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Preliminary Results of a Micropulsation Experiment at Conjugate Points [1]

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This paper summarizes the preliminary results obtained by different scientists working at the two Institutes on a common program concerned mainly with micropulsation studies between two conjugate areas at a geomagnetic latitude of 57°. Morphological studies and digital computations of correlation functions are made on the basis of the chart records obtained at the two stations. The signal being recorded independently on magnetic tape, spectral analyses are available also. The principal conclusions are the following:

Pc 1 events occur simultaneously at the two stations, the amplitude being stronger in the northern hemisphere for the period studied (January and February 1964). The frequencies of the oscillations, and more generally the spectral shape of the signal as a function of time, are very similar at the two stations. The trains of oscillations are time-shifted between the two hemispheres by approximately half the repetition period, confirming some other experimental results and excluding some theories. The correlation function method seems to be able to give more details about the spatial and time relations between phenomena in two conjugate areas.

Some results concerning the polarization at a single station and the phase relations between different points are also given.

1. Introduction

Since the discovery of the fine structure of pearl oscillations [Gendrin and Stefant, 1962a, b; Heacock and Hessler, 1962; Mainstone and McNicol, 1963; Tepley and Wentworth, 1962], now defined as Pc 1 events [Jacobs et al., 1964], the comparison of magnetic signals recorded at different stations has become of considerable interest, especially in conjugate areas. Some experimental results have been already reported; these are concerned with the worldwide distribution of micropulsations [Jacobs and Jolley, 1962], or with their conjugate point relationships either at high or at low latitudes [Lokken et al., 1963; Yanagihara, 1963; Tepley, 1964].

In order to improve our knowledge of this phenomenon, a joint experiment was arranged between Soviet and French scientists. Equipment was installed at the French station in the Kerguelen Islands (South Indian Ocean) and also at some points in the corresponding conjugate area in the northwestern part of the U.S.S.R. (fig. 1). Due to the lack of communications with the Kerguelen Islands, only the results from Borok, Lovozero, and Kerguelen Islands for the months of January and February 1964 are yet available for analysis (table 1).

Sogra, where the equipment has been put at the end of the winter, is the conjugate point of Kerguelen (geomagnetic latitude 57°), as computed by the integration of the line of force [Bitoun, 1963]. Records from the two conjugate stations will be available at the beginning of 1965.

TABLE 1. *Coordinates and recording equipments of the different stations*

	Stations	Geographical coordinates	Component recorded	Kind of record	Period of record
Southern Hemisphere	Port-aux-Français	70°10′E 49°19′S	Hx	Pen recorder Magnetic tape	Since 10/1/64
	Borok	38°20′E 57°24′N	Hx	Pen recorder Magnetic tape	20/1/64 – 28/2/64
Northern Hemisphere	Lovozero	35°05′E 67°58′N	Hx and Hy	Photo oscillographic film	Permanent
	Sogra	46°15′E 62°48′N	Hx	Pen recorder Magnetic tape	Since 17/3/64

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

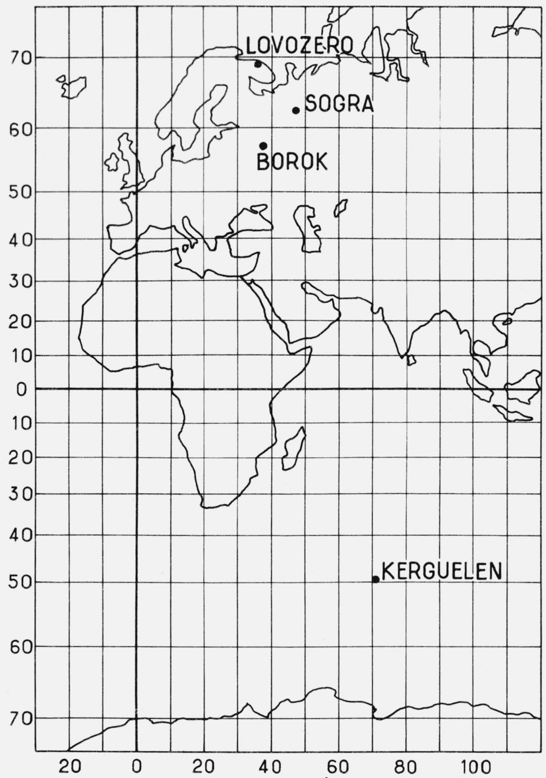

FIGURE 1. *Map showing locations of the experimental stations.*

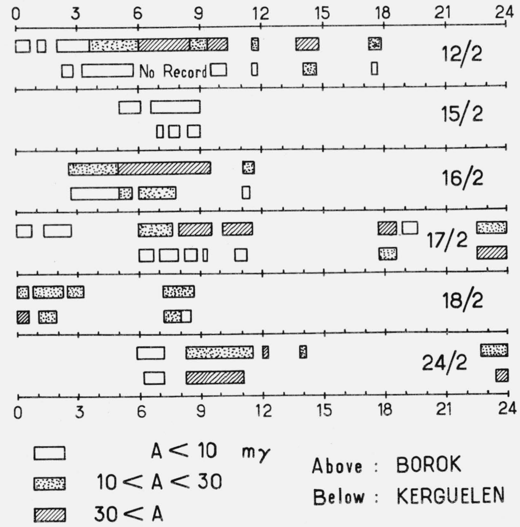

FIGURE 2. *Comparison of the occurrence and the intensity at Borok and Kerguelen during the month of February 1964.*

