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

Equatorial Effects[1]

Rosemary Hutton

Department of Physics, Ahmadu Bello University, Zaria, Nigeria

(Received February 3, 1965; revised March 5, 1965)

Experimental studies of electromagnetic field variations at stations in the equatorial electrojet region are reviewed, with special reference to anomalous equatorial features, such as the amplitude enhancement of the longer period fluctuations and the evening occurrence of pc micropulsations during the IGY. The dependence of the amplitude enhancement on the position of the station relative to the center of the electrojet and on the strength of the S_q current is also discussed.

Attention is drawn to the many outstanding problems in the ULF band in the equatorial region, to the relation between magnetic events in the auroral and equatorial zones, and to the great need for a coordinated program of research at equatorial stations.

1. Introduction

Despite the interest which the magnetic equatorial region holds generally for magnetic and ionospheric workers, relatively few studies of electromagnetic field varaitions in the ultra-low-frequency band have yet been undertaken in this region. There is, however, likely to be some increase in activity in this field at equatorial stations during the next few years. It is thus particularly opportune to review the experimental results obtained so far, to note the major gaps in our observational knowledge, to examine the relation between equatorial and nonequatorial data, and to consider the dependence of equatorial pulsational phenomena on the equatorial electrojet.

2. Long Period Fluctuations

The contributions to this field of study have so far been concerned mostly with fluctuations observed on normal magnetograms, i.e., fluctuations of period greater than 60 sec and amplitude of 1 gamma or more; cf. Sugiura [1953], Forbush and Vestine [1955], and Maeda and Yamamoto [1960] using Huancayo magnetograms, Onwumechilli [1959, 1960] and Onwumechilli and Ogbuehi [1962] using data from Nigerian stations, Knapp and Gettemy [1963] using Koror and Guam records, Glover [1963] using data from the Philippines, and Osborne and Rivers [1963] using magnetograms from Ghana and Sierra Leone.

The fluctuations discussed in these reports have, for the most part, been individual indentations, including *SC*'s and *si*'s, superimposed on the normal daily variations, rather than series or trains of pulsations, which are of primary interest to this Symposium. They do, however, deserve our attention, as some of the fluctuations of shorter period, if not all, may have the same features and the same source.

The outstanding feature of these fluctuations and one which is common to all types of indentation in the period range above 60 sec is the enhancement of the amplitude of the fluctuation in a region about 4 deg broad in latitude, centered near the magnetic dip equator. This enhancement decreases with distance from the dip equator in the manner shown in figure 1 [Onwumechilli and Ogbuehi, 1962]. This graph also

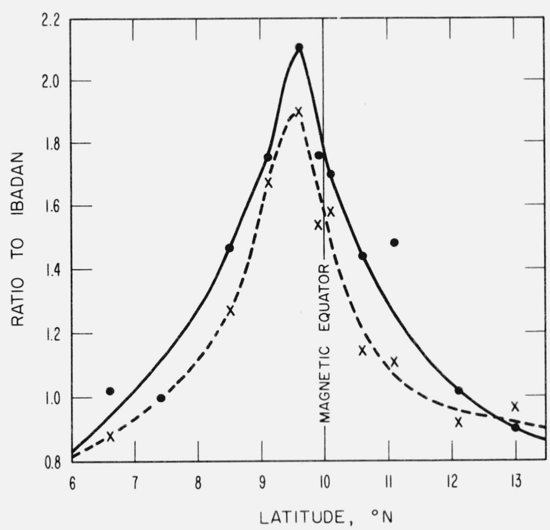


FIGURE 1. *Variation of the ratio of the amplitude of fluctuations at equatorial stations to amplitude at Ibadan (solid line) and the amplitude ratio for the daily range (broken line) with latitude; taken from Onwumechilli and Ogbuehi* [1962].

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

shows clearly the close relationship between the strength of the S_q current at any one station, as given by the daily range in H, and the degree of enhancement of the fluctuations at that station. A similar dependence of enhancement on dip angle was found by Knapp for fluctuations at Koror and Jarvis. It has also been clearly established that the enhancement of the amplitude of the fluctuations varies with local time in the same manner as S_q, with a maximum just before local noon. This point may be illustrated by further reference to the work of Onwumechilli and Ogbuehi. Figure 2 illustrates midday fluctuations at Ibadan simultaneous with those at Eskdalemuir, Koror, and Guam; figure 3 [Akasofu and Chapman, 1963] shows the effect produced by a particular polar magnetic substorm at stations situated along the magnetic equator.

