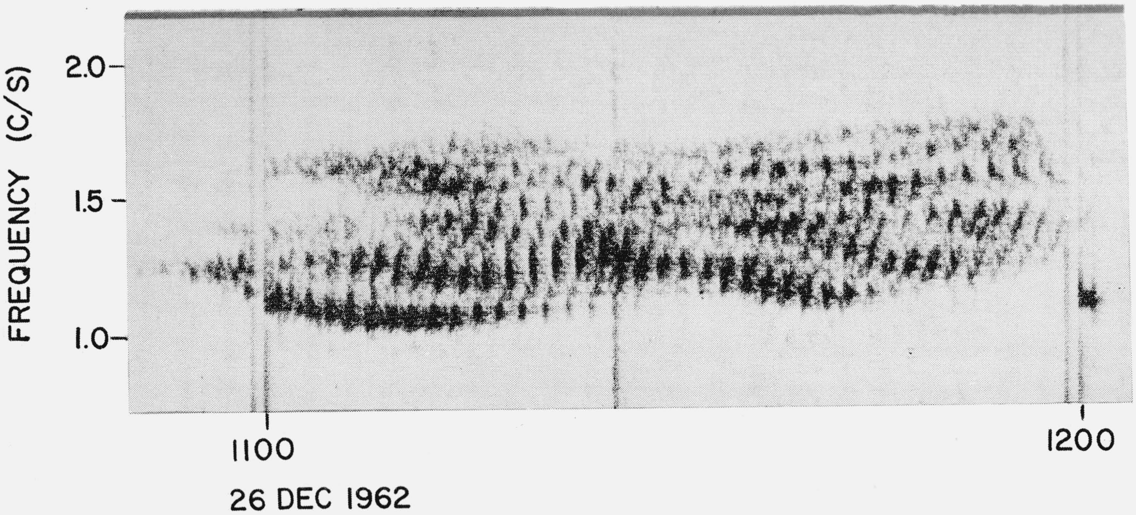


FIGURE 1. *Broadband hm emission containing both rising and falling frequency fine structure.*

This emission appears to be made up of a number of narrow-band emissions which seem to merge at about 1125 and then separate. The vertical line at about 1125 is produced by the sub-ELF components of a lightning-induced sferic. Note the rapidly falling-frequency structural elements immediately to the left of this line. Note also that just before 1200 rising- and falling-frequency structural elements appear simultaneously.

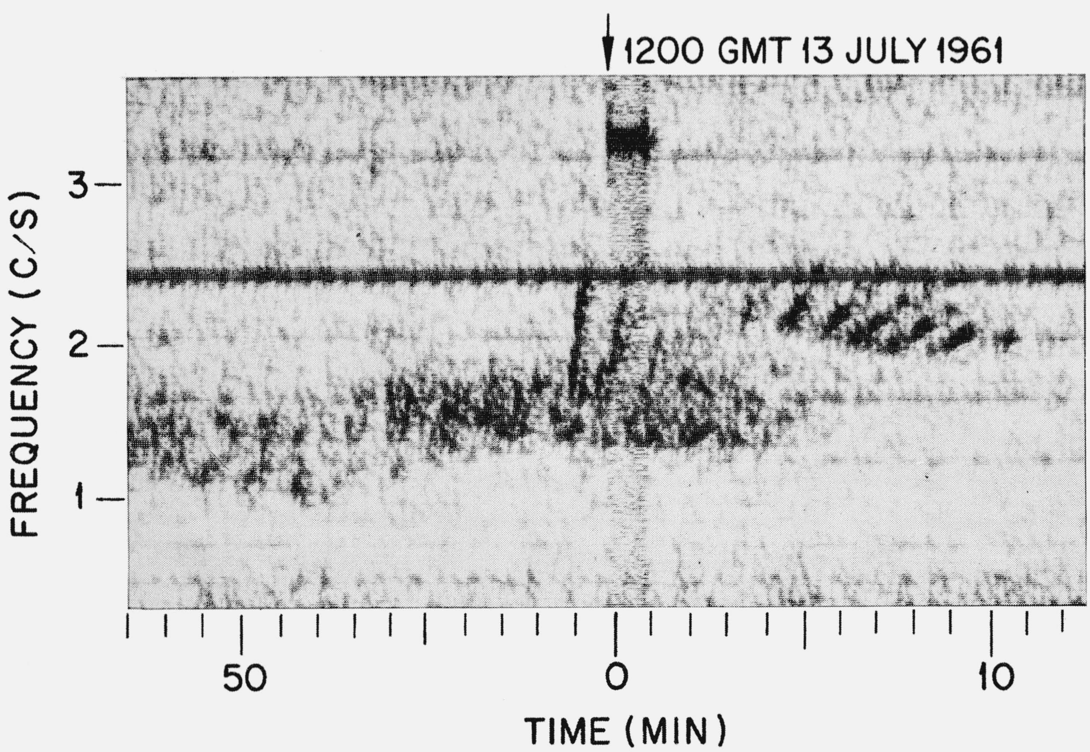


FIGURE 2. *Hm emission exhibiting a fan-shaped rising frequency fine structure.*

Note the sharply defined element of rapidly rising frequency just before 1200. Note the transition in the structural elements with increasing time from rapidly rising to slowly rising frequencies. Events of this type are observed rarely. Many hm emissions (such as the event in fig. 3) may be interpreted as being made up of a superposition of events (displaced in time) similar to the event shown in this figure.

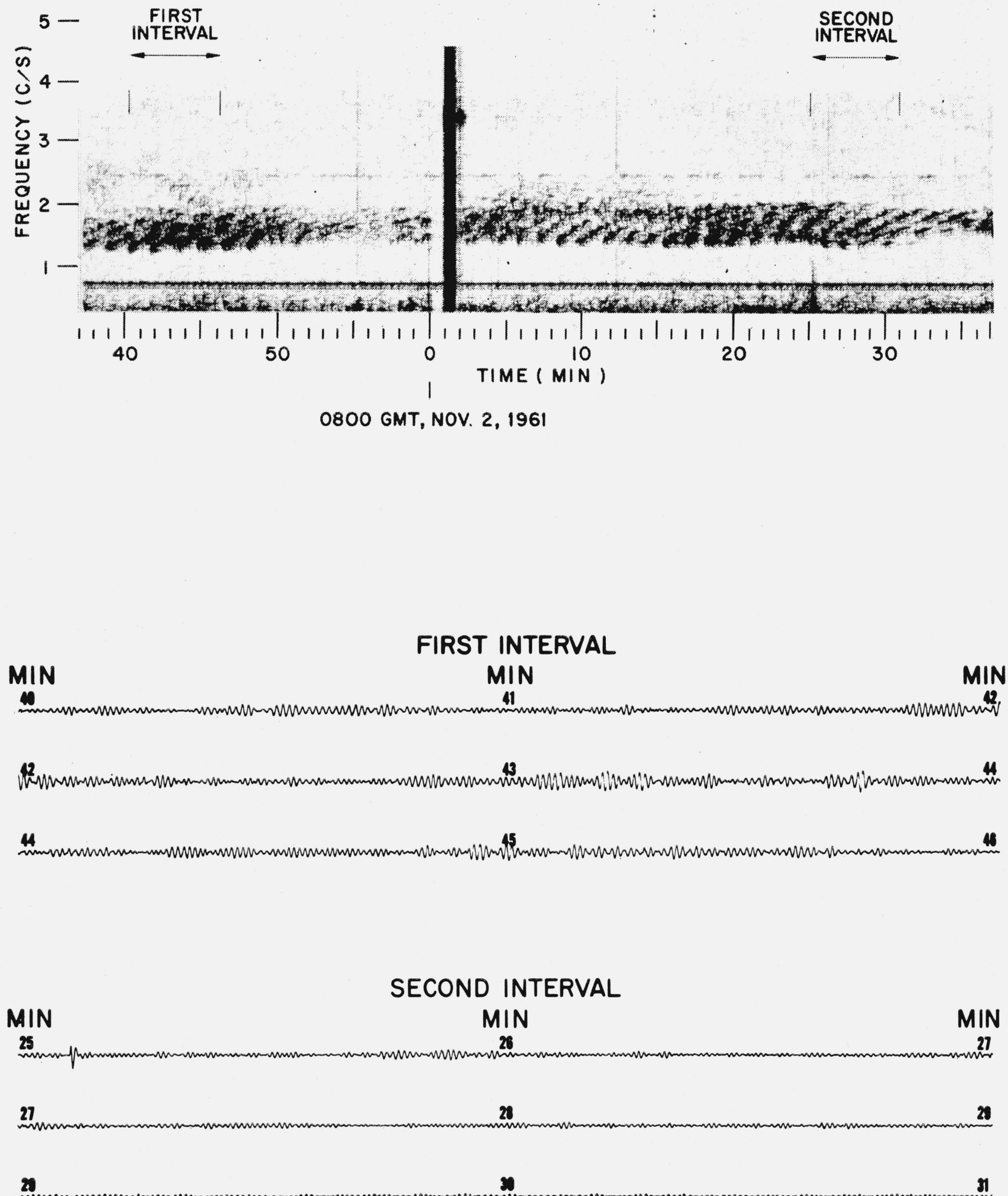


FIGURE 3. *Comparison of frequency-time and amplitude-time displays.*

The sonagram shows a portion of a broadband hm emission recorded during a magnetically quiet period. It clearly shows a pattern of fine structure consisting of a series of repetitive wave trains of rapidly increasing frequency. Note that after 0825, the slope of successive structural elements decreases with increasing time. Note also that in the intervals 0740 to 0750 and 0815 to 0825 two series of wave trains of different slopes seem to be occurring simultaneously.

