Recent Investigations of Hydromagnetic Emissions Part I. Experimental Observations

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Abstract

A review is presented of some of the more important properties of Pc 1 (0.2–5 cps) 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) *Simultaneity 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) *Times 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_oF_2 .

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 1000–2000), it is characterized by a sound similar to bubbles blown under water.

1. Introduction

Part I of this paper reviews some of the more important properties of signals in the Pc 1 category (regular oscillations in the frequency range 0.2–5 cps). Emphasis is placed on relatively recent results obtained at Lockheed, but 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* (1964). Emphasis is also placed on observations at middle and low latitudes, but results of some high latitude observations are also presented.

Most of Part I 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 Part II various models are considered for the generation and propagation of the signals.

Brief mention is also made in Part I 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 0.05–1 cps).

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) to describe regular oscillations in the frequency range 0.2–5 cps 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 sub-categories are defined, the possibility always exists of finding hybrid signals between these sub-categories. 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 3 sub categories which (presumably) describe the same type of signal. The sub categories referred to as fine-structured regular, non-structured regular, and fine-structured semi-regular 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 among the 3 sub categories. 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 (0.2–5 cps)

- 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, 1962 b)
 4. CpSp, CpLp (Yanagihara, 1963)
 5. Hydromagnetic Whistlers (Obayashi, 1964; Jacobs and Watanabe, 1964 b)
- B. Non-structured regular oscillations (<1 cps)
 1. Type B oscillations (Benioff, 1960)
 2. CpLp (Yanagihara, 1963)
 3. Continuous emissions (Tepley and Amundsen, 1964 b)
- C. Fine-structured semi-regular oscillations
 1. IPDP (Troitskaya, 1961)
 2. SIP (Troitskaya, 1961)
 3. Storm-time emissions (gurglers) (Tepley and Amundsen, 1964 a)

In the following sections, the writer will use the term “Hydromagnetic (hm) emission” to describe signals in the sub category of fine-structured regular oscillations. The term “Pearl” will also be used occasionally to describe the same type of signal when referring to results reported 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 some-

times 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 (see Figure 1a where $\Delta f/f_c \approx 1/10$). A number of such narrow-band emissions are sometimes observed simultaneously at slightly different center frequencies. In Figure 1b a series of narrow-band emissions merge and then separate. 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 broad-band emissions, the fine structure can usually be interpreted as a series (or several successive series) of repetitive overlapping wavetrains of rapidly rising frequency. Typically the slope, df/dt , of each wavetrain is on the order of 0.1 cps/min. The slope of successive wavetrains 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 wavetrains are rare. More often hm emissions

Fig. 1 Narrow and broad-band hm emissions containing both rising and falling frequency fine structure. The upper sonagram illustrates a narrow-band hm emission. Note the slow increase in intensity of successive structural elements which exhibit both rising and falling frequencies. The time spacing between 10 structural elements is indicated on the sonagram by $10T$, where T is the fine structure repetition period. The lower sonagram depicts a broad-band emission which 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 component of a lightning induced eferic. 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.

Fig. 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. Many hm emissions (such as the event in Figure 3) may be interpreted as being made up of a superposition of events (displaced in time) similar to the event shown in this figure. The fan-shaped characteristic of this event may be interpreted as indicating dispersion of a bouncing hydromagnetic wave packet. Assuming this to be the case Wentworth has studied the dispersion characteristics of a number of hm emissions (part II of this paper). He found the dispersion for this particular event to be exceptionally large and attributed this result to an extremely low value of magnetospheric ion density at the time of the event. This result may be due to the fact that the event occurred shortly after a sudden commencement of a magnetic storm and may indicate a reduced magnetospheric ion density at that time.

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 wavetrains resembles the event in Figure 2. However in other intervals (0740–0750 and 0815–0825), two series of wavetrains of different slopes seem to be occurring simultaneously.