By comparing the amplitudes of simultaneous fluctuations at different equatorial stations, Onwumechilli and Ogbuehi [1962] have shown that the amplitude of the fluctuations is closely related to the strength of the S_q current. They have demonstrated this point by determining the daily variation of the ratio of the amplitude of fluctuations at equatorial stations, east and west of Ibadan, to the amplitude at Ibadan (fig. 4). For example, curve (a) represents the daily variation of this ratio, s, for Addis Ababa and Ibadan. It may be seen that between 0400 and 0500 hr UT, when Addis Ababa is in daylight and Ibadan is in darkness, s is large—the S_q current at Addis Ababa at that time being greater than at Ibadan. Then s decreases around 0600 when Ibadan begins to be in daylight and again slightly after local noon at Addis Ababa, when the S_q current begins to decay there. Curve (b) illustrates the variation of s for stations within Nigeria. In addition, Onwumechilli and Ogbuehi have shown, by statistical tests, that even for stations separated by only 4 deg of longitude the daily variation of s is significant. It thus appears that the amplitude of the fluctuations provides a sensitive indicator of the instantaneous strength of the S_q current.

Several investigators of this equatorial enhancement have considered the relation between the amplitudes of the H and Z components of the fluctuations. This is of considerable importance on account of the information which the ratio of the H to Z components provides about the current system responsible for the fluctuations. Onwumechilli [1959, 1960], Hope

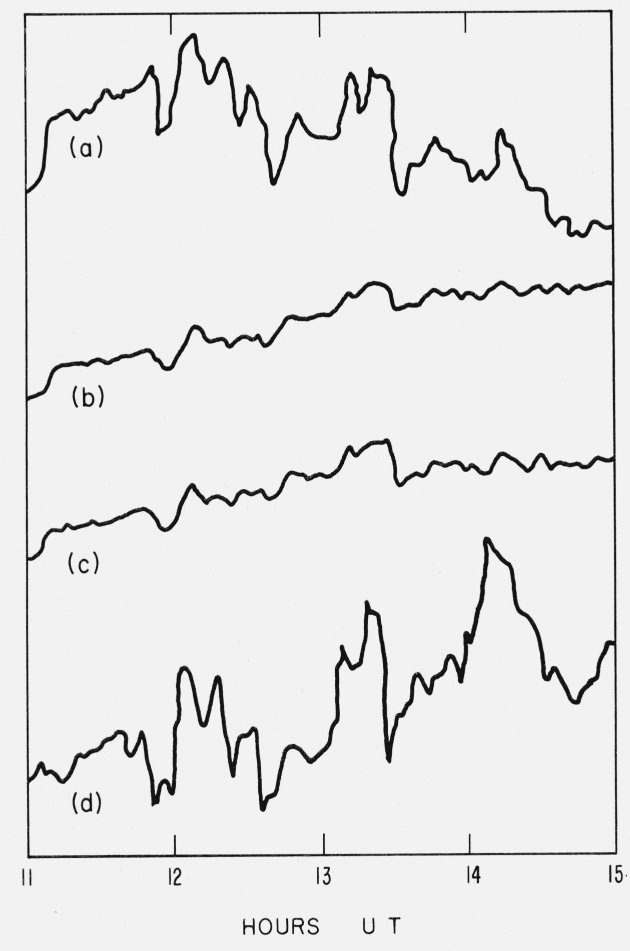


FIGURE 2. *A sample of fluctuations in* H *on 2 April 1958 taken from (a) Ibadan, (b) Koror, (c) Guam* [1962], *and (d) Eskdalemuir; taken from Onwumechilli and Ogbuehi* [1962].

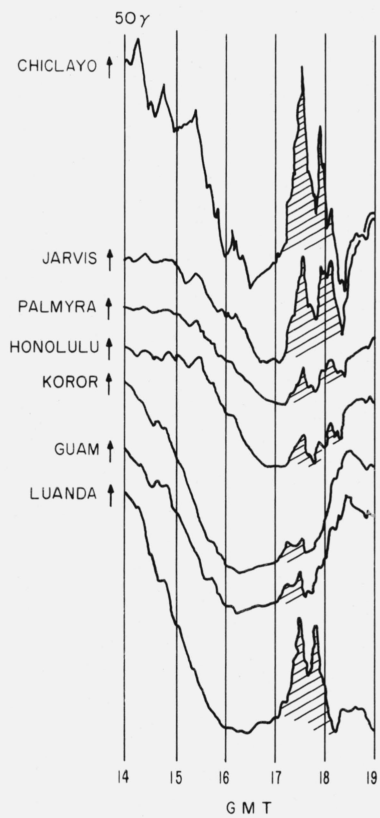


FIGURE 3. *The* H *component magnetic records from the low-latitude stations distributed widely in longitude (1400–1900 GMT, September 29, 1957); taken from Akasofu and Chapman* [1963]