Also shown are two waveform intervals from part of the same period of time covered by the sonagram. It is clear that the waveform recordings give little information on the structural characteristics of the signal.

the slope, df/dt, of each wave train is on the order of 0.1 c/s/min. The slope of successive wave trains in each series often decreases slowly as shown in the event of figure 2. Events of this type consisting of a single series of rising frequency wave trains are rare. More often hm emissions seem to consist of several overlapping series, each of which is similar to the event of figure 2. The sonagram of figure 3 illustrates this effect. At the right of the sonagram (after 0825) the series of wave trains resembles the event in figure 2. However in other intervals (0740 to 0750 and 0815 to 0825), two series of wave trains of different slopes seem to be occurring simultaneously.

This particular broadband emission is rather unusual in that both the bandwidth and the midband frequency remain almost constant for the 1 hr period indicated. However, the presence of the rising frequency fine structure within the emission band is not unusual. From a study of sonagrams of a great many hm emissions over a 3-year period, it has been ascertained that most hm emissions observed during magnetically quiet periods contain the same type of rapidly rising-frequency fine structure.

A repetitive rising-frequency fine structure is also sometimes observed in narrow-band emissions, but the repetitive wave trains are less likely to overlap than in broad-band emissions.

A falling-frequency fine structure is also occasionally observed (again refer to fig. 1).

The spacing between the fine-structured elements is usually quite regular, so that we can define the fine-structure periodicity T as the time between successive structural elements (T is the reciprocal of the fine-structure repetition frequency). Relatively greater values of T usually accompany lower values of the emission-band center frequency [Heacock and Hessler, 1962; Gendrin 1963a, c; also see fig. 4 of this paper].

A type of fine-structured emission is sometimes observed during magnetic storms in which the frequency band is not clearly defined and in which the structural elements are irregularly spaced. The characteristics of storm-time emissions are considered briefly in section 5 of this paper.

An amplitude-time (waveform) display of a broadband hm emission can be interpreted as a superposition of a number of overlapping wave trains of rapidly rising frequency; the amplitude at any particular time is then the algebraic sum of the amplitudes of a number of overlapping wave trains. Since the amplitude of each wave train may vary irregularly, the amplitude of the resultant wave train may also vary irregularly. To further complicate the situation, a number of emission bands may exist simultaneously, each one contributing to the resultant signal amplitude on a waveform display.

Despite these complications, the waveform of a broadband emission tends to vary symmetrically about the baseline; it resembles a modulated carrier signal, but the modulation pattern is irregular and ordinarily exhibits no characteristic modulation frequency (refer to the lower part of fig. 3). Descriptive terms such as "pearl necklace," "pearl beads," etc., do not adequately describe broadband emission waveforms and, in fact, lead to the impression that the structure of the signals is less complex than it is actually found to be. On the other hand, the structural elements of

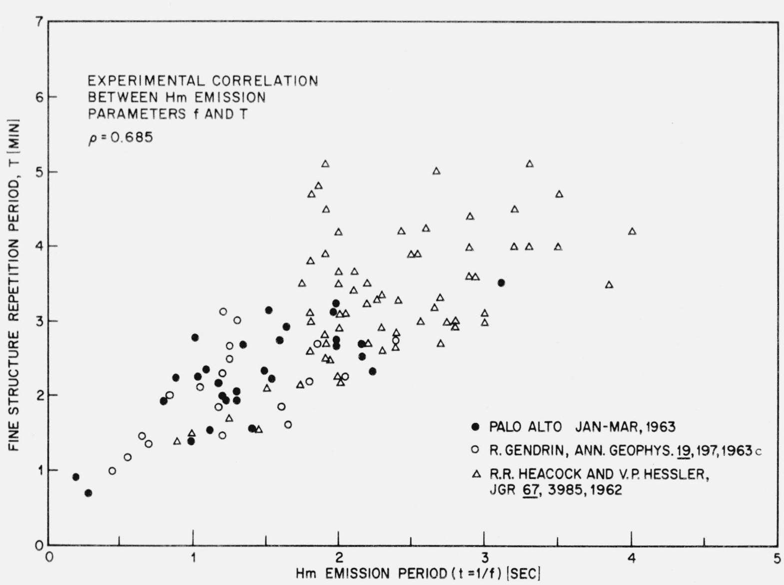


FIGURE 4. *Plot of fine-structure repetition period versus hm emission period at three locations.*

The scatter diagram shows that a relationship exists between the two quantities plotted (correlation coefficient of 0.685). The points were obtained for over 100 hm emission events at different times and at different locations. The triangles, circles, and dots represent events observed at College, Alaska (lat. 65°), Chambon la Farêt, France (lat. 50.4°), and Palo Alto, Calif. (lat. 43.5°), respectively. Note that the triangles tend to occur at relatively higher values of both emission period and fine-structure repetition period than do the circles and dots. This indicates a latitude variation of the plotted hm emission characteristics.

relatively narrow-band emissions exhibit little or no overlapping. The elements are represented by well-separated repetitive wave trains on an amplitude-time display. If the time scale is chosen appropriately, the waveform of an isolated narrow-band emission may resemble a series of "pearls" and the pearl repetition frequency corresponds to the fine-structure repetition frequency on a sonagram.

3.2. Simultaneity of Occurrence of Hm Emissions at Widely Separated Locations

In attempting to determine the degree of simultaneity of occurrence of broadband hm emissions at widely separated stations from waveform records, little or no correlation is ordinarily found between the amplitude modulation patterns of the signals; hence, it is only possible to say that the general activity level is likely to be high at several widely separated stations in a given time interval. Observations of this type at high and middle latitudes have been reported by a number of workers [Benioff, 1960; Troitskaya et al., 1962; Smith, 1964] and also at conjugate auroral latitudes [Lokken, Shand, and Wright, 1963; Yanagihara, 1963; Dawson and Sugiura, 1963]. Only in rare cases have close time correlations been observed from amplitude modulation records.

In comparing the frequency-time variations, however, a striking degree of simultaneity is found in signals observed at the widely separated Lockheed Pacific Ocean Stations (their locations are shown in fig. 5). For example, by studying the series of sonagrams of the events of figures 6 and 7 we see that the individual *f-t* structural elements are almost identical at the four Lockheed Pacific stations. The intensity (darkness) of corresponding elements is subject to wide variation, however, and, in fact, the same elements are not always observed at all locations.

Another example of an extremely close *f-t* correlation between structural elements of emissions observed at high, middle, and low latitudes is shown in figure 8. The results depicted in this figure were obtained in an informal cooperative project between Lockheed and the Institute of Geophysics at College, Alaska. Close correlations between hm emissions observed simultaneously at high and middle latitude stations are however, probably less common than correlations between events observed at middle and low latitudes.

It is clear that in many respects *f-t* displays are more suitable than waveform records for the investigation of the degree of simultaneity of occurrence of hm emissions. Only in the case of extremely narrow-band emissions can we expect a close correspondence in the appearance of the "pearl" waveforms at distant stations, and even in this case wide variations in intensity, associated with ionospheric hydromagnetic-wave attenuation and with other unknown effects, frequently occur (see sec. 3.4d).

It is important to determine if the *f-t* structural elements occur simultaneously at widely separated stations or if there is a consistent measurable time lag. It was found [Tepley, Wentworth, and Amundsen, 1963], that for emissions observed simultaneously at stations in the same hemisphere, the *f-t* structural elements occurred simultaneously within a measurement accuracy of ±12 sec. However, for emissions observed simultaneously in opposite hemispheres, the structural elements were displaced in time by 1/2 the fine structure periodicity (time shift of T/2 or 180° phase shift) within the same measurement accuracy indicated above. The method for measuring this time shift is shown in figure 9. A doubling of the fine structure repetition frequency is also observed occasionally at middle and low latitude stations [Tepley, Wentworth, and Amundsen, 1963; also figs. 7 and 10 of this paper]. This effect is presumably due to a superposition of structural elements which would exhibit a 180° phase shift when observed at higher latitudes at stations in opposite hemispheres.

The result of interhemisphere 180° fine structure phase shift was based on analysis of eight separate emissions covering active periods of many hours. The result is in agreement with a single observation made earlier during a high-latitude conjugate-point measurement program and reported by Lokken, Shand, and Wright [1963] and Yanagihara [1963]. In those papers, records from Byrd Station, Antarctica, and Great Whale River, Quebec, were compared for an event that occurred on January 23, 1961. In the interval 1100 to 1110 GMT, a 180° phase shift was clearly observed between occurrences of pearls on waveform records from these high latitude magnetically conjugate stations. In view of the short duration of the part of the event analyzed (10 min) and the fact that only a single event was reported, the result did not seem conclusive. It would not be surprising if no other similar events were observed in the PNL–Stanford program because, as has been pointed out, waveform records are generally less suitable than sonagrams for determining simultaneity of occurrence. Only in an isolated narrow-band emission does the waveform appear as a series of "pearls," and only in this case is it ordinarily possible to unambiguously determine phase shift from a waveform record.