The decrease of slope of successive wavetrains in a series of structural elements is suggestive of dispersion of a hydromagnetic wave packet bouncing between hemispheres and closely guided by the geomagnetic field. Recent work by *Booker and Dyce* (1963) and *Jacobs and Watanabe* (1964) indicates that close field-line guidance is plausible for the left-hand polarized hydromagnetic wave (sometimes called the “Alfvén” or “Ion Cyclotron” wave). The wave packet will exhibit noticeable dispersion, however, only when the wave frequency approaches the local cyclotron frequency. For hm emissions this is likely to occur only in the vicinity of the equatorial plane when the wave packet is moving along relatively high latitude field lines. Under reasonable assumptions for exospheric plasma density and magne-

Fig. 3 Comparison of frequency-time and amplitude-time displays. The sonagram shows a portion of a broad-band 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 0740–0750 and 0815–0825 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.

tic field strength, Wentworth has recently shown that the apparent dispersion of the hm emission of Figure 3 is consistent with propagation of a bouncing wave packet at $L=6$ (refer to Part II of this paper).

The broad-band emission of Figure 3 is rather unusual in that both the bandwidth and the mid-band frequency remain almost constant for the one-hour period indicated. (In Figure 4 an unusual event is shown in which the center frequency increases by a factor of two in 15 minutes.) 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 magnetical-

Fig. 4 Hm emission observed during a magnetically disturbed period. During the three-hour period including the time interval shown here, the magnetic Kp index increased abruptly. The emission shown here was first observed at 0740. The emission frequency (initially 0.6–0.8 cps) remain approximately constant until about 0820 at which time it increased abruptly as shown above. Also at 0820 irregular long period micropulsation activity commenced. Note the impulsive noise burst at 0832 after which time the emission characteristics change abruptly and the emission is apparently broken up into two bands. (A magnetic paywas Recorded Starting at 832). This event was of relatively low amplitude (5–20 milligammas) and is partially obscured by background noise presumably due to sub ELF sferics. The early portion of the event (0815–0830) is characterized by regularly spaced elements of rapidly rising frequency, but—in contrast to most hm emissions—the structural elements exhibit an increasing slope with increasing time. Despite the relatively poor signal-to-background noise ratio, this event is one of the most unusual ever recorded at the Lockheed Palo Alto Magnetic Observatory.

ly 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 wavetrains are less likely to overlap than in broad-band emissions.

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

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 Figure 5 of this paper).

A type of fine-structured emission is sometimes observed during magnetic storms in

Fig. 5 Plot of fine-structure repetition period vs. hm emission period at 3 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 Faret, France (Lat. 50.4°), and Palo Alto, California (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.

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 4 of this paper.

An amplitude-time (waveform) display of a broad-band hm emission can be interpreted as a superposition of overlapping wavetrains of rapidly rising frequency; the amplitude at any particular time is then the vector sum of the amplitudes of overlapping wavetrains. Since the amplitude of each wavetrain may vary irregularly, the amplitude of the resultant wavetrain 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 broad-band emission tends to vary symmetrically about the base line; 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 Figure 3). Descriptive terms such as "pearl necklace," "pearl beads," etc., do not adequately describe broad-band 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 relatively narrow-band emissions exhibit little or no overlapping. The elements are represented by well-separated repetitive wavetrains 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 broad-band 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

Fig. 6 Locations of Pacific Ocean micropulsation recording stations. Geographic latitudes are indicated at the left of the map. Geomagnetic latitudes are indicated at the right. The middle and low latitude stations at Palo Alto, Kauai, Canton Island, and Tongatapu were operated continuously by Lockheed for about 1 1/2 years. Results obtained at these stations are illustrated in Figures 7 and 8. The station at College, Alaska was operated by the Geophysical Institute, University of Alaska. The station at Christchurch, New Zealand was operated by the University of Canterbury. Results obtained by comparing hm emission data recorded simultaneously at College, Palo Alto, Kauai and Christchurch are shown in Figure 9 and also in Tepley, et al. (1965). Note that 5 of the 6 stations were located close to the same geomagnetic meridian (260°E). In addition the station pairs Palo Alto : Christchurch and Kauai : Tongatapu were located at approximately conjugate geomagnetic latitudes.