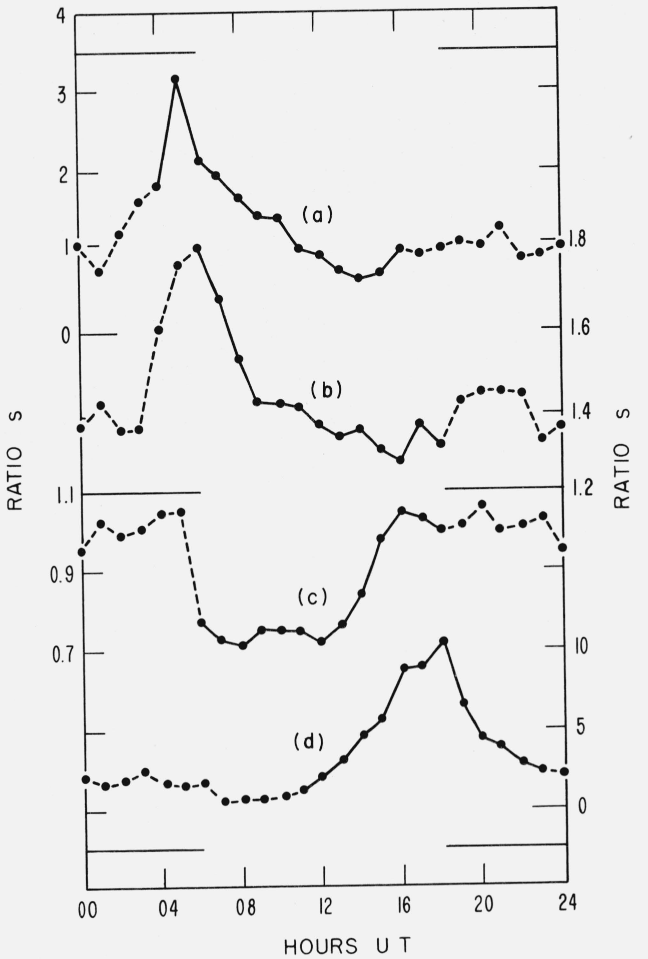


FIGURE 4. *Daily variation of the amplitude ratio* s *at stations east and west of Ibadan.*

The broken lines cover the hours of darkness at the test stations. The horizontal lines show the hours of darkness at Ibadan, 1800–0600 hr U.T. (a) Addis Ababa/Ibadan; (b) Jos + Zaria + Katsina/Ibadan; (c) Legon/Ibadan; (d) Huancayo/Ibadan; taken from Onwumechilli and Ogbuehi [1962].

[1961] and others have considered the enhancement of the Z fluctuations, as well as of the H fluctuations, that will arise from localized current filaments. At Ibadan near the southern edge of the electrojet current, it has been found that both the H and Z fluctuations are enhanced, and that, on quiet days, the ratio of the amplitudes of the H and Z components of the fluctuations is equal to the ratio of the daily range of H to Z, viz, approximately 2.1 during daytime. Knapp has found that both the H and Z fluctuations are enhanced at Koror, whereas at Guam only the Z fluctuations are enhanced. It thus seems reasonably well established that the components of the fluctuations are enhanced at equatorial stations by the same amount as are the components of S_q, i.e., enhancement of H fluctuations only at the dip equator, but enhancement of H and Z fluctuations at stations nearer the edges of the jet. At coastal stations the enhancement of the Z fluctuations may be markedly affected by currents induced in the ocean.

Onwumechilli [1959] also studied the relation between the ratio $r = r_H/r_Z$ of the amplitudes of the H and Z fluctuations at Ibadan, and the period T of the fluctuations. His results (fig. 5) show that r increases linearly as T decreases, for periods less than 35 sec. No explanation of this relationship has yet been proposed, but it would appear, from the work of Price [1962] and others, that the effect of the induced currents on the ratio H/Z is a function of the period of the fluctuations.

Another point of interest resulting from these studies is that the amplitude ratio r_H/r_Z at any one station varies little during daylight hours, or from day to day, or month to month; it also appears to be independent of the degree of magnetic distrubance as determined by K_p. This suggests that during daytime the mean position of the current filaments responsible for the fluctuations remains relatively constant. During night hours, however, the ratio r_H/r_Z at Ibadan has been found to be approximately double that obtained during daytime, as shown by figure 6 [Onwumechilli, 1959]. This suggests that the current system responsible for the nighttime fluctuations differs from that responsible for daytime fluctuations; an increase in r_H/r_Z would arise, for example, if the current system consisted of a current strip rather than of localized current filaments. Another feature of the nighttime fluctuations [Onwumechilli, 1959] is that their occurrence is linked with the planetary K index, no nighttime fluctuations being observed for $K_p \leq 3+$, whereas quiet and disturbed days do not differ greatly in the frequency of occurrence of daytime fluctuations, as shown in figure 7. It may also be noted that the nighttime maximum of equatorial fluctuations on disturbed days agrees with the maximum occurrence of polar substorms near midnight.