More recently Pope [1964] and Campbell [1964] have given preliminary results from high latitude conjugate area stations which seem to verify the 180° interhemisphere fine-structure phase shift. Their results are based on a comparison of sonagrams obtained from magnetic tape data recorded simultaneously at conjugate stations.

It is difficult to measure time with high accuracy from sonagrams. Hence comparison of sonagrams is not extremely well suited for the determination of small time shifts which may occur between structural elements of emissions observed at widely separated stations in the same hemisphere. Time shifts of a few seconds are to be expected due to hydromagnetic wave propagation times in the lower exosphere and ionosphere. It presently appears that the determination of small time shifts are best made from waveform records and are subject to the difficulties discussed previously in determining simultaneity from this type of presentation. A preliminary measurement of this

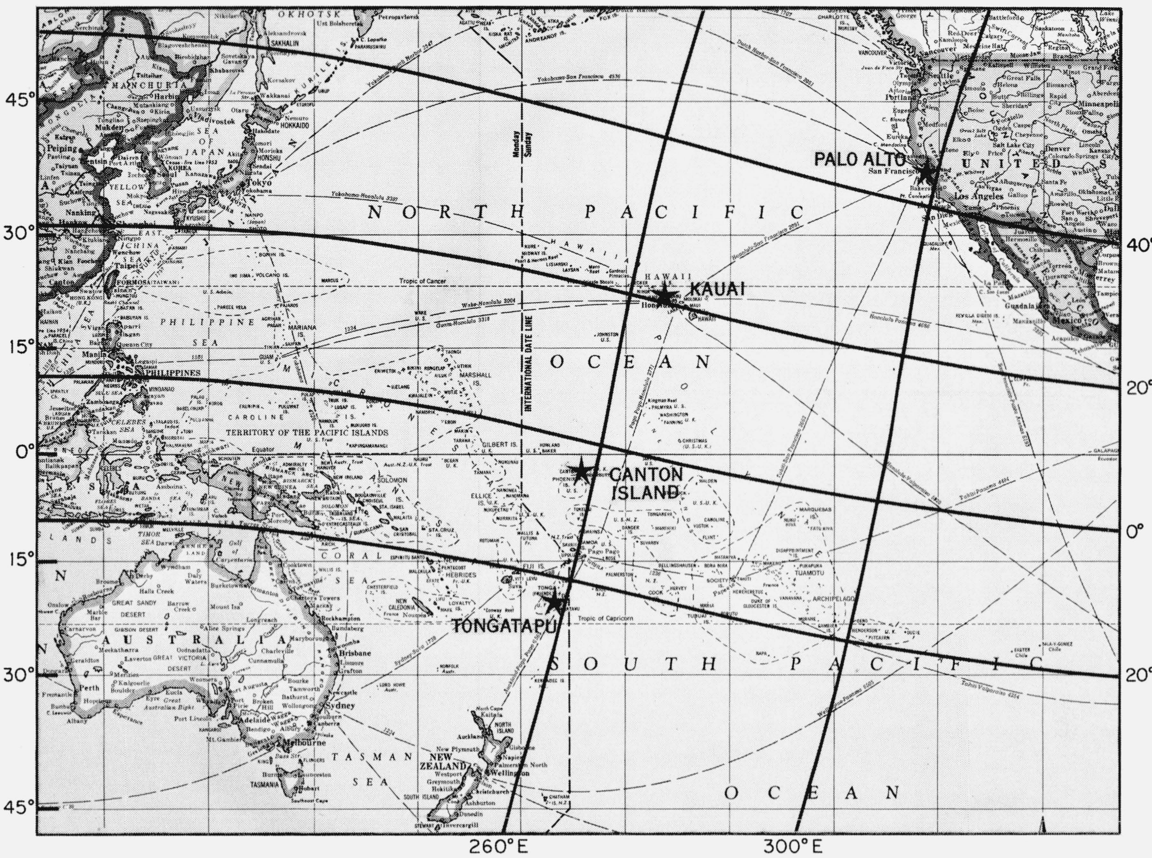


FIGURE 5. *Locations of the Lockheed Pacific Ocean stations.*
Geographic coordinates are indicated at the left of the above map. Geomagnetic coordinates, based on the center-dipole approximation—are indicated at the right. The coordinates of the stations are as follows:

	Geographic latitude	Geographic longitude	Geomagnetic latitude	Geomagnetic longitude
Canton Island (Phoenix Group)	02°46′ S	171°43′ W	05.1° S	258.0° E
Kauai, Hawaii	22°09′ N	159°18′ W	21.7° N	265.6° E
Palo Alto, Calif.	37°26′ N	122°10′ W	43.5° N	299.0° E
Tongatapu (Tonga Group)	21°14′ S	175°08′ W	24.0° S	258.5° E

type from "pearl" waveforms showing a 4 sec time shift between Palo Alto and Kauai was reported by Tepley, Wentworth, and Amundsen [1963]. A more convincing result was reported recently by Smith [1964] showing a 2 to 3 sec time shift between Oregon and Texas. Results showing time shifts of 1 to 5 sec between Palo Alto and Kauai are now being obtained in an investigation now under way at Lockheed.

The 180° interhemisphere fine-structure phase shift was again verified recently in a high-latitude conjugate-point cooperative project conducted by scientists in France and the U.S.S.R., (private communication from R. Gendrin concerning work by Barssoukov and Ponsot). Their results, based on a statistical comparison of a large number of elements of pearl waveforms, indicate an interhemisphere phase shift significantly different from 180° but still within the measurement error (approximately ±36°) of the results reported earlier by Tepley [1964]. The observation of 180° interhemisphere fine-structure phase shift has been associated with hydromagnetic waves bouncing along geomagnetic field lines (Cornwall, 1965; Jacobs and Watanabe, 1964a, b; Obayashi, 1964). Small departures from 180° phase shift may be attributed to hydromagnetic wave propagation effects similar to those discussed above observed during simultaneous observations in the same hemisphere. The relatively large departures indicated by the Soviet-French results cannot easily be explained in terms of presently available models.

3.3. Correlations Between Occurrences of Hm Emissions and Other Geomagnetic Effects

One of the most intriguing characteristics of hm emissions is the fact that their occurrence times do not correlate closely with any other geophysical

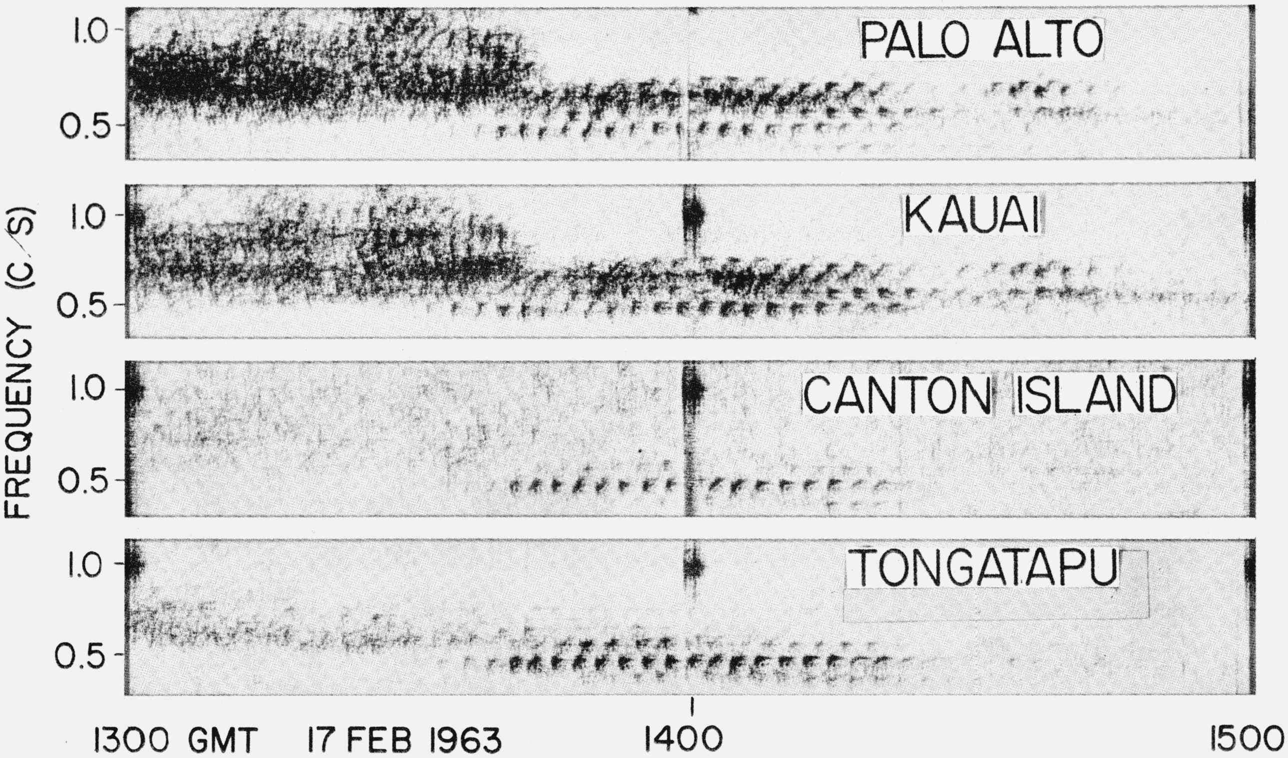


FIGURE 6. *Four station sonagrams of hm emissions (February 17, 1963).*

Note the close similarity between the Palo Alto and Kauai record and between the Canton Island and Tongatapu record. Note in particular the occurrence of the lower band (near 0.5 c/s) at all stations. The 180° phase shift between Kauai and Tongatapu is seen most clearly in this band (as demonstrated in fig. 9). Note also the rising-frequency fine structure, and the variation in the emission bandwidth at the different stations. The vertical band at 1400 is caused by overloading of the hourly calibration signal (1.12 c/s at Palo Alto and 1.00 c/s at the other stations). The calibration signal is preceded by a 1-min short-out period at all stations except Kauai. For this event, the crystal controlled clock at Palo Alto was found to be 25.3 sec slow. Consequently, the short-out period and calibrate signal occur late as indicated in the figure.