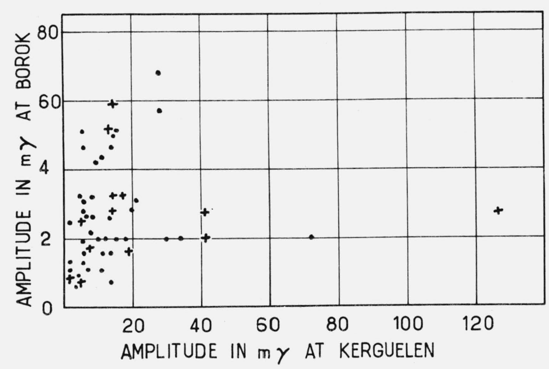

FIGURE 3. *Comparisons of the intensity of oscillations at Borok and Kerguelen during the month of February 1964.*
Points: events lasting less than 45 min. Crosses: events lasting more than 45 min.

2. Experimental Procedure

At Lovozero, the equipment was of the type generally used by the Soviet Group [Troitskaya, 1961] and consisted of coils, amplifiers, and photooscillographs. At the other points, the equipment was of the type described elsewhere [Gendrin and Stefant, 1963], the signal being recorded both on magnetic tape and on a pen recorder. The speeding up of the magnetic tape at the reproduction allows spectral analyses to be made in a way that has already been used by the French Group [Gendrin and Stefant, 1962b], while the reading of the chart records (the speed of which could be as high as 10 mm/sec) gives direct information on the simultaneity, the frequency and the amplitude of the oscillations, and permits the correlation function to be computed. Special attention was paid to accuracy of timing at each point [Blondau et al., 1965], and also to the calibration in amplitude. Details about each method are given in the different papers, the results of which will be now summarized.

3. Morphological Study

By examination of the best pen records from Borok and Kerguelen, Laurent et al., [1964] have been able to draw some conculsions about the simultaneous occurrence, intensity and frequency of Pc 1 events.

3.1. Figure 2 shows the time of occurrence of Pc 1 events at Borok and Kerguelen from the 12th to the 24th of February 1964. Every Pc 1 event that appears at Kerguelen appears at the same time at Borok. The converse is not true because of the difference in intensity, which will be discussed in the next paragraph.

3.2. It is clear from figure 2 (as well as from fig. 3, where the different intensities have been plotted more precisely) that signals are generally stronger at Borok than at Kerguelen. This fact explains why some weak signals observed at Borok are not detected at Kerguelen. This discrepancy could be attributed to ionospheric propagation characteristics, which could have been better during the month of February in Borok (winter hemisphere) than in Kerguelen (summer hemisphere). One might also ascribe part of it to properties of the ground below or around the two stations. The fact that these two stations are not exactly conjugate must also be taken into account. In any case, more results must be analyzed before any

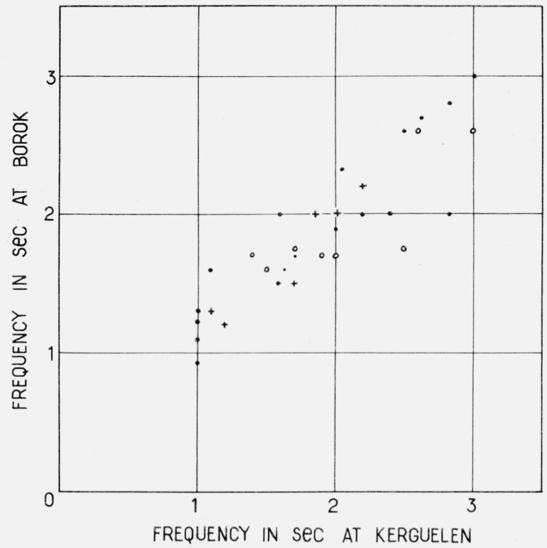

FIGURE 4. *Comparison of the frequency of oscillations at Borok and Kerguelen during the month of February 1964.*
Points: events lasting less than 45 min. Circles: events lasting more than 45 min and less than 90 min. Crosses: events lasting more than 90 min.

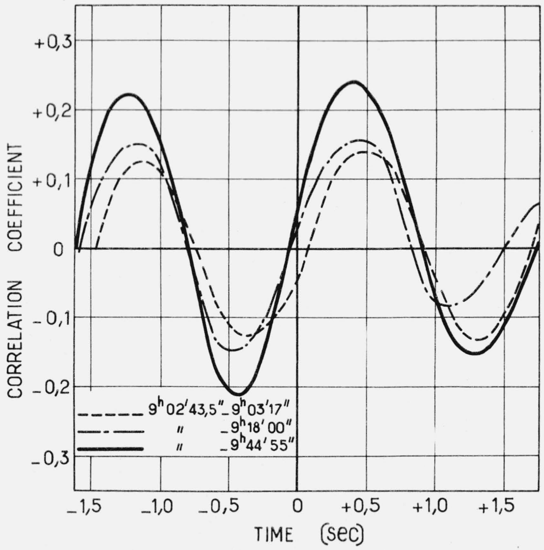

FIGURE 5. *Correlation coefficient between two orthogonal components at Lovozero for the 24th of February.*
The different curves correspond to different time intervals. Note that the maximum do not occur for $\Delta t = 0$.

definite conclusion can be drawn on this subject (see sec. 6.1).