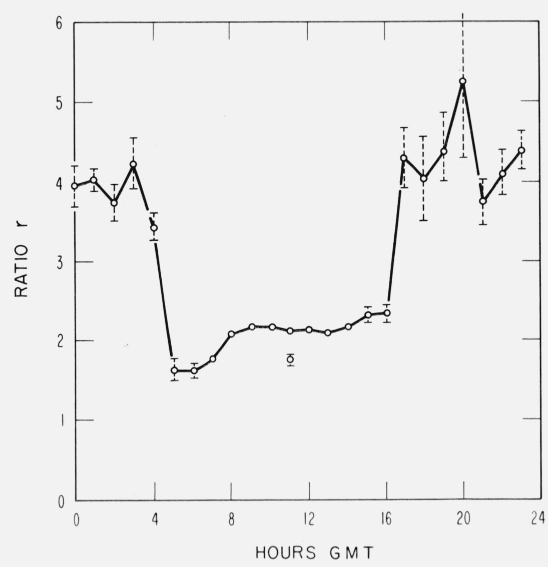


FIGURE 5. *The daily variation of the ratio* r *of the amplitude of a fluctuation in* Z*; taken from Onwumechilli* [1959].

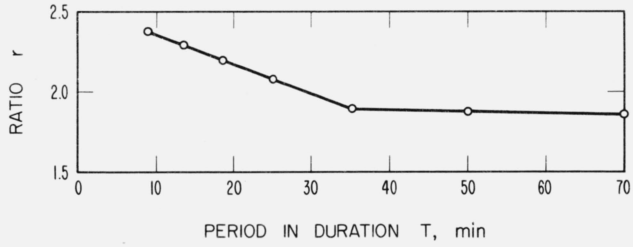


FIGURE 6. *The variation of the ratio* r *with the period of duration; taken from Onwumechilli [1959].*

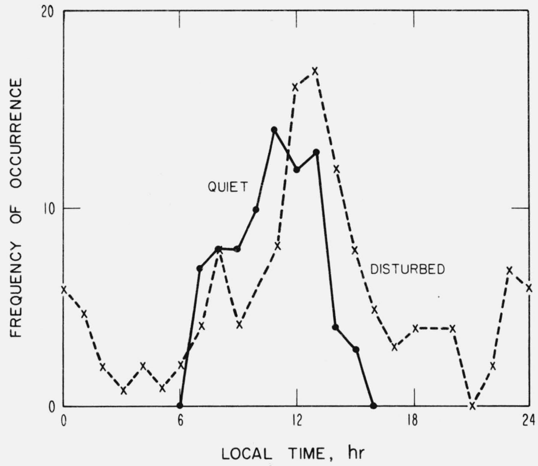


FIGURE 7. *Frequency of occurrence of fluctuations in* H *during quiet and disturbed conditions; taken from Onwumechilli [1960].*

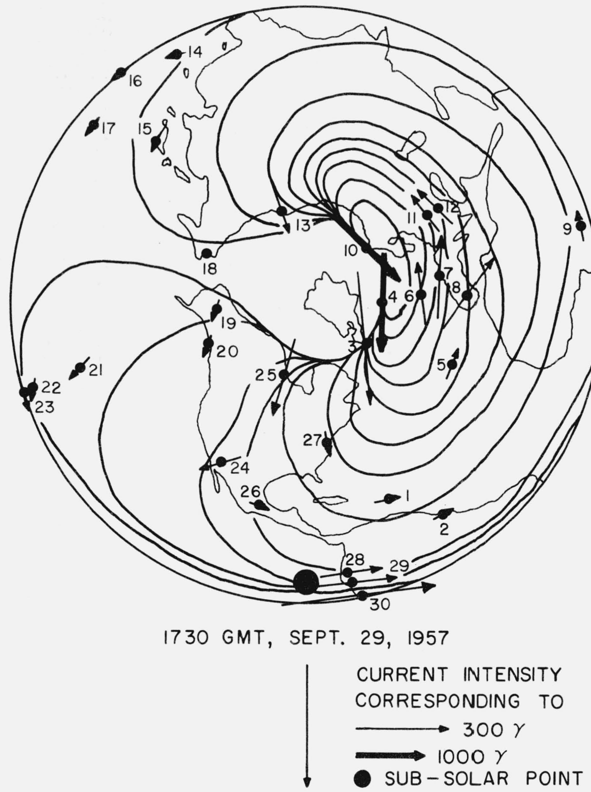


FIGURE 8. *The electric current system of the DP at 1730 GMT, September 29, 1957 at 30 stations; taken from Akasofu and Chapman [1963].*

In 1955, to explain the close relationship between the magnitude of *SC* and the magnitude of $S_q(H)$ at equatorial stations, Forbush and Vestine [1955] suggested that the major currents responsible for *SC* must flow in or near the *E* region, the currents themselves being driven by electrojets in the polar regions. Since then, Onwumechilli [1960], Hope [1961], Matsushita [1962], Akasofu and Chapman [1963], and others have suggested that the enhancement of certain types of fluctuations in the equatorial region is also due to the channeling of the return currents of auroral zone jets along the region of enhanced conductivity near the magnetic equator. Figure 8 [Akasofu and Chapman, 1963] shows the current system responsible for the polar magnetic substorm at 1730 hr on the 29th September 1957. This is particularly interesting, as it suggests that not only is the return path of the auroral jet currents over the equatorial region, where it is enhanced, but that the return current can extend as far as the late afternoon side along the magnetic equator. This correspondence between auroral and equatorial magnetic events appears to warrant considerably more attention.