Fig. 7 Four station sonagrams of hm emissions (17 February 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 cps) at all stations. The 180° phase-shift between Kauai and Tongatapu is seen most clearly in this band (as demonstrated in Figure 10). 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 cps at Palo Alto and 1.00 cps at the other stations). The calibration signal is preceded by a one-minute short-out period at all stations except Kauai. For this event, the crystal controlled clock at Palo Alto was found to be 25.3 seconds slow. Consequently, the short-out period and calibrate signal occur late as indicated in the figure.

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.*, 1963; *Smith*, 1964) and also at conjugate auroral latitudes (*Lokken et al.*, 1963; *Yanagihara*, 1963; *Dawson and Sugiura*, 1964). 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 has been found in signals observed at widely separated Pacific Ocean Stations (locations are shown in Figure 6). For example, by studying the series of sonagrams of the events of Figures 7 and 8 we see that the individual f - t structural elements are almost identical at the four Lockheed Middle and Low Latitude Pacific Ocean 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 simultaneously in the auroral zone and at middle and low latitudes is shown in Figure 9 (taken from *Tepley et al.*, 1965). 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.

Fig. 8 Four-station sonagrams of hm emissions (1 March 1963). During this event instrumental difficulties at Palo Alto resulted in a continuous calibration signal (at 1.12 cps) and a short-out every 10 minutes. 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 aspect of this event is the occurrence of a double structure at Kauai in the band (or bands) just below the 1 cps calibration signal in the time interval 1255–1320. There is some indication of “structure-doubling” at all stations in the bands above 1 cps. However, the effect is shown much more clearly in Figure 11.

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 absorptior and with other unknown effects, frequently occur (see Section 3.4).

Fig. 9 Simultaneous occurrence of hm emissions at high, middle and low latitudes. The f - t characteristics of this rather complex event are closely similar at all stations. The signal at Palo Alto, however, is relatively weak (except near 1400). This may be attributed to the increase in ionospheric hydromagnetic wave absorption attenuation near local sunrise (about 1340) at this station. For this event the signal at College more closely resembles the signal at Kauai than it does the signal at Palo Alto. The same effect has been noted for other hm emission events observed simultaneously at College, Palo Alto, and Kauai (Tepley *et al.*, 1965), thus indicating that signal characteristics change more rapidly with longitude than with latitude.

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. In early measurements (Tepley *et al.*, 1963; Tepley, 1964), it was found that for emissions observed simultaneously at stations in the same hemisphere, the f - t structural elements occurred simultaneously within

Fig. 10 Transparency overlay technique for measurement of inter-hemisphere 180° fine-structure phase-shift. The data sample shown here 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 minute 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 cps 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 seconds. Note that on the lower picture the emission bands are lighter, and that the band at 0.5 cps 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 seconds. A different technique for the measurement of phase shift is illustrated in Figure 12.

a measurement accuracy of ± 12 seconds. 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 employed for measuring this time shift is shown in Figure 10.

A doubling of the fine structure repetition frequency is also observed occasionally at

Fig. 11 An example of structure doubling. Note that the structural elements at Canton Island are more closely spaced than those at Kauai. This effect—referred to as “structure doubling”—is attributed to a superposition at Canton Island of signals characterized by 180° phase shift at stations at higher latitudes in the northern and southern hemispheres. These signals must propagate across the magnetic field to reach Canton Island from higher latitudes. The propagation may occur either above, in, or below the ionosphere. Note on the Kauai record the a relatively faint emission band at a frequency of 1 cps seems to exhibit a series of equally spaced structural elements of rapidly falling frequency in the interval 1420–1430 G.M.T. This effect is shown more clearly in Figure 1b.

middle and low latitude stations (*Tepley et al.*, 1963; *Tepley*, 1964; also Figures 8 and 11 of this paper). This effect is presumably due to a superposition of structural elements which would exhibit a 180° phase shift when observed at stations in opposite hemispheres.

The result of inter-hemisphere 180° fine structure phase shift was based on analysis of eight separate emission 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 et al.* (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 1100–1110 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 minutes) 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 wave-

form record.