phenomena in a way which suggests a cause and effect relationship. Thus the source of the emissions remains a mystery. Most of the correlations reported in recent years are discussed briefly below.

a. Possible Correlations Between Occurrences of Hm Emissions and Charged Particle Events

Troitskaya [1961] reported that "very often PP are excited during periods of sharp increases of (solar flare) cosmic ray intensity in the stratosphere." Tepley [1961] found that the intense hm emissions of November 19–21, 1960, correlated closely with strong polar cap absorption. However, hm emissions observed on other occasions did not correlate well with polar cap events. Tepley and Wentworth [1962b] reported that hm emissions are sometimes present during periods of x-ray bursts and high riometer absorption, but that noise bursts (Pi 1) correlate more closely with these events than do hm emissions. Heacock [1963b] has observed that when large amplitude pearls appear quite suddenly in the auroral zone, they are accompanied by significent riometer absorption but that no riometer absorption accompanies low amplitude events characterized by a gradual increase in amplitude.

Observations of the type given above imply that a relationship exists between hm emissions and particle events. It appears, however, that the relationships may be indirect. To the writer's knowledge, *no extremely close correlations have yet been reported between occurrences of hm emissions and charged particle events.*

b. Occurrence Before Magnetic Storms

From an analysis of magnetic storms in 1959, Troitskaya et al. [1962], reported that 28 of 30 storms were preceded by pearls in the interval 0 to 12 hr before the storms. "Most frequent are cases when the pearls are observed some scores of minutes to 2 hr before the beginning of the storm." Troitskaya et al. [1962], suggest that "the corpuscular streams exciting them commence to arrive in high latitudes in advance of the main stream causing the magnetic storm."

c. Occurrence During Sudden Commencements

Tepley and Wentworth [1962b] and Troitskaya et al. [1962], observed independently that magnetic storm sudden commencements at middle latitudes are often accompanied by relatively regular oscillations near 1 c/s. More recently Heacock (private communication), has studied the same effect in the auroral zone. Sonagrams of this effect are given in figures 2 and 3 of Tepley and Wentworth [1962b]. For these two

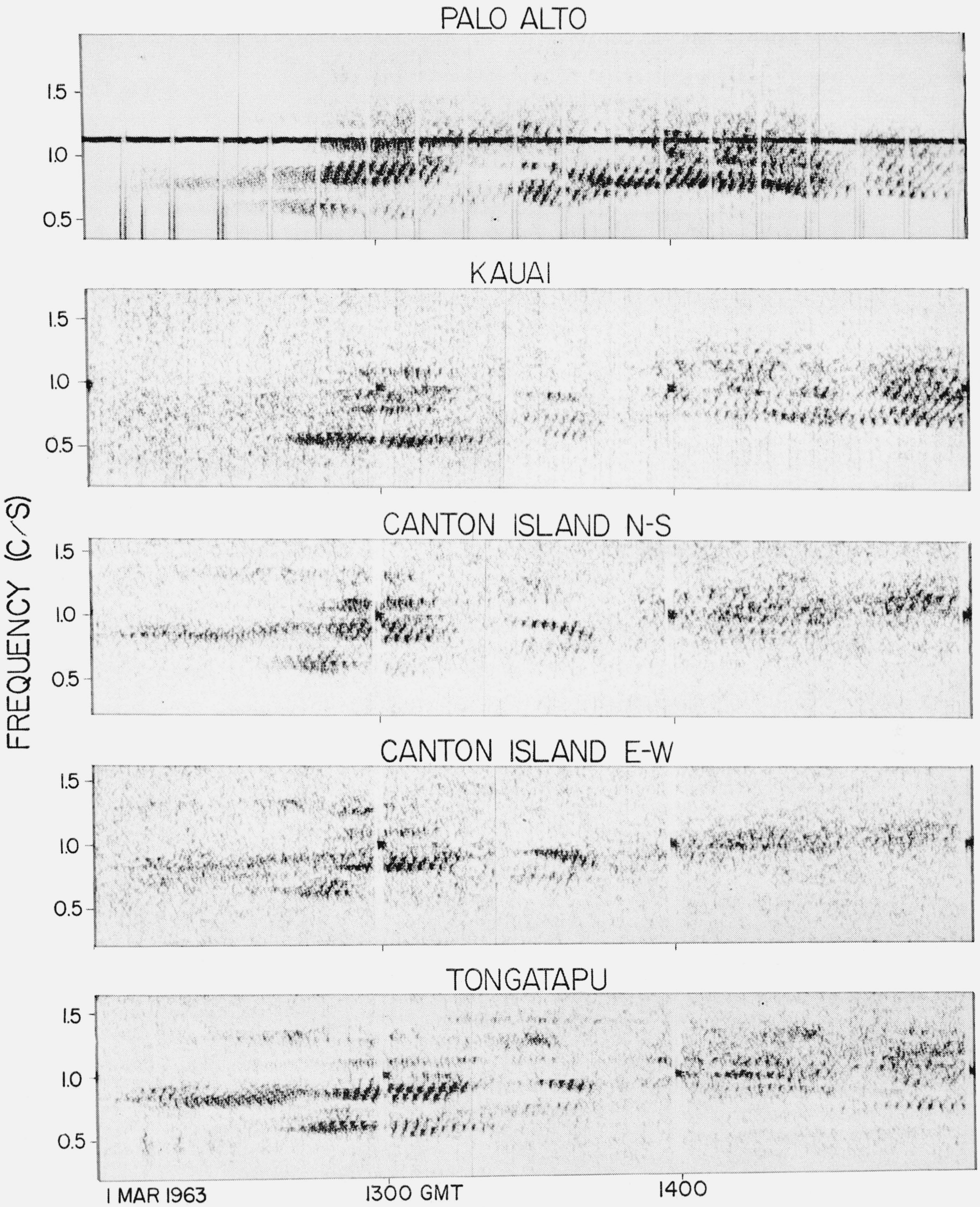


FIGURE 7. *Four-station sonagrams of hm emissions (March 1, 1963).*

During this event instrumental difficulties at Palo Alto resulted in a continuous calibration signal (at 1.12 c/s) and a short-out every 10 min. Accurate timing, however, was maintained. The event was characterized by the simultaneous occurrence of a number of narrow-band emissions at all stations. Furthermore the signal characteristics differed for the various bands. Perhaps the most unusual feature of this event is the occurrence of a double structure at Kauai in the band (or bands) just below the 1 c/s calibration signal in the time interval 1255 to 1320. There is some indication of "structure-doubling" at all stations in the bands above 1 c/s. However, the effect is shown much more clearly in figure 10.

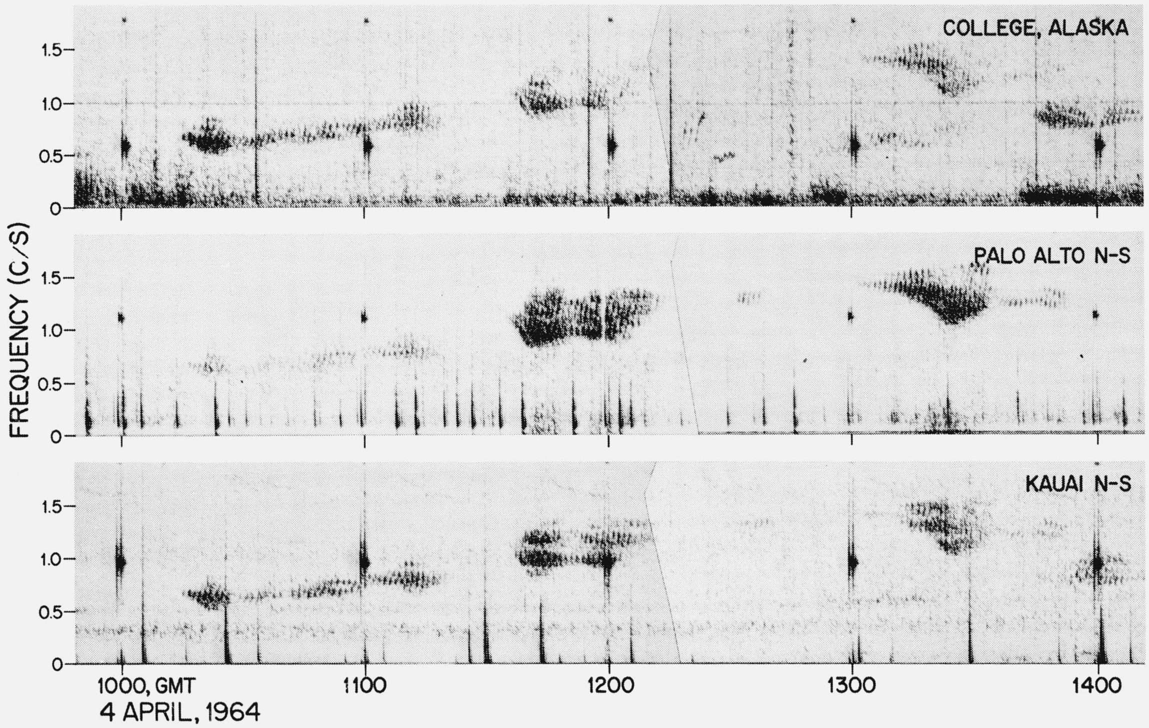


FIGURE 8. *Simultaneous occurrence of hm emissions at high, middle, and low latitudes.*