3. Continuous Pulsations, Pc

In considering micropulsations, that is fluctuations of shorter period, the notation recommended by IAGA at the Berkeley meeting of IUGG, 1963, will be used: continuous pulsations, pc, being classified according to period,

pc 1 — 0.2–5 sec
pc 2 — 5.1–10 sec
pc 3 — 10.1–45 sec
pc 4 — 45.1–150 sec
pc 5 — 150.1–600 sec.

and irregular pulsations, pi, being classified

pi 1 — 1–40 sec
pi 2 — 40–150 sec.

Unfortunately, few observations of this kind have been made at the equator and of the studies completed so far, the earth current technique is the one which has been mainly used. On account of the great difficulty in interpreting earth current data fully, these earth current studies can only serve as a guide to points worthy of study by more direct methods.

Osborne and Rivers [1963] detected pulsations of category pc 4 in normal magnetograms for 1962–3 at Tamale, Ghana and Freetown, Sierra Leone. The pulsations had period of approximately 2 min and amplitude approximately 1 gamma; their duration was from several minutes to several hours. They were clearly visible only on the *H* records, but as both stations are near the dip equator one cannot rule out the possibility that they might represent fluctuations in the jet current, as appears to be the case for the longer period fluctuations.

These pc 4 have also been detected by Glover in the Philippines and by Hutton, using the earth current technique, in Ghana. Glover summarized his results on the variation of occurrence frequency in figure 9, which illustrates very clearly the seasonal change in the daily variation. The season, during which at his station a single maximum occurs appears to differ from that at Tamale and Freetown. Figure 10 for Legon, Ghana, shows (a) the average increase in occurrence frequency of pc 4, as sunspot minimum is approached—as found also by Osborne and Rivers [1963], and (b) a midday maximum of occurrence frequency agreeing with Glover's results for the period February–May 1962.

During these months, on several occasions at Legon, Ghana, daytime radio-star scintillations of the same frequency accompanied pc 4, but these observations were too few to establish a reliable association between the two phenomena.

For regular micropulsations of period approximately 30 sec—pc 3—earth current studies in Ghana have given several interesting results [Hutton, 1960, 1961, 1962]. In particular (cf. fig. 11) the occurrence frequency showed three maxima, the principal one being at 20 hr, instead of only one at midday as at midlatitude stations.

Figure 12 shows simultaneous earth current and magnetic records during the evening hours, on 27th May 1958. Rapid run magnetograms (unfortunately, available at Legon only for a few months) confirmed that a similar occurrence frequency pattern also existed for the magnetic pulsations, as may be seen in figure 11. The triple maxima in figure 11a could not thus be attributed to errors in the earth current technique.

Later, using IGY data from a number of equatorial stations, Cardus [1962] showed that the occurrence frequency of pc 3 at these stations likewise had maxima at times other than midday. This supported the equatorial anomaly in pc occurrence, first observed at Legon.

It was also found that the amplitude of pc 3 at Legon was greatest in the early evening, but, unfortunately, there were insufficient magnetic data to give reliable value of the amplitude. The order of magnitude of the maximum amplitude was approximately 0.5 gamma, which fits well with the morphological results of Jacobs and Sinno [1960]; and Kato, Tamao, and Saito [1962]. These morphological studies indicate that the amplitude of pc 3 decreases with decrease in latitude. It is doubtful, however, whether the equa-

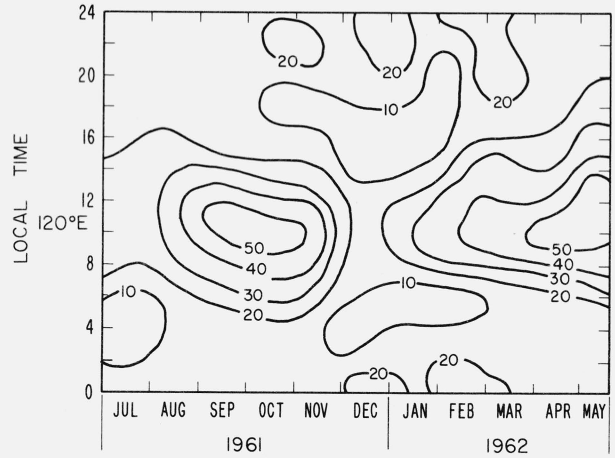
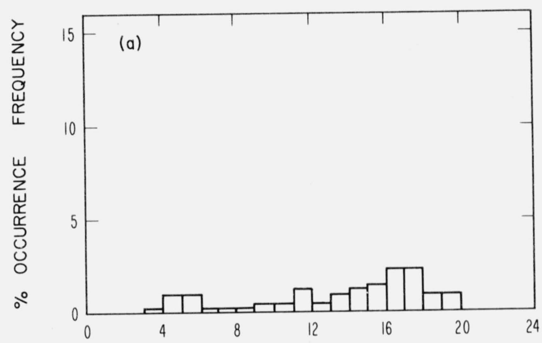