More recently *Pope* (1964), *Campbell* (1964), and *Gendrin and Troitskaya* (1964) have given preliminary results from high latitude conjugate area stations which seem to verify the 180° interhemisphere fine-structure phase shift within the measurement accuracy indicated above. The results of Pope and Campbell are based on a comparison of sonagrams obtained from magnetic tape data recorded simultaneously at conjugate stations. Gendrin and Troitskaya have also used this technique and have also compared waveform records.

It is difficult to measure time with high accuracy from sonagrams. Hence comparison of occurrence times of structural elements from sonagrams is not well-suited for the determination of smalltime 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 is best made from waveform records which are, however, subject to the difficulties discussed previously. A preliminary waveform measurement showing a 4 second time shift between Palo Alto and Kauai was reported by *Tepley et al.* (1963). More recently *Smith* (1964)

Fig. 12 "Cultured pearl" technique for measurement of intra-hemisphere fine-structure phase shift. The sonagrams at the upper left of this figure show broad-band hm emissions observed simultaneously at Palo Alto and Tongatapu. The sonagrams at the upper right of the figure show the corresponding narrow-band emissions produced in the laboratory by passing the broad-band emissions through a narrow-band filter. The chart records at the bottom of the figure show waveforms ("cultured pearls") of the narrow-band emissions for the time periods indicated. Comparison of the waveform records clearly shows the 180° phase shift between Palo Alto and Tongatapu. The technique illustrated in this figure permits the preparation of waveform records from which small time shifts (or phase shifts) can be measured with high accuracy. In contrast waveforms of broad-band emissions generally exhibit an irregular amplitude modulation pattern which does not ordinarily permit a comparison of waveform elements at widely separated station.

Fig. 13 Preliminary results of intra and inter-hemisphere phase shift obtained from the "cultured pearl" technique. The upper portion of this figure shows the measured time lag between Palo Alto and Kauai for 10 cultured pearl events (the data reduction and analysis technique is illustrated in Figure 12). Note that for all events the signal arrives earlier at Palo Alto than at Kauai. The lower portion of the figure shows preliminary results of interhemisphere phase shift between Palo Alto and Tongatapu obtained by the same data reduction technique. For the 5 events shown the phase shift is always greater than 180° but it can be demonstrated that the difference is within the statistical error associated with the measurement of small time shifts due to intra-hemisphere propagation.

north-south direction. East-to-west propagation cannot be ruled out, but if we consider the present result in conjunction with the independent observation (discussed later) that the signal amplitude is usually greater at Palo Alto than at Kauai, it appears that the signal source is north of Palo Alto.

Also shown in Fig. 13 are preliminary results of fine-structure phase-shift between the difference between the measured phase-shifts and a phase shift of 180° may be attributed (within measurement accuracy) to the phase shift associated with intra-hemisphere propagation times on the order of those indicated above. Hence our results indicate an inter-hemisphere phase-shift of 180° . This result is in apparent conflict with recent preliminary results of Gendrin and Troitskaya (1965) on inter-hemisphere fine-structure phase-shift. These workers obtain phase-shifts which differ from 180° by amounts which they consider

reported a 2–3 second time shift between Oregon and Teas.

An extensive study of propagation time-shifts is now underway at Lockheed. Time-shifts are determined from waveform records: In order to minimize the measurement uncertainty which arises because broad-band waveforms consist of a super-position of overlapping structural elements, measurements are made only from "pearl" waveforms (pearls being the waveform elements of narrow-band emissions). Since pearls occur relatively rarely at middle and low latitudes, the present Lockheed study utilizes "cultured pearls" (a term suggested by J.R. Winckler). These are prepared in the laboratory by passing broad-band hf emissions through a narrow-band filter. The data reduction technique is illustrated in Figure 12.

Preliminary results of the study, obtained by *Wentworth and Tepley* (1965), are shown in Fig. 13. For the 10 events considered the signal at Palo Alto was found to always lead the signal at Kauai by between 1 and 6 seconds. This is interpreted as indicating that in the northern hemisphere, hf emissions have a propagation velocity component in the

significantly greater than their measurement uncertainties.