3.3. As far as we can speak of one frequency of oscillation (because of the finite bandwidth of the emissions clearly shown on sonagrams) it is obvious on figure 4 that the period of oscillations recorded in these two conjugate areas, are the same.

4. Correlation Method

Measuring the ordinates of a great number of points on the amplitude-versus-time records, Borsoukov and Ponsot [1964] have calculated some correlation coefficients and autocorrelation functions.

The method was applied both to the oscillations themselves and to their envelopes. Working with the oscillations themselves, they analyzed:

- the polarization of signals recorded at one station
- the phase coherence between signals received at a distance of 1100 km
- the phase coherence and the frequency of signals received in two conjugate areas.

Studying the envelopes, they obtained results concerning the emission received in the two hemispheres and the time-shift between them.

4.1 The correlation coefficient between the two orthogonal components $X_L(t)$ and $Y_L(t+\Delta t)$ recorded at Lovozero is plotted as a function of Δt in figure 5. Assuming that the signal received at the ground is the result of two elliptically polarized oscillations at slightly different frequencies, the authors are able to conclude that the two ellipses have different axes and that their parameters vary with time. These results are to be compared with those recently obtained by Pope [1964b].

4.2. Studying the North-South component at Lovozero and Borok, they obtained the correlation coefficient between $X_L(t)$ and $X_B(t+\Delta t)$, which is plotted as a function of Δt for different time intervals (fig. 6). The maximum of the coefficient occurs always for $\Delta t=0$, showing that there is no difference in phase between the two signals, at least none greater than the limit of the accuracy of measurement (0.1 sec). The fact that the maximum is close to unity indicates that the ratio of amplitudes along the two orthogonal directions is the same at Borok and Lovozero.

4.3. The same method applied to Borok and Kerguelen records, gives correlation coefficients always less than 0.2, showing that the oscillations themselves have no phase-coherence, as it would have occurred, if the fast proton bunches theory had been right [Gendrin, 1963c]. But the correlation coefficient has not been computed for large values of Δt (of the order of half the repetition period T). Indeed, as it will be shown later, there are good reasons to think that $T/2$ is the time of propagation for the waves from one hemisphere to the other (due to the finite group velocity). The phase velocity will be of the same order of magnitude, so that perhaps the signals will be found to be coherent, when correlating oscillations delayed by this time.

The equality of frequencies, as deduced from the similarity of the autocorrelation functions taken at the two points (fig. 7) has a great importance with respect to this argument.

4.4. The method applied to the envelopes of oscillations shows the similarity between the repetition pattern in two conjugate areas. However, the fact that the similarity of the autocorrelation functions is greater in some cases if one chooses Borok (fig. 8) and in other cases if one chooses Lovozero (fig. 9), shows that the conjugacy must vary with time.

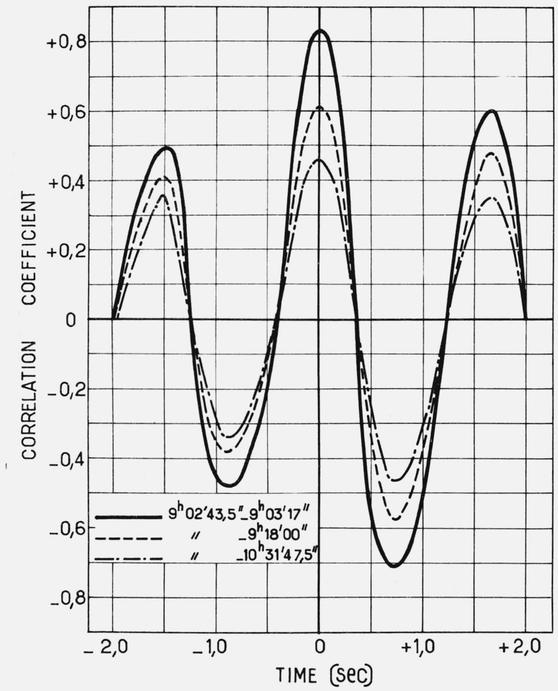

FIGURE 6. *Correlation coefficient between the X component at Lovozero and Borok for the 24th of February.*

The different curves correspond to different time intervals. Note that coherence lasted for time intervals as great as 1½ hr.

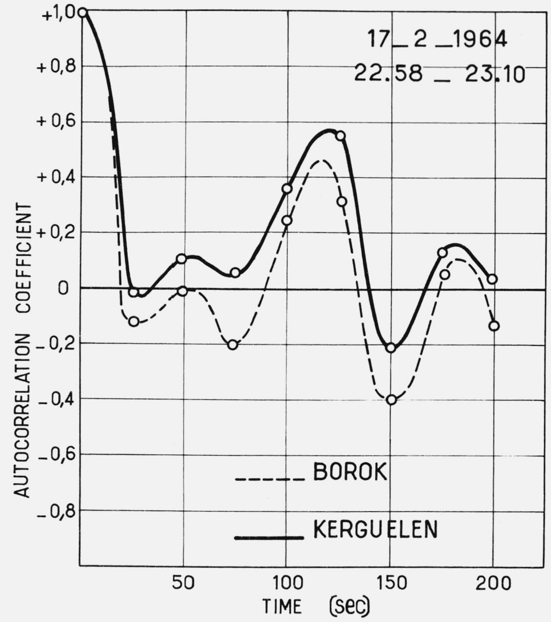

FIGURE 8. *Autocorrelation functions of the envelopes of the two signals received at Borok and Kerguelen.*

There is a striking similarity between the two signals. The principal repetition period is 120 sec. A secondary maximum, near 50 sec is probably due to overlapping trains.