The sonagrams shown here cover an interval of about 4½ hr. Note the close similarity in the structural elements at all stations, but note also that the emission is sometimes intense at one station and faint (or sometimes absent) at another. The sonagrams from College, Alaska were prepared from magnetic tape records provided by R. R. Heacock and V. P. Hessler. The results shown in this figure were obtained during an informal cooperative project between Lockheed and the Institute of Geophysics, University of Alaska.

events, the sonagrams reveal that the events are less regular in appearance than hm emissions observed during quiet periods. Hence the signals may belong in a transition category similar to those discussed later in this paper.

d. Occurrence 2–8 Days After the Beginning of a Magnetic Storm

From a study of 25 isolated magnetic storms over a 3-year period, Wentworth [1964a] observed a strong tendency for emissions to occur in the interval 3 to 7 days after the beginning of the storm (fig. 11). The result does not imply a correlation with K_p and as discussed later, no such correlation has been observed.

e. Tendency to Occur at Times of Low Ionospheric Ion Density

Benioff [1960] suggested that type A oscillations (hm emissions) occur at times when the ionosphere becomes transparent to transmission of this type of signal, and at these times the electron density of the F layer is at a minimum. Results supporting Benioff's suggestion were obtained at Lockheed as illustrated in figure 12 where the ion (electron) density at the F_2 peak (F_0F2) is plotted as a function of local time of day at Palo Alto, Calif. Also plotted for the same period in 15-min intervals is the amplitude of several hm emission events. The inverse relationship existing between the emission amplitude and F_0F2 has also been observed for many other periods [Tepley, 1962; Wentworth, 1964b], but is not always as striking as indicated in figure 12.

As a first approximation, the ion density throughout a large part of the ionosphere may be taken to be proportional to the quantity F_0F2 [Tepley, 1962]. Hence F_0F2 might be expected to be a useful parameter in certain types of ionospheric attenuation studies. Studies of this type, conducted by Tepley [1962] and Wentworth [1963, 1964b, c] have demonstrated the importance of ionospheric attenuation on the amplitude of hm emissions observed on the ground. Of particular interest is the result shown in figure 13 which demonstrates that ionospheric attenuation is so great at middle latitudes that hm emissions generated preferentially on the daylight side of the earth would still usually be observed at night at midlatitude stations (such as Palo Alto). At higher latitudes (such as College, Alaska) where ionospheric attenuation is much less, the signals are usually observed during the daytime.

f. Occasional Tendency to Repeat at 24-Hr Intervals

Occasionally hm emissions are found to occur at about the same time for a number of nights in succession as illustrated in figure 14. This is observed most commonly in the interval 3 to 7 days after a magnetic storm as depicted in that figure and also in figure

11. The result may be partially explained in terms of ionospheric attenuation effects since low values of F_0F2 often occur at about the same time for many nights in a row. In all probability the result is also greatly influenced by conditions at the source of the emissions, that is, the source may turn on or become more intense at about the same time for many successive nights.

g. Lack of Correlation of Occurrence Times With Magnetic K_p Index

In a statistical study, Tepley [1962] found no correlation between occurrence times of the emissions and the magnetic K_p index. This result was verified by Wentworth [1964a].

3.4. Other Interesting Hm Emission Characteristics

a. Relationship Between Emission Frequency and Magnetic K_p Index

Results reported by Troitskaya [1961] indicate that, although the higher oscillation frequencies occur only rarely during quiet periods, they are relatively common during periods of unusual solar activity. In a statistical study Tepley [1962] found that high emission frequencies are more likely to occur during periods of high K_p. Troitskaya et al., [1962] have made similar observations.

b. Tendency for Emission Frequency to Increase Toward Dawn

Smith [1964] reported that "during nights when separate intervals of oscillations occur, there is a tendency for lower frequencies to occur earlier in the night and higher frequencies before dawn." We have observed a similar but not very pronounced tendency by studying times of occurrence and emission frequencies tabulated in Tepley and Wentworth [1962a]. The result may be due, at least in part, to attenuation effects. Since the higher emission frequencies are more severely attenuated in the ionosphere [Francis and Karplus, 1960], they are most likely to be observed when F_0F2 approaches its minimum value. At middle latitudes this often occurs shortly before sunrise.

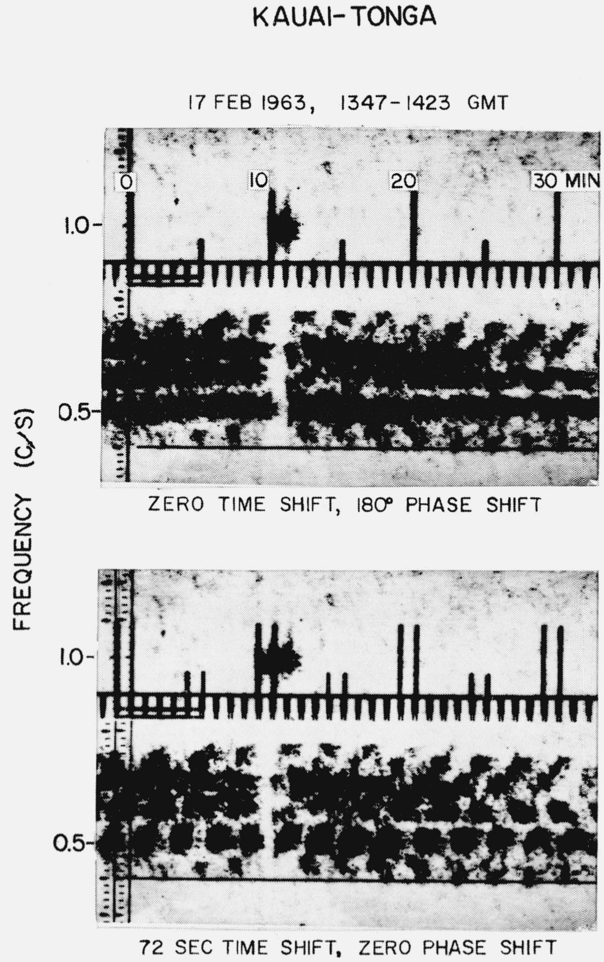


FIGURE 9. *Illustration of interhemisphere 180° fine-structure phase shift.*

An example is presented of the transparency overlay technique for measurement of phase shift. The data sample is taken from the event shown in figure 6. The top portion of the figure shows a superposition of transparencies from Kauai and Tongatapu for a 35 min time interval. The photograph includes an accurate frequency-time scale (actually a superposition of two superimposed identical frequency-time scales). Note the overall darkness of the hm emission bands, and in particular note that the band at 0.5 c/s appears as a dark line. The photograph immediately below was obtained by shifting the Kauai transparency to the left a distance equivalent to a time-interval of 72 sec. Note that on the lower picture the emission bands are lighter, and that the band at 0.5 c/s appears as a series of equally separated dark spots. Note also the change in appearance of the time scale which now appears as 2 scales separated by 72 sec.

c. Latitude Variation of Signal Amplitude

Careful studies of the variation of emission signal amplitude with latitude have not yet been conducted for a large number of stations. It is clear, however, from rapid examination of helicorder records obtained at the four Lockheed Pacific Ocean stations over a long period of time that the signal amplitude is generally largest at the middle latitude Palo Alto station and on the average decreases by a factor of about 3 for events observed simultaneously at Palo Alto and Kauai. On the average the signal amplitude is about the same at the conjugate stations Kauai and Tongatapu. The average amplitude decreases by another factor of about 3 at the near equatorial Canton Island station. It should be emphasized, however, that for specific hm emission events observed simultaneously at all stations—and especially for subintervals of specific events—there can be a large spread in the amplitude-latitude variation around the average values. This point is discussed further in the next section.