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 known geophysical phenomena in a way which suggests a cause and effect relationship. Thus the source of the emissions remains a mystery and can only be predicted from theoretical considerations (see Part II of this paper). 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 Nov. 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 significant riometer absorption but that no riometer absorption accompanies low amplitude events characterized by a gradual increase in amplitude.

As discussed in Part II, theoretical considerations suggest that hm emissions may be generated by trapped protons of relatively low energies (2–80 keV) near the equatorial plane at L values of 3 to 8. It would therefore be of special interest to search for a correlation between hm emission occurrence times and increases in low energy trapped proton fluxes observed by satellites. Although satellite data of the desired type are not yet available, the following recent observations may be of some interest:

- 1) Satellite observations by *Davis and Williamson* (1963) first revealed the existence of a high intensity belt of 100 keV–4.5 MeV protons from 2 earth radii to the edge of the magnetosphere. It was found that shortly after the sudden commencement of the severe magnetic storm of Sept. 30, 1961, the intensities of low pitch angle ($\alpha \leq 34^\circ$) protons in this belt increased by a factor of about 3 and remained high through Oct. 1 and Oct. 2 (*Davis and Williamson*, 1963). Hm emissions were observed at Palo Alto for 9 consecutive hours on Oct. 1 (*Tepley and Wentworth*, 1963).

- 2) We have recently compared our data on occurrences of hm emissions at Palo Alto with increased counting rates for low energy protons (5–250 keV) observed on a low altitude polar orbiting satellite. The satellite was launched on 30 October 1963, shortly after the beginning of a magnetic storm. During the period 01–03 November, the satellite recorded intense proton fluxes in the auroral zones. During the same period intense hydromagnetic emission activity was recorded at the Lockheed Magnetic Observatory near Palo Alto, California (*Cladis et al.*, 1965).

Since hm emission activity is often observed to increase several days after the beginning of a magnetic storm (as discussed further below), the observations reported above are only

suggestive of a close correlation. It may also be of interest that in recent satellite measurements (*Williams and Smith, 1965*), it has been found that at $L \geq 3$, the intensities of relatively high energy trapped electrons (≥ 280 keV and ≥ 1.2 MeV) tend to peak 2-4 days after the start of a magnetic storm.

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. (1963)* reported that 28 of 30 storms were preceded by pearls in the interval 0-12 hours before the storms. "Most frequent are cases when the pearls are observed some scores of minutes to 2 hours before the beginning of the storm." *Troitskaya et al. (1963)*, suggest that "the corpuscular streams

Fig. 14 Occurrence of hydromagnetic emissions relative to magnetic storms. The quantity W is a logarithmic index for the number of 15 minute intervals containing hm emissions in a 24 hour period. W is related to N (the number of 15 minute intervals) as follows

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

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

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 (1962 b) and *Troitskaya et al.* (1963) observed independently that magnetic storm sudden commencements at middle latitudes are often accompanied by relatively regular oscillations near 1 cps. More recently Heacock (private communication) has studied the same effect in the auroral zone. Sonograms of this effect are given in Figures 2 and 3 of *Tepley and Wentworth* (1962 b). For these two events, the sonograms 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* (1964 a) observed a strong tendency for emissions to occur in the interval 3-7 days after the begin-

Fig. 15 Ion density and hm emission occurrence at Palo Alto (Mar 1 and Mar 2, 1961). The ion (electron) density curve represents the quantity F_oF_2 and was obtained by recluring 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 minute interval. The emission peak amplitudes were obtained from helicorder records at the Lockheed Palo Alto magnetic observatory.

ning of the storm (Figure 14). The result does not imply a correlation with Kp and as discussed later, no such correlation has been observed. However, as discussed above, certain types of particle events may exhibit the same tendency.

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 15 (from *Tepley and Wentworth, 1962a*) where the ion (electron) density at the F_2 peak (F_oF_2) is plotted as a function of local time of day at Palo Alto, California. Also plotted for the same period in 15-minute intervals is

Fig. 16 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 absorption 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 mid-latitude stations because of the heavy daytime mid-latitude ionospheric absorption of downward propagating hydromagnetic waves.

the amplitude of several hm emission events. The inverse relationship existing between the emission amplitude and F_0F_2 has also been observed for many other periods (Tepley, 1962; Wentworth, 1964 b), but is not always as striking as indicated in Figure 15.