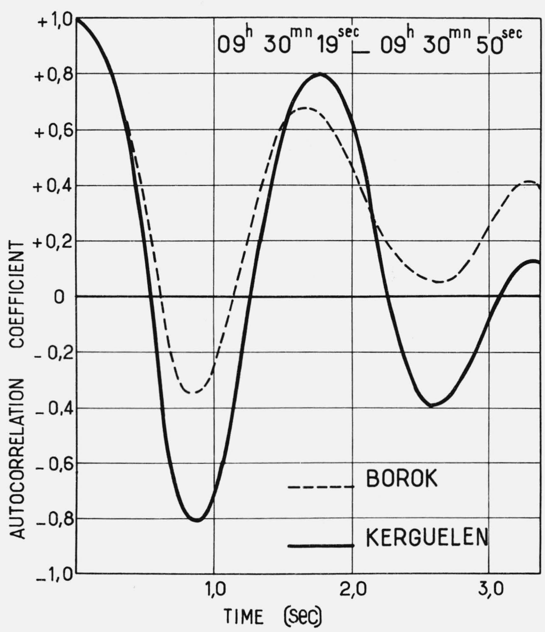

FIGURE 7. *Autocorrelation functions at Borok and Kerguelen for the 24th of February.*

The "frequency" of oscillations is clearly shown to be the same at the two stations (approximately 1.7 sec).

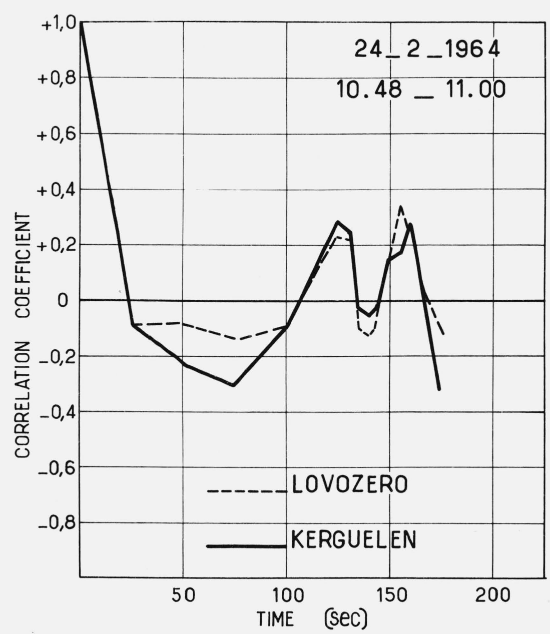

FIGURE 9. *Autocorrelation functions of the envelopes of the two signals received at Lovozero and Kerguelen.*

At this time the autocorrelation function at Borok had a completely different shape.

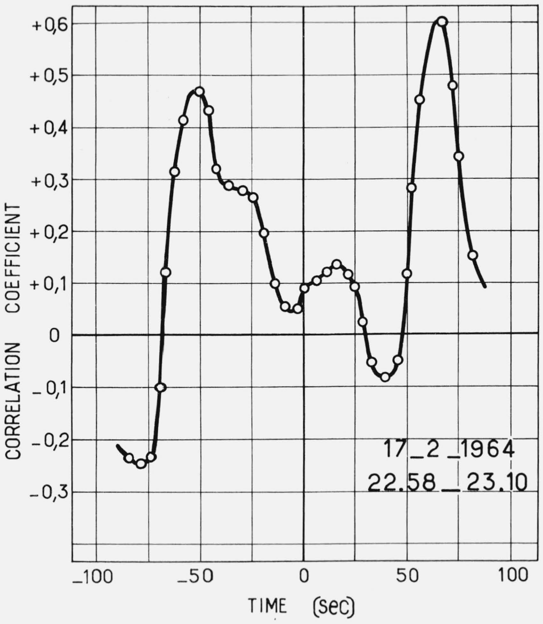

FIGURE 10. *Correlation function of the envelopes of signals received at Borok and Kerguelen.*

The two maxima do not have the same amplitude and are not symmetric around the value $\Delta t=0$. The correlation function being taken between $K(t)$ and $B(t+t)$, and the greatest maximum occurring for $\Delta t=+70$ sec, it is better to say that the signal appears at Kerguelen 70 sec after its appearance at Borok than to say that it appears at Borok 50 sec after its appearance at Kerguelen. This is often the case (see fig. 12).