FIGURE 9. *Hourly values of the monthly percentage of occurrence of micropulsation with a peak to peak amplitude of 1 gamma or more; taken from Glover [1963].*



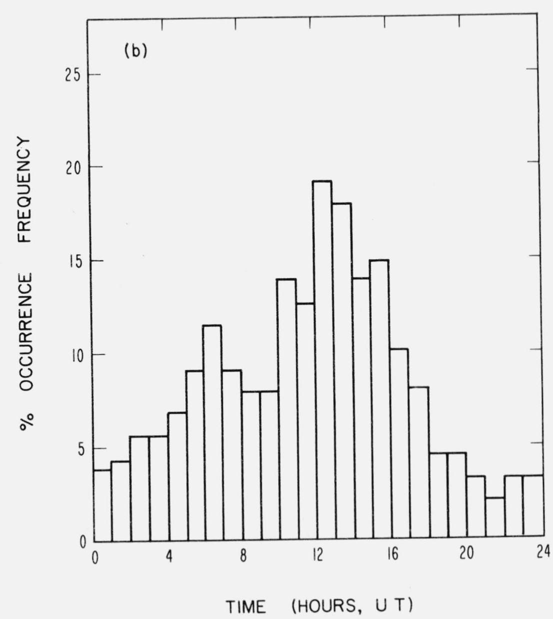


FIGURE 10. *Daily variation of occurrence of regular pulsations, pc 4, period 30 to 120 sec, at Legon, Ghana, during (a) 1957–8 and (b) 1961–2.*

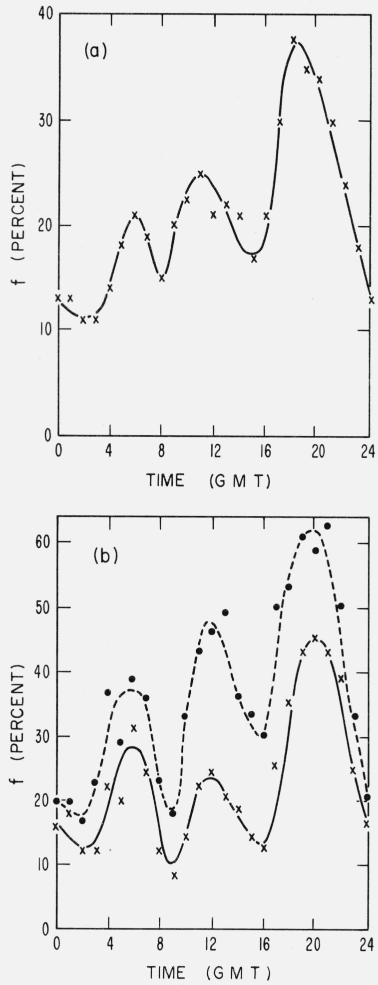


FIGURE 11. *Daily variation of frequency of occurrence,* f, *of regular pulsations, pc 3, at Legon.*

(a) Telluric Pulsations for October 1957–December 1958; (b) telluric and magnetic pulsations for May–July 1958. Telluric, ———; magnetic, – – – –; taken from Hutton [1960].

torial stations considered in these studies provided sufficient data to determine whether or not there is pc 3 enhancement at those stations where S_q is enhanced.

On more than 50 percent of the occasions, when large pc occurred at Legon at least 5 other stations widely spaced in longitude and latitude showed simultaneous pc. The Legon earth current data, could not, however, be incorporated in an accurate morphological study of magnetic pc since there was insufficient information about the relation between the earth current and magnetic variations.

The daily variation of occurrence frequency of pc 3 like that of pc 4 was found to vary from season to season at Legon, the evening maximum being predominant in the December solstice. Similarly, there has been a considerable change in this daily variation for pc 4 as well as for pc 3, with decrease in sunspot activity since the IGY, as shown in figure 13. It may be noted, from a comparison of the two histograms (figs. 13a and b) that the evening maximum is less predominant and the total occurrence of this type of micropulsation has reduced considerably with decrease in solar activity.