As a first approximation, the ion density throughout a large part of the ionosphere may be taken to be proportional to the quantity F_0F_2 (Tepley, 1962). Hence F_0F_2 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, 1964 b, c) have demonstrated the importance of ionospheric absorption on the amplitude of hm emissions observed on the ground. Of particular interest is the result shown in Figure 16 which demonstrates that

Fig. 17 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 minute intervals. The horizontal dimension of the rectangle is proportional to the maximum emission amplitude in the 15 minute interval specified by the location and vertical dimension of the rectangle. Darkened and nondarkened rectangles represent emissions occurring in the frequency range 0.5–1.5 cps and 1.5–2.5 cps respectively. Also plotted is the magnetic Kp 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 Dr. H. Benioff at Caltech. Similar plots for a 9 month interval are presented in Tepley and Wentworth (1962 b).

ionospheric absorption 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 mid-latitude stations (such as Palo Alto). At higher latitudes (such as College, Alaska) where ionospheric absorption is much less, the signals are usually observed during the daytime.

f. Occasional tendency to repeat at 24-hour intervals

Occasionally hm emissions are found to occur at about the same time for a number of nights in succession as illustrated in Figure 17. This is observed most commonly in the interval 3–7 days after a magnetic storm as depicted in that figure and also in Figure 14. The result may be partially explained in terms of ionospheric attenuation effects since low values of F_0F_2 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. Little is known at present about the source although a number of theoretical models (reviewed in Part II of this paper) have been presented recently relating the source to protons trapped in the magnetosphere. In this connection *Jacobs and Jolly* (1962) have reported 2 cases in which onset times of hm emission events were measured at a number of stations at well separated longitudes around the world. The onset times indicated a drift of the hm emission event in a westerly direction. The results could be interpreted as indicating a relationship between the emissions and a stream of protons of approximate solar wind energies drifting in the same direction. Alternatively the observation might only indicate a relationship between the emissions and low values of F_0F_2 which also drift in a westerly direction as do all other phenomena which are approximately fixed respect to the sun-earth line.

g. Lack of correlation of occurrence times with magnetic Kp index

In a statistical study, *Tepley* (1962) found no correlation between occurrence times of hm emissions and the magnetic *Kp* index. This result was verified by *Wentworth* (1964 a).

3.4 Other interesting hm emission characteristics

a. Relationship between emission frequency and magnetic Kp 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 *Kp*. *Troitskaya et al.* (1963) 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* (1962 a). The result may be due, at least in part, to absorption 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_0F_2 approaches its minimum value. At middle latitudes this often occurs shortly before sunrise.

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 Tongataqu. 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 sub intervals 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 at any ground station is strongly influenced by hydromagnetic wave attenuation in the local ionosphere, and local ionospheric conditions may vary greatly with both latitude and local time (or longitude). In a preliminary attempt to investigate this effect, *Wentworth and Tepley (unpublished paper)* determined the Palo Alto-to-Kauai peak amplitude ratio for a large number of events observed simultaneously at the 2 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 time variation in ionospheric conditions at the 2 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 affected by conditions other than ionospheric absorption. 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, (Figure 7, 8 and 9), 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 kilometers. 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 low latitude stations (*Tepley and Wentworth, 1962b, Heacock and Hessler, 1962; Troitskaya et al. 1963, 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 5. Possible explanations for this effect are considered in Part II of this paper in connection with mechanisms for the generation and propagation of hm emissions.

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 2 other types of events which may be placed in reasonably well defined sub categories.

4.1 Continuous emissions

In Figure 18, a series of sonagrams are presented showing the presence of bands of

Fig. 18 Four-station sonagrams of continuous Pc 1 emissions (2 August 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 0800–1300. 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 1000–1900, signals are observed simultaneously at all stations at frequencies below 0.1 cps. 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 cps result from instrumental noise.

energy observed 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 1–2 hours. The signals are sometimes observed for many nights in succession: for example, in the period Aug. 5–20, 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.