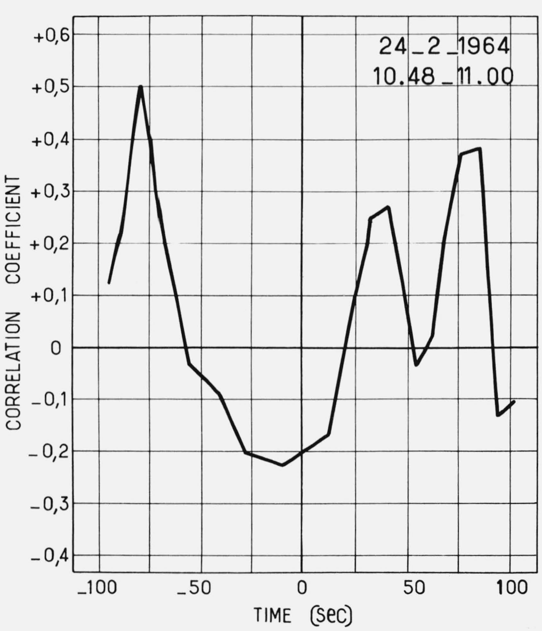

FIGURE 11. *Correlation function of the envelopes of the signals recorded at Lovozero and Kerguelen.*

The part of the signal which has the periodicity of 150 sec is symmetric. The part of the signal which has the periodicity of 120 sec (see fig. 9) is not symmetric. It appears at Lovozero 80 sec after the time at which it appeared at Kerguelen. For the fidelity of such results see section 4.6 and for their hypothetical explanation, section 6.3.

The secondary maximum which is observed in the two cases analyzed there, is probably due to the complex structure of the signal which can consist of two overlapping trains (see sec. 4.6. and 5.2.).

4.5. The autocorrelation functions being identical, the two signals do have the same shape, the only difference being a time shift between the two oscillations. This time shift can be obtained by computing the correlation functions between the two envelopes. The results of such a computation are given for the two cases which have been analyzed (figs. 10 and 11). The principal conclusions to be drawn from these figures is that the signals are received alternately in the two hemispheres.

But the fact that the curves are not symmetrical around the value $\Delta t=0$ means that the time shift is not exactly equal to half the repetition period. For instance, in the case of the Pc 1 recorded the 17th of February, the signal appeared 70 sec later in Kerguelen than in Borok, while the repetition period was 120 sec.

4.6. The amplitude-versus-time records must be used very cautiously when more than one frequency is present. Pope [1964a] has shown that the envelope of oscillations is strongly dependent on the number of beating frequencies. Sometimes also some frequency bands in the spectra do not have the same amplitude at the two points. This will change the time of maximum amplitude of the envelope (see for instance fig. 13 from 0100 UT to 0140 UT). We can avoid these difficulties by choosing analyzing periods which do not contain more than one frequency. Such periods occur generally at the beginning or the end of emissions. It is also possible that the wave is changing its polarization along its path through the magnetosphere. In this case the time of maximum amplitude on one component will be delayed by a small amount. This difficulty could be overcome by measuring and analyzing two components at each station.

Nevertheless the correlation method seems to be of great interest, if used with constant reference to the sonagrams, and with the help of two components.

5. Magnetic Tape Records

The use of magnetic tape, which stores the information, provides the possibility to make any kind of analysis that may be needed. Troitskaya et al., [1964] used it in two different ways. They obtained both amplitude-versus-time displays and sonagrams, which make possible measurements of the time-shifts, and comparisons of the frequency-time structures.

5.1. In general the operators of the different stations do not use the same chart-speed or the same amplification factor at the same time, thus reducing the number of charts that can be compared for a given time.

However, if we read the magnetic tapes and send the signal to an oscilloscope in front of which there is a camera, it is possible to have the same time scale and to adjust the gain in order to have the same level. An example of the results thus obtained is given in figure 12, which shows that the maximum amplitude in the X component is not exactly shifted by half the repetition period. This technique will be made the basis for the new correlation method we intend to apply.

5.2. The sonagraph has often been used to analyze micropulsations [Duffus et al., 1958; Tepley, 1961; Gendrin and Stefant, 1962a, b; Tepley and Wentworth, 1962, 1963; Campbell, 1963; Pope, 1964a; Tepley and Amundsen, 1964]. Its great advantage is to give a striking picture of the frequency-time structure of the emissions.

Figures 13 and 14 show the great similarity that exists between the signals recorded at two conjugated points, a fact that is also demonstrated, though less precisely, by other methods (see sec. 3.3, 4.3, and 4.4).

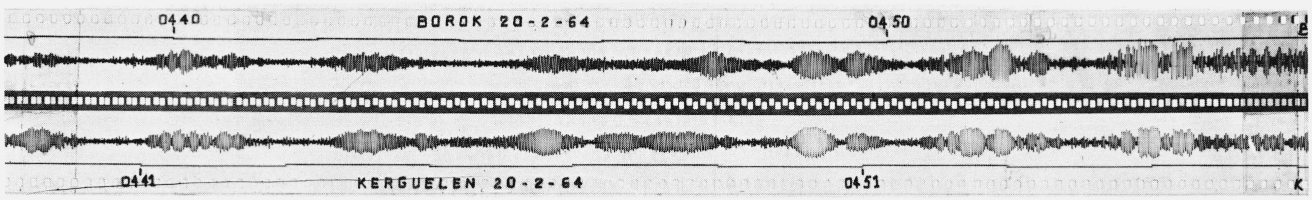

FIGURE 12. *Amplitude time displays obtained from the magnetic tape.*

This is an example of the method described in section 5.1. One can see that the two patterns are not exactly shifted by half the repetition period. In this case, the signal at Kerguelen is delayed by 80 sec and 56 sec later there appears at Borok another signal of different shape.