It is likely that the average signal amplitude is generally larger in the auroral zone than at middle latitudes, but the latitude of maximum signal intensity has not yet been ascertained.

d. Local Variation of Signal Amplitude

As discussed previously, the signal amplitude observed at any ground station is strongly influenced

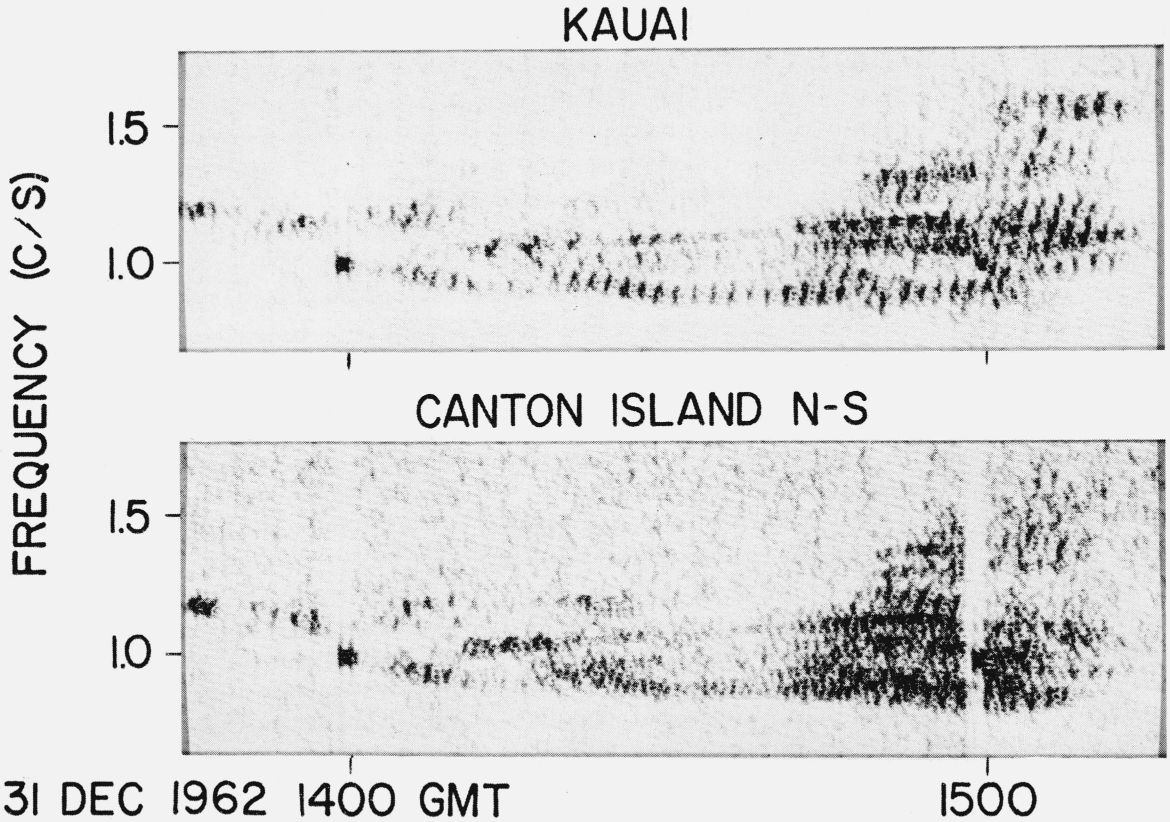
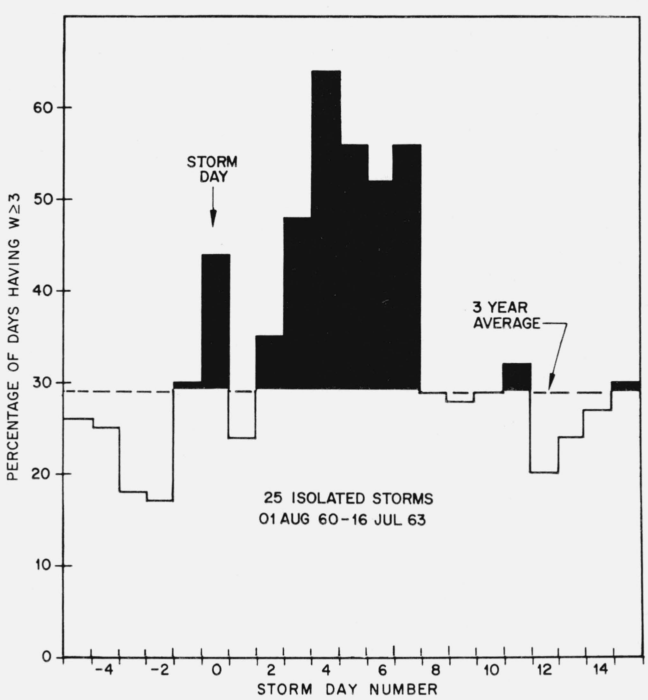


FIGURE 10. *An example of "structure-doubling."*

Note the difference in the spacing of the structural elements at Kauai and Canton Island. Also note on the Kauai record that a relatively faint emission band at a frequency of 1 c/s seems to exhibit a series of equally spaced structural elements of rapidly falling-frequency in the interval 1420 to 1430 GMT. This effect is shown more clearly in figure 1.



by hydromagnetic wave attenuation in the local ionosphere, and ionospheric conditions may vary greatly with both latitude and local time (or longitude). In a preliminary attempt to investigate this effect, Wentworth and Tepley (private communications) determined the Palo Alto-to-Kauai peak amplitude ratio for a large number of events observed simultaneously at the two stations. A plot of the ratio against Universal Time for many events showed that the time variation in the ratio was consistent with that expected due to the time variation in ionospheric conditions at the two

FIGURE 11. *Occurrences of hydromagnetic emissions relative to magnetic storms.*

The quantity W, is a logarithmic index for the number of 15 min intervals containing hm emissions in a 24 hr period. W is related to N (the number of 15 min intervals) as follows

N	W
0	0
1	1
2–3	2
4–7	3
8–15	4
16–31	5
32–63	6
64–96	7

The figure clearly shows the tendency for hm emissions to occur preferentially on the day of the storm and also 3 to 7 days after the storm.

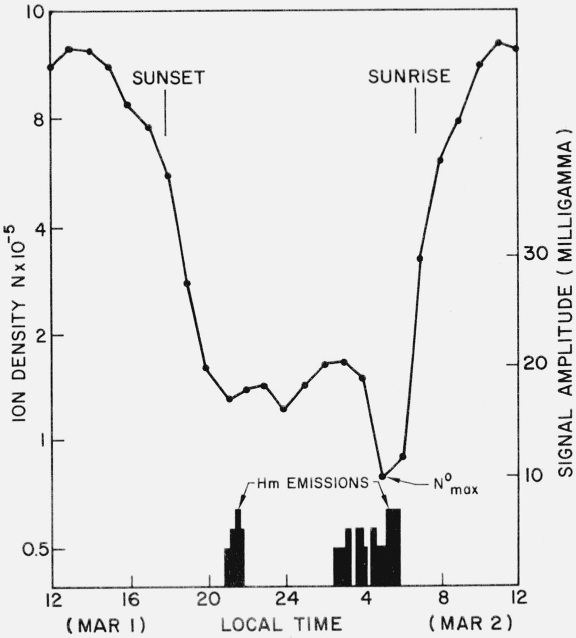


FIGURE 12. *Ion density and hm emission occurrence at Palo Alto (March 1 and March 2, 1961).*

The ion (electron) density curve represents the quantity F_0F2 and was obtained by reducing ionograms obtained from the vertical ionospheric sounder at Stanford University. The hm emission histograms represent the largest hm emission peak amplitude in the indicated 15 min interval. The emission peak amplitudes were obtained from helicorder records at the Lockheed Palo Alto magnetic observatory.

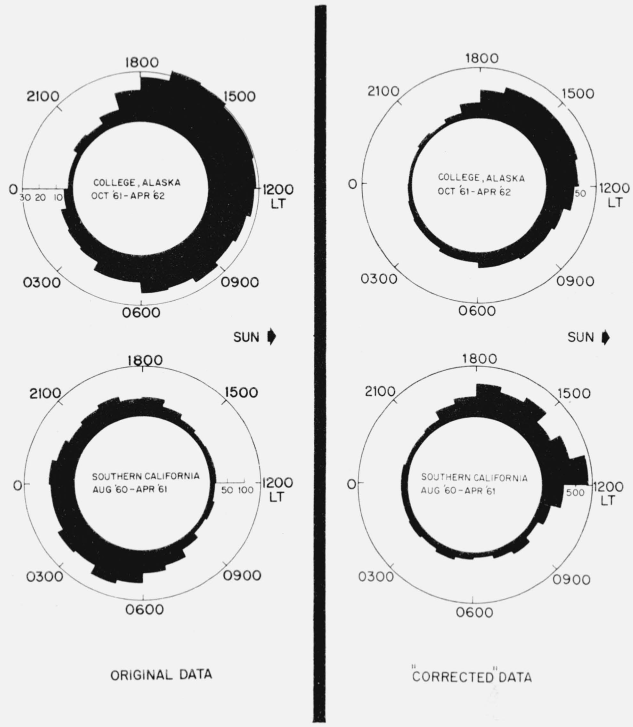


FIGURE 13. *Comparison of occurrences of hm emission events observed at sea level and estimated at 550 km.*

The polar plots at the left of the figure illustrate that hm emissions are generally observed during the day in the auroral zone and at night at middle latitudes. The polar plots at the right depict the same data after application of a theoretically calculated correction factor [Wentworth, 1964c] to take into account differences in ionospheric attenuation at the two observation stations. Thus it appears that hm emissions are generated preferentially on the daylight side of the earth but are usually observed at night at midlatitude stations because of the heavy daytime midlatitude ionospheric attenuation of downward propagating hydromagnetic waves.

stations. However, an extremely large scatter was found in the plotted points; this indicates that the signal amplitude at a ground station may also be greatly effected by conditions other than ionospheric attenuation. The result is not in conflict with the close resemblance of *f-t* characteristics of emissions occurring simultaneously at widely separated stations. Although individual structural elements can often be observed simultaneously at great distances (figs. 6, 7, and 8), the intensity of the elements may vary greatly. The structural elements often occur in "patches" of greatly varying intensity at the different stations; the patches may even be very strong at one station and absent at another. Also *f-t* displays only indicate intensity in a qualitative manner, and attempts to measure this quantity from such displays are apt to be misleading.