Following the suggestion made by Campbell and Matsushita [1962], that the onset of micropulsation storms is associated with an increase in ionospheric disturbance, several unsuccessful attempts were made to relate anomalous occurrence of pc 3 at Legon with ionospheric parameters available from Ibadan, approximately 400 miles distant. On the other hand, a significant correlation was obtained [Hutton, 1962] between the magnitude of the disturbance daily variation of earth currents at Legon and the onset of micropulsations at that station (fig. 14). In other words, since the earth currents reflect the rate of change of magnetic field variations and hence also the rate of change of current strength in the ionosphere, it may be concluded that the onset of pc 3 micropulsations occurs preferentially when the ionospheric current strength is changing most rapidly. Hutton also suggested that the nighttime peaks of $|S_D|$ at 22 and 2 hr may be associated with the occurrence of irregular pulsations.

Apart from the interesting results from Canton Island, reported at this Symposium by Tepley, very little is yet known about the properties of pc 2 and pc 1 in the equatorial region. From examination of Legon IGY earth current records, pc 2 were clearly observed on only 22 days, predominantly during night hours and during periods of above average magnetic activity.

Redding [1964, private communication] has recently observed series of pulsations of period 0.5 sec, in trains lasting from 10 to 20 sec, in earth current records obtained with a high speed recorder now established at Legon, Ghana. He reports that these occur on most days and that the diurnal variation of occurrence frequency has maxima at 16 and 20 hr.

4. Irregular Micropulsations, Pi

Studies at Legon have shown that pi 2 occur most frequently and with greatest amplitude between 22 and 23 hr local time—a result in good agreement with results obtained over a worldwide network of stations. During the IGY period, this phenomenon occurred on relatively few occasions at Legon; a considerable increase in its occurrence frequency was found during 1962, as shown by the two histograms in figure 15.

Thus it appears that the whole pattern of micropulsation activity, at least at the equator, changes during the sunspot cycle. It has already been noted that during the period 1957 to 1962 there was a considerable reduction in the occurrence of pc 3, whereas now it is noted that pi 2 occurrence has considerably increased during these years, together with the increase in pc 4 occurrence already noted.

It was also found that during the IGY when pi 2 was observed at Legon it was also reported as occurring at other stations over a large range of longitude and latitude. As in the case of pc pulsations, however, a detailed morphological study could not be made, because some of the records, including those at Legon,

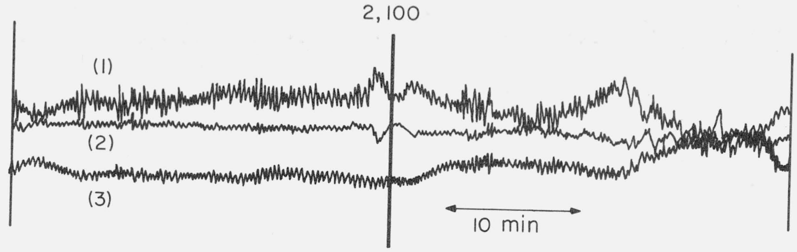


FIGURE 12. *Example of night pulsations, pc 3, at Legon on both telluric and magnetic traces: May 27, 1958 2030–2130 hr.*
(1) E-W telluric current; (2) dH/dt; (3) N-S telluric current; taken from Hutton [1960].

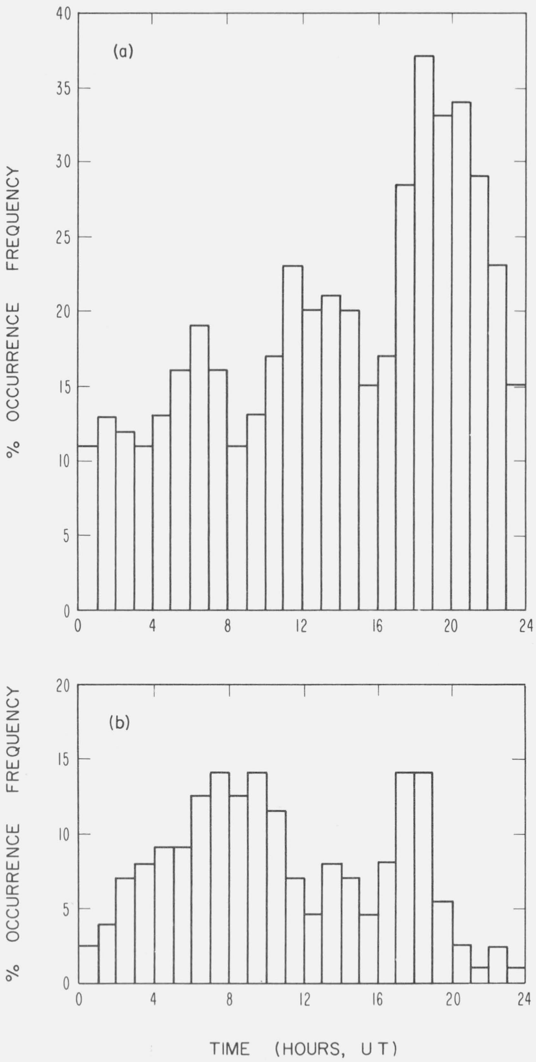


FIGURE 13. *Daily variation of occurrence of regular pulsations, pc 3 at Legon, Ghana, during (a) 1957–8 and (b) 1961–2.*