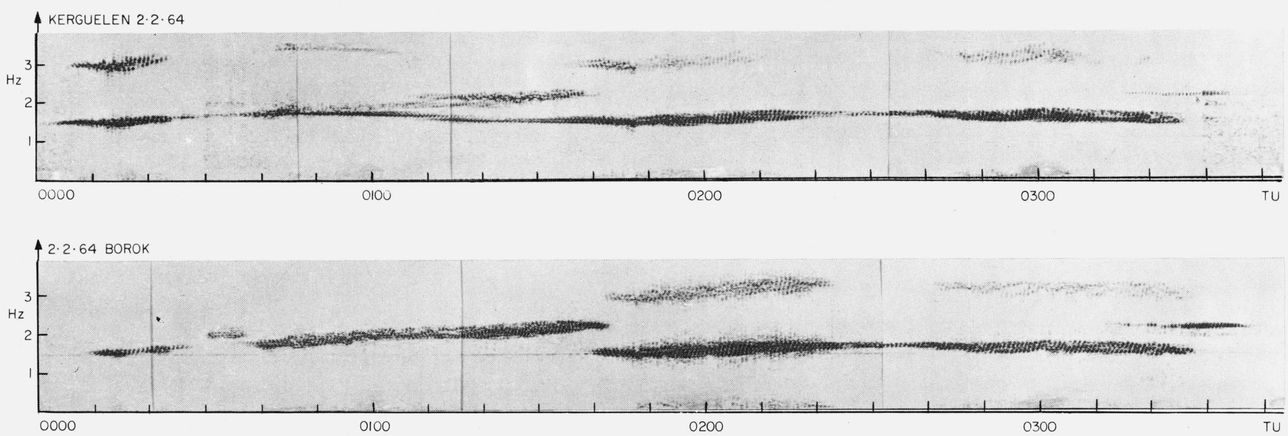

FIGURE 13. *Sonagrams from Borok and Kerguelen.*

The similarity of the two signals received at the two stations is a very striking one. Nevertheless the relative intensity of each frequency component is sometimes different (for instance between 0100 and 0140).

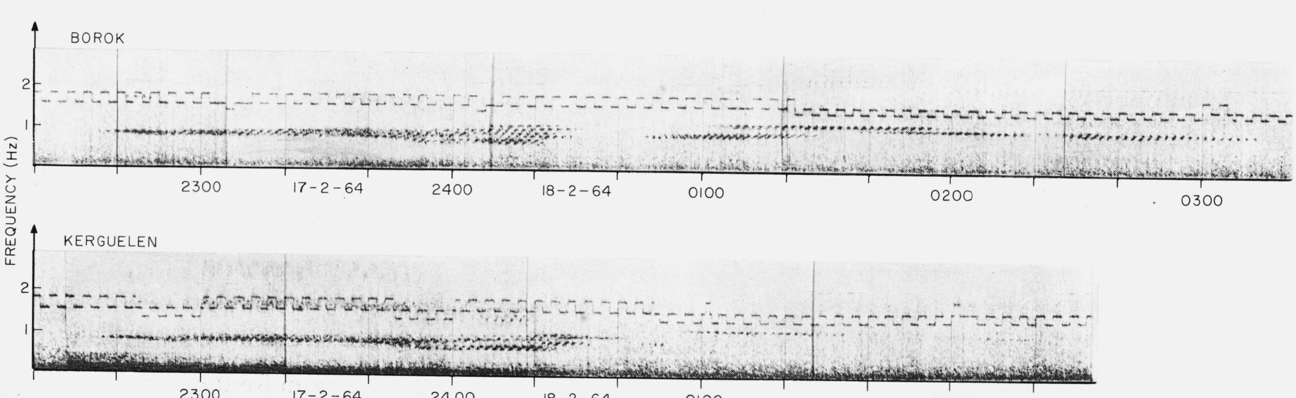

FIGURE 14. *Sonagrams from Borok and Kerguelen.*

The time marks recorded on a second channel are mixed with the signal. Each frequency change occurs every 2 min. A code indicates the hour. (In this example, the code system was working badly at Borok before 0300.) One sees that the intensity at Borok is greater than in Kerguelen. Note the pure frequency at the beginning and the end of the emission.

However, there are some differences, not in the shape but in the intensity of each frequency received at the two points (see for instance fig. 14, from 0100 UT to 0130 UT, where only the highest frequency is present at Kerguelen).

Such differences cannot be explained by different ionospheric conditions, because of the small differences between the frequencies involved. It is better to think about some longitudinal expansion of the phenomenon (Borok and Kerguelen do not have the same magnetic longitude); slight differences in generation and propagation conditions along different lines of force may lead to small changes in the spectra of signals received at the two stations. A third experimental point at the same magnetic latitude is needed, and this will be provided in the future.

5.3. Troitskaya et al., [1964] tried to obtain also the antiphase relation first shown with the use of sonagrams by Tepley [1964]. They measured the time at which a precise frequency (0.68 Hz) appeared at the two stations (fig. 15). They found that the signal was delayed by 98.0 ± 3.2 sec from Kerguelen to Borok and by 67.0 ± 2.5 sec from Borok to Kerguelen (these figures are the mean values and mean quadratic errors). This might seem to be the same effect as the one that has been observed by the correlation method (see sec. 4.5). However the following discussion will show that here again we must take a careful criticism of the experimental method.