A number of workers have reported large variations of signal amplitude for emissions observed simultaneously at stations separated by less than 1000 km. This effect may be more pronounced at stations near the auroral zone [Campbell, 1964].

e. Variation of Emission Frequency With Latitude

From studies of waveform records it has been found that higher emission frequencies tend to occur more frequently and with higher amplitudes at relatively low latitude stations [Tapley and Wentworth 1962b; Heacock and Hessler, 1962; Troitskaya et al., 1962; Gendrin, 1963a, c]. The effect would probably stand out less clearly on *f-t* displays since these displays provide only a crude measure of signal amplitude.

f. Relationship Between Emission Frequency and Fine-structure Repetition Frequency

Statistically the fine-structure repetition frequency tends to decrease with increasing latitude in the same way as does the emission frequency. The experimentally observed relationship between these two quantities is shown in figure 4.

4. Other Types of Emissions in the Pc 1 Category

Although investigations of hm emissions have recently stimulated considerable scientific interest, it should be kept in mind that there may be other types of signals in the Pc 1 category of comparable scientific importance. It may sometimes be difficult to distinguish between different types of Pc 1 emissions since, as discussed earlier, transitions between categories appear to be continuous. However, in this section we briefly discuss two other types of events which may be placed in reasonably well-defined subcategories.

4.1. Continuous Emissions

In figure 15, a series of sonagrams are presented showing the presence of bands of energy observed

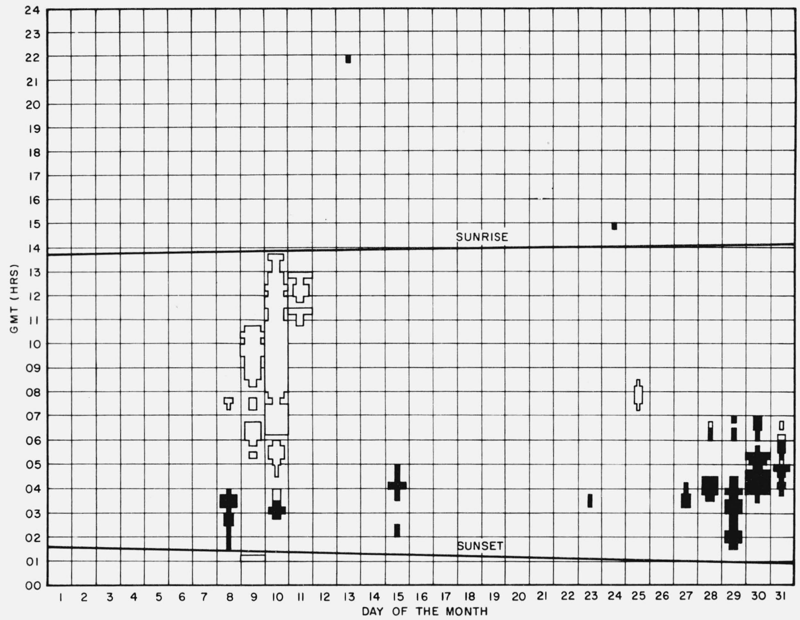


FIGURE 14. *Occurrences of hm emissions in Southern California (October 1960).*

The figure consists of a number of rectangles (many of which are adjacent) representing the occurrences of hm emissions in 15 min intervals. The horizontal dimension of the rectangle is proportional to the maximum emission amplitude in the 15 min interval specified by the location and vertical dimension of the rectangle. Darkened and nondarkened rectangles represent emissions occurring in the frequency range 0.5 to 1.5 c/s and 1.5 to 2.5 c/s respectively. Also plotted is the magnetic K_p index. The figure illustrates (a) the nocturnal occurrence of hm emissions at middle latitudes, (b) the tendency for emissions to occur after magnetic storms and (c) the occasional tendency for emissions to occur at about the same time for a number of nights in a row. The data were obtained through the courtesy of H. Benioff at Caltech. Similar plots for a 9 month interval are presented in Tepley and Wentworth [1962b].

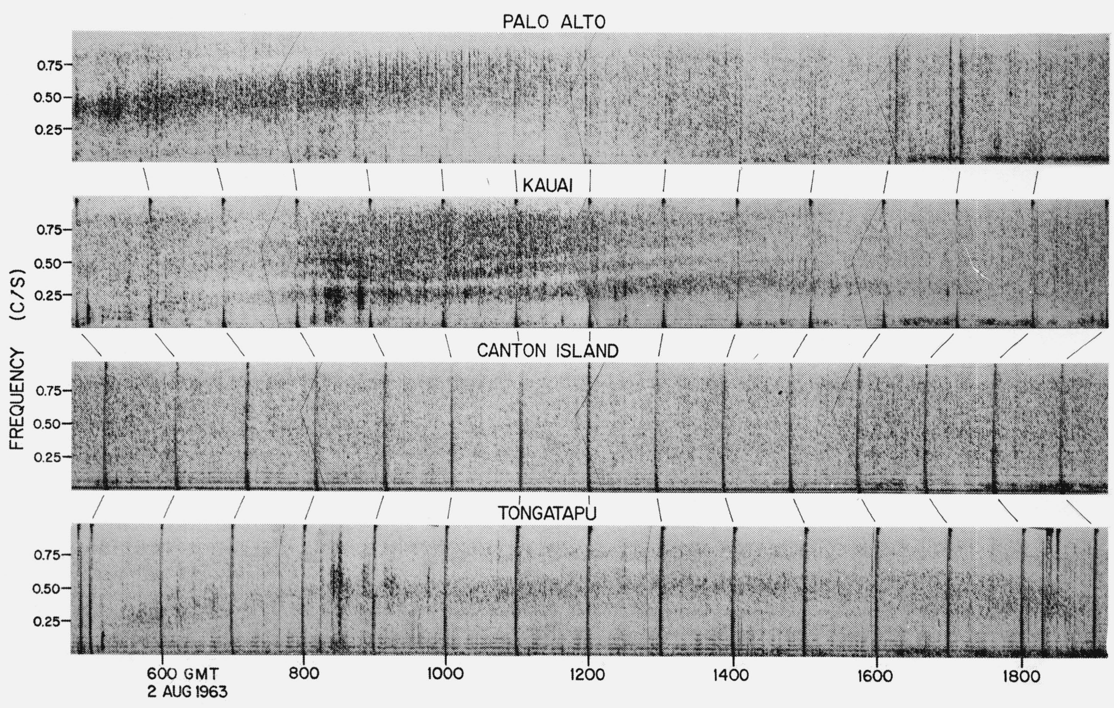


FIGURE 15. *Four-station sonagrams of continuous sub-ELF emissions (Aug. 2, 1963).*

Continuous emissions are observed at the Lockheed Pacific Ocean Stations at Palo Alto, Kauai, and Tongatapu. Note the different appearance of the bands at the different stations. In particular note that at Kauai, three bands are observed simultaneously in the interval 0800 to 1300. Note also that the mid-frequencies of all bands increase slowly throughout the night and then decrease relatively rapidly near sunrise (the effect is not observed at Palo Alto where the signal fades out in the middle of the night). In the time interval 1000 to 1900, signals are observed simultaneously at all stations at frequencies below 0.1 c/s. These represent long period micropulsations. The series of faint equally spaced horizontal narrow bands which are observed all across the sonagrams at frequencies below 0.2 c/s result from instrumental noise.