Fig. 19 Four-station sonagrams showing excitation of bands by 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 burst-like emissions excite resonant oscillations (possibly in the lower exosphere) or are intensified by the existence of natural resonance bands.

The properties of continuous emissions are discussed in more detail elsewhere (*Tepley and Amundsen*, 1965). 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 burst-like emission but are greatly enhanced during the burst (*Tepley et al.*, 1964 b, also see Figure 19). In addition a tendency toward band formation is sometimes observed on sonagrams of the storm-time emission considered briefly below (*Tepley et al.*, 1964 b). If pronounced resonance effects actually exist in the lower exosphere, they might also significantly influence the spectral energy distribution of hydromagnetic emissions which, according to the recent models discussed in Part II are supposedly generated at much higher altitudes.

4.2 Emissions observed during magnetic storms (*gurglers*, *Pi 1* emissions, *gurgler-Pi 1* transition emissions)

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 20. 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

Fig. 20 Storm-time sub ELF emission (*gurgler*) observed at Palo Alto (18 December 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.

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 1000–2000), 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*, 1964; *Tepley et al.*, 1964).

Sonagrams of Pi 1 emissions observed simultaneously at the four Lockheed Pacific Ocean stations are shown in Figure 19. These signals—characterized by bursts of energy occurring simultaneously over a broad frequency range—have been referred to elsewhere as “noise bursts” (*Tepley and Wentworth*, 1962 b). Occasionally rising frequency structural elements are superimposed on events of this type and the composite signal may be placed in a transition category which we have referred to elsewhere as “gurgler-Pi 1” (*Tepley et al.*, 1964). Transition signals are characterized aurally by bubbly sounds similar to those made by gur-

Fig. 21 Times of occurrence of storm-time sub ELF emissions at Palo Alto, California 1962–1963. The diurnal occurrence curve is plotted for 84 events observed at Palo Alto over a two year period. The events include both gurglers and signals in the gurgler-Pi 1 transition categories as obtained from aural monitoring of magnetic tape records. The chart (taken from *Tepley et al.*, 1964) indicates a strong occurrence maximum near 2000 local time (0400 GMT). Compare this result with Figure 16 of *Helms and Turtle* (1964). The latter figure—showing the diurnal occurrence of auroral correlated high-frequency magnetic micropulsation bursts at Byrd Station, Antarctica—is almost identical in appearance to the figure shown here and exhibits a strong maximum at the same GMT time. The two results apparently refer to the same type of micropulsation.

glers.

Figure 21 shows the occurrence times of gurglers and gurgler-Pi 1 transition signals at Palo Alto as determined by aural monitoring of magnetic tape data obtained at that station. A strong maximum in occurrence occurs at 2000 local time (0400 GMT). *Helms and Turtle* (1964) have presented an almost identical occurrence curve (Figure 16 of their paper) for impulsive high-frequency micropulsations recorded at Byrd Station, Antarctica. They reported a strong intensification of visual auroral activity with each micropulsation burst. It seems likely that the impulsive micropulsation studied by Helms and Turtle and the gurgler-Pi 1 transition signals considered here are actually the same phenomenon.

Acknowledgements

That part of the work reported above which was 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 5-3656; 3) ONR under contract NONr-4454(00); 4) DASA under contract DA-49-146-XZ-338. 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.

The results depicted in Figure 9 were obtained in the course of an informal cooperative project between Lockheed, The Geophysical Institute at College, Alaska and the University of Canterbury, Christchurch, New Zealand. The data at College were obtained by R.R. Heacock under contract AF 19 (628)-1695 for the Air Force Cambridge Research Laboratories, Office of Aerospace Research. The work at Christchurch was carried out by B.J. Fraser at the University of Canterbury under grant NONr(G)-00033-64 for the Office of Naval Research.

I would like to acknowledge R.C. Wentworth, M. Wolt, J. Cladis, and M.A. Cleveland for their helpful criticisms of this manuscript.

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