5.4. The resolution time of the sonagraph is of the order of 5 msec. After multiplying by the speeding-up factor 2^{11}, this gives an equivalent resolution time of the order of 10 sec. The mean quadratic error given above is less than this value due to the great number of measurements. Thus the repetition time which is constant for a great part of the phenomenon for a given frequency can be measured with a good precision.

But any error in positioning the frequency line on the two sonagrams will lead to an error in the absolute time of arrival, because of the oblique shape of the emissions. The same kind of error will occur for the absolute value of abscissae deduced from the time marks recorded on another channel of the magnetophone.

All these effects give an absolute precision of the order of 20 sec. But only the first one has a physical reason (the bandwidth of the analyzing filters). The two others will not appear if one uses the digital method described in section 4, which is the only one to give accurate measurements of the wave propagation time.

6. Discussion

These preliminary results are in agreement with our present knowledge on hydromagnetic emissions and give new ideas about the future development of experimental and theoretical work. The principal points which must be clarified are: ionospheric absorption, spatial extent, structure and origin of the waves.

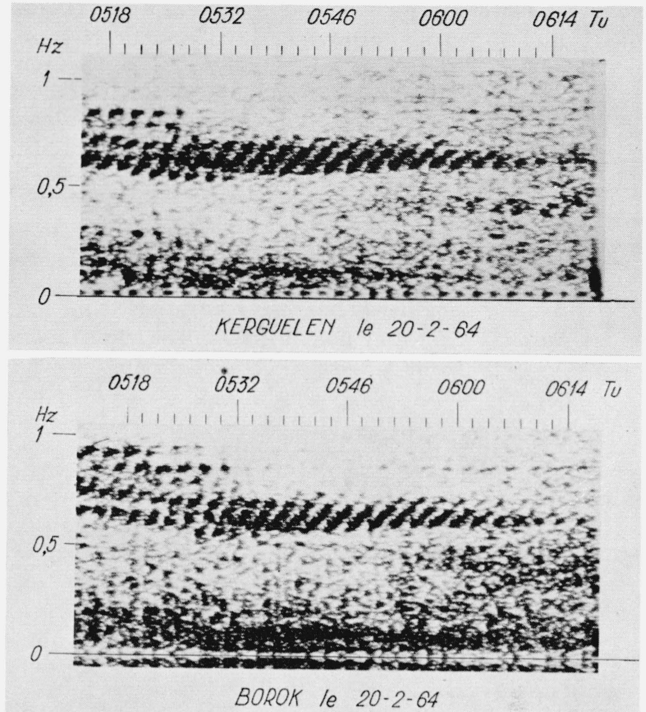

FIGURE 15. *Part of sonagrams from which measurement of the time shift between the two hemispheres have been made.*

These three aspects will be now briefly reviewed.

6.1. Ionospheric absorption in the frequency range of interest has been theoretically computed by Karplus et al., [1962]. According to these computations hydromagnetic waves of frequency around 1 Hz are attenuated by a factor of 1 to 30, depending on the ionospheric conditions (day or night, solar minimum or solar maximum). On the contrary, Jacobs and Watanabe [1962] have shown that hydromagnetic waves can be reinforced in some frequency bands, due to a resonance effect occurring between $\simeq 80$ and $\simeq 1500$ km.

Studying in detail the results of Francis and Karplus, Wentworth [1964b] found a simple empirical formula relating the absorption to the F_2 peak electron density. Using this formula, he was able to deduce the amplitudes of the signals above the ionosphere from the ground measurements. Diurnal variations which looked different at different ground stations were shown to be the same in the exosphere, due to the great differences in the ionospheric conditions [Wentworth, 1964c].

The experimental fact that the intensity of signals was stronger in the winter hemisphere than in the summer hemisphere (sec. 3.2), gives support to this theory. Moreover, the signal having the same origin must have the same intensity in the exosphere above the two points. If we knew the values of $foF2$ at the two stations, the empirical formula could be tested and even improved. This work will be done in the future.

6.2. Once the effect of the ionosphere has been taken into account, the question arises of the spatial extent of the waves. Are the regions of generation limited in L value, and in longitude? Are these regions fixed with respect to the sun, or do they follow the longitudinal drift of the particles that are sometimes assumed to be responsible? Do the conjugate areas slightly move in time during magnetic disturbances? Few experimental results have been reported on this subject.

Coherence of signals occurring at great distances (2000 to 3000 km) has been demonstrated [Komack and Orange, 1964] and phase differences have been measured [Duffus et al., 1962a, b]. But this applies to longer periods (10 to 100 sec). Tepley [1964] received at an equatorial station an emission which was the composition of the signals that appeared alternately at the ends of a low latitude line of force. He called this effect "structure doubling." Our experimental evidence that there is no phase difference between Lovozero and Borok shows that the emission has an extent of more than 1000 km (sec. 4.2). But we have inferred, from the difference in the frequency-time displays at two conjugate stations (sec. 5.2), that the phenomenon must have a finite extent in longitude. Records at a third station with the same geomagnetic latitude will be of a great interest with respect to this problem.