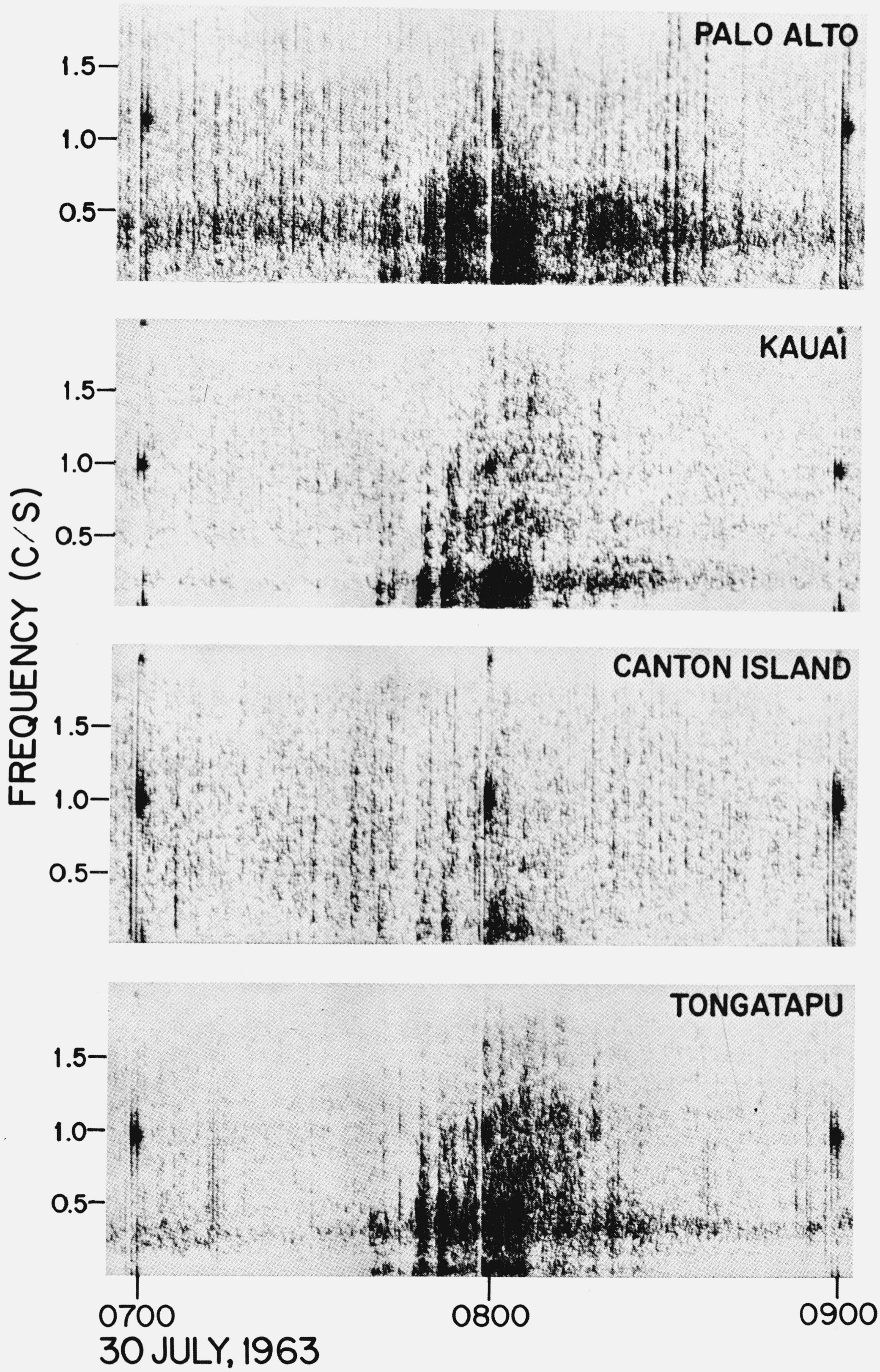


FIGURE 16. *Four-station sonagrams showing excitation of bands of burstlike signals (July 30, 1963).*

The signals around 0800 resemble noise-bursts (Pi 1) but also contain traces of a rising frequency fine structure. In addition some of the signal energy is concentrated into relatively narrow bands which are also observed faintly before and after the intense portion of the signal. Thus it appears that the burstlike emissions excite resonant oscillations (possibly in the lower exosphere) or are intensified by the existence of natural resonance bands.

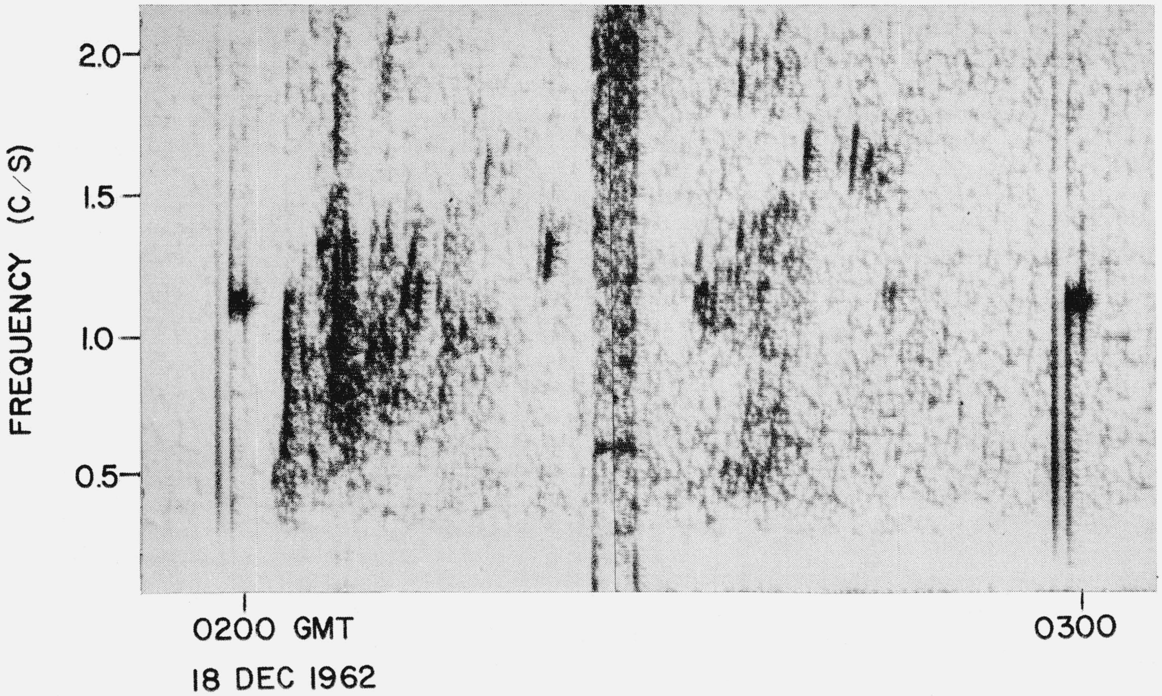


FIGURE 17. *Storm-time sub-ELF emission (gurgler) observed at Palo Alto (Dec. 18, 1962).*

Note the irregularly spaced structural elements of very rapidly rising frequency. The vertical band in the center of the sonagram is of instrumental origin. It is associated with the dead-time of the tape recorder when magnetic tapes were being changed in the middle of the event.

throughout most of the night at Palo Alto, Kauai, and Tongatapu. The signals are referred to as "continuous emissions" because of their characteristic duration of many hours (often throughout the entire night) in contrast to hm emissions which typically last about 1 to 2 hr. The signals are sometimes observed for many nights in succession: for example, in the period August 5 to 20, 1963 they were observed every night at Palo Alto. They do not ordinarily exhibit a repetitive fine-structure as do hm emissions, but hybrid signals are sometimes observed between the continuous and hm emission categories.

The properties of continuous emissions are discussed in more detail elsewhere [Tepley and Amundsen, 1964b]. In that paper, a possible origin of the signals is discussed in terms of hydromagnetic resonance effects in the lower exosphere as indicated in theoretical calculations by Jacobs and Watanabe [1962] and more recently by Prince and Bostick [1964]. The existence of such resonance effects is also suggested by observations of signals resembling continuous emissions which are sometimes observed faintly before and after a burstlike emission but are greatly enhanced during the burst [Tepley, Wentworth, and Amundsen, 1964 a, b. Also see fig. 16.] In addition a tendency toward band formation is sometimes observed on sonagrams of the storm-time emission considered briefly below [Tepley, Wentworth, and Amundsen, 1964 a, b]. If pronounced resonance effects actually exist in the lower exosphere, they might also significantly influence the spectral energy distribution of hydromagnetic emissions which, are supposedly generated at much higher altitudes.

4.2. Emissions Observed During Magnetic Storms (Gurglers)

Hydromagnetic emissions may be observed during magnetic storms as well as during quiet periods. In addition other types of signals may be observed, particularly during stormy periods, which are less regular in appearance than the oscillatory hydromagnetic and continuous emissions but are more regular than noise bursts (Pi 1). Signals referred to as SIP and IPDP by Troitskaya [1961] may possibly be placed in this transition category. A sonagram of an interesting transition-category signal is presented in figure 17. The signal is characterized by a rising frequency fine structure similar to that of hm emissions but the structural elements do not repeat periodically. We refer to these signals as "storm-time emissions" since all events observed so far have occurred during magnetically disturbed periods—often in conjunction with magnetic bays. We also refer less formally to the signals as "gurglers" since when monitored aurally on "time-compressed" magnetic tape (speed-up factor of 1000 to 2000), the signals are characterized by a sound similar to bubbles being blown underwater. Properties of these signals are discussed in more detail elsewhere [Tepley and Amundsen 1964a; Tepley, Wentworth, and Amundsen, 1964b].

The work reported above conducted at Lockheed was supported by the following Government agencies:

(1) AFCRL under contracts AF 19(604)–5906 and AF 19(628)–462; (2) NASA under contract NAS 5–3701 (3) ONR under contract NOnr–4454(00). A number of individuals participated in the operation of the Lockheed Pacific Field Stations including K. D. Amundsen, D. R. Hillendahl, K. G. Lambert, H. V. Prentiss, and R. C. Wentworth. Also K. D. Amundsen and R. C. Wentworth were largely responsible for reduction and analysis of much of the Lockheed data. I would like to acknowledge R. R. Heacock and V. P. Hessler for permission to use their College, Alaska, data shown in figure 8. Finally I would like to acknowledge M. Walt for his helpful criticisms of this manuscript.

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