With this third station, we could also answer the question of the movement of the illuminated area. Jacobs and Jolley [1962], on the basis of two worldwide events, found a westward motion of the appearance of the pearls. The statistical study of Wentworth [1964c] infers a worldwide afternoon maximum above the exosphere. The question is complicated by the fact that the subsolar point has the same westward motion as protons of low energy that are sometimes assumed to be responsible for these emissions (a proton of 10 keV, on a magnetic shell of $L=4$, will have a bouncing period of $\simeq 80$ sec, and a drift period of approximately one day).

Finally we will discuss the notion of conjugacy, which is the last question related with the spatial distribution of emissions. By comparing magnetograms of different stations it was not difficult to define a conjugate area [Wescott, 1961, 1962]. Boyd [1963], using a correlation method was even able to distinguish between three points at a distance of 80 km. But he analyzed only one case, and the study of variation of conjugacy was not made. Wescott and Mather [1963] found a diurnal effect in magnetic conjugacy, due to the change of the shape of the magnetic lines of force, produced by the solar wind. This effect is a very high latitude one, but there is no doubt that high latitude stations can also be influenced by the presence of the cavity. Conjugacy will be more and more fluctuating as one approaches the neutral lines. The results described in section 4.4 show that such a variation exists, but give no details about it.

6.3. The most important result obtained recently, concerning micropulsations, has been the discovery of the antiphase relation between the two hemispheres. First shown by Lokken et al., [1963] from chart records of very high latitude stations, then by Yanagihara [1963] on a histological form, this effect has been clearly demonstrated [Tepley, 1964] by a comparison of sonagrams obtained at low latitudes. We have shown either by the use of sonagrams (sec. 5.3), either by visual analysis (sec. 5.1) or by a computation technique (sec. 4.5) that this relationship is valid at high latitudes.

The consequence of such an experimental fact on the different theories has been thoroughly discussed by Tepley in his paper; the principal conclusion being that the fast proton bunches theory might be rejected [Heacock and Hessler, 1962; Heacock, 1963; Gendrin, 1963a, b, c]. According to his own results he was not able to decide about the theory of the ionospheric duct excited by slow proton bunches [Jacobs and Watanabe, 1963]. But the experimental fact that the frequency-time displays are almost identical at two conjugate points above which the ionosphere is completely different (sec. 3.2 and 5.2) precludes this theory which implies different frequencies for different ionospheric conditions.

The slow-wave magneto-ionic mode is now generally admitted as the one which propagates the energy between the two hemispheres [Obayashi, 1964; Jacobs and Watanabe, 1964]. It gives the right order of magnitude for the repetition period T, which is proportional to the length of the line of force. The high frequency cutoff—which is the ion gyrofrequency at the top of the line—decreases with increasing latitude. Thus the experimental fact that frequency f of emissions is lower at higher latitudes [Heacock and Hessler, 1962; Tepley and Wentworth, 1962; Gendrin, 1963a; Matveeva and Troitskaya, 1963; Wentworth, 1964b] and the empirical law $f \cdot T \simeq c^{te}$ [Gendrin and Stefant, 1962a; Gendrin, 1963a, c] receive some justification. The experimental results (figs. 10, 11, and 12) which seem to bring out the idea that there is not an exact antiphase relation must be interpreted in the light of this theory. Faraday effect, first suggested by Pope [1964a], could be the origin of these little shifts.

But one cannot only make a transposition of the whistler theory in this frequency range and assume that an impulse is the source of these emissions, because we ought to receive the complete spectrum below the high frequency cutoff. On the contrary very narrow bands of frequencies are often received (see fig. 14 from 0100 UT to 0200 UT). A selective mechanism has been suggested, which is the interaction of a proton stream with the magneto-ionic plasma [Tepley and Wentworth, 1964] in a way similar to the one used by people trying to explain VLF emissions. The idea that bunches of protons are involved seems to be supported by different experimental facts, such as the increasing of emissions after geomagnetic disturbances [Wentworth, 1964a] or the change in frequency occurring in some conditions able to accelerate particles [Schlich, 1963a, b]. The study of the longitudinal drift and of the phase coherence of the oscillations will be of great interest with respect to these theoretical approaches.

7. Conclusion

Preliminary results, which show the striking identity of signals received at two conjugate areas have been given. The frequencies of the oscillations are the same, as is their repetition period. The frequency time displays are almost identical except for the fundamental antiphase relation.

Slight differences have been made conspicuous. The intensity of the signals is not the same at the two ground stations. The conjugacy seems to vary with time and the antiphase relation seems not to be an exact one when measured on one component only.

One can try to find the explanation for such discrepancies in the ionospheric condition and in some polarization effects. More experimental results will thus give information about the ionospheric absorption in this frequency range, the intensity of signals in the exosphere, and the true mode of propagation. The mechanism of emission has not been clarified at all by our experiments but a third station will surely be of interest with this fundamental respect.

We would like to acknowledge the work of each of our colleagues from which the essential part of this paper has been taken. We are indebted also to M. Bercy and to B. de la Porte des Vaux who have been operating the station in Kerguelen for almost one year.

We would express our great appreciation to the Academy of Sciences of the U.S.S.R. for granting us permission to operate a station at Sogra, and for giving us every technical help. The Administration des Terres Australes et Antarctiques Françaises must also be acknowledged for the same reasons, concerning Kerguelen Islands.

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