were based on the earth current technique. The dependence of pi amplitude on geomagnetic latitude has, however, been studied by Jacobs and Sinno [1960] and it appears that, as in the case of pc 3, pi 2 shows a decrease in amplitude as the latitude of the station decreases. In view of the marked dependence of the fluctuation amplitude at equatorial stations on the position of the station relative to the center of the electrojet and on local time, it is suggested that more detailed study of the latitudinal dependency in the equatorial region is required for pi as well as for pc.

5. Summary of Experimental Results

To conclude, the main experimental results are here summarized, and some of the main outstanding problems are indicated.

(1) The amplitude of certain types of equatorial pulsation is known to be enhanced by an amount which is well correlated with the strength of the equatorial electrojet, and, as such, depends both on the position of the recording station relative to the center of the electrojet and on local time. The amplitudes of all types of pulsation at the equator should now be carefully compared with those at other latitudes and longitudes; data from equatorial stations on both the day and night sides of the earth must be considered and it must be remembered that maximum enhancement of H and Z fluctuations is to be expected only at the center and edges of the electrojet respectively.

(2) Disturbances in the auroral zone produce the long period fluctuations observed at the equator. Whether an association between the auroral zone and the equatorial zone also exists for other types of activity should now be investigated in some detail. It will also be of interest to trace the extent to which events originating in each of the polar regions is reflected in the records of different equatorial stations.

(3) At equatorial stations fluctuations of period greater than 60 sec are observed most frequently around midday, with a secondary maximum around midnight; shorter period pc pulsations have several maxima in their daily variation of occurrence frequency. The daily variation of pc occurrence appears to depend both on the season and the sunspot cycle. Hence care is needed when comparing statistical data from different stations, except for corresponding time intervals.

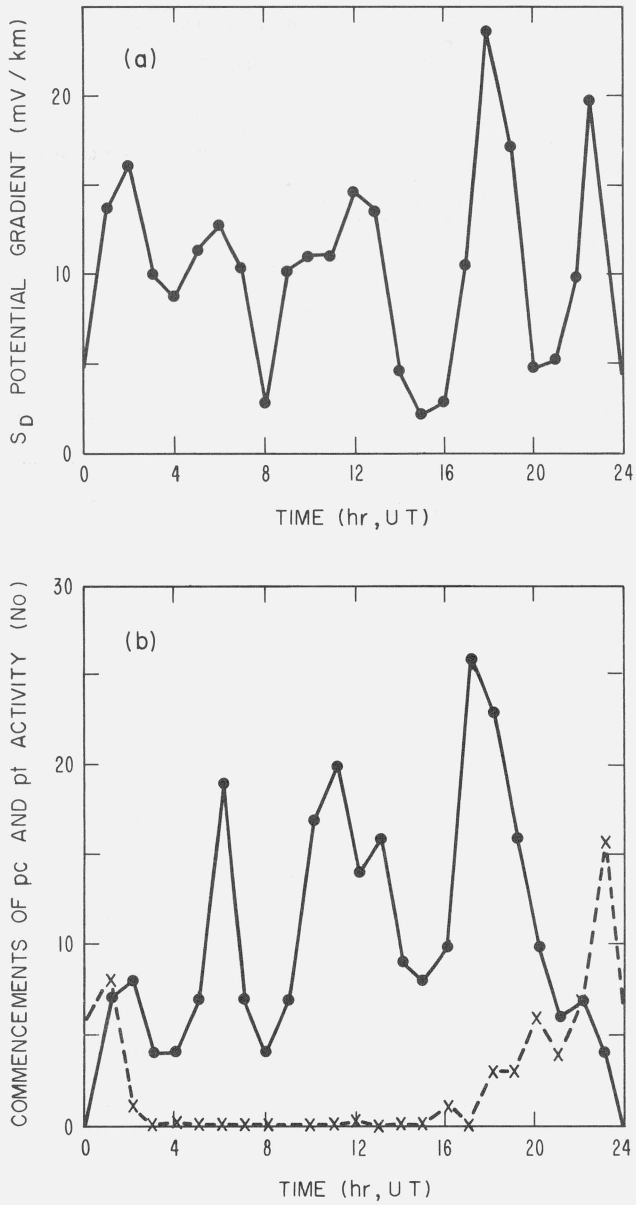


FIGURE 14. (a) *The annual mean* S_D *variation of earth current potential gradients at Legon.*
(b) *The daily variation of the number of commencements of pc 3 and pi 2 activity during one year at Legon, pc 3 pulsations, ———; pc 2 pulsations, – – – –; taken from Hutton [1962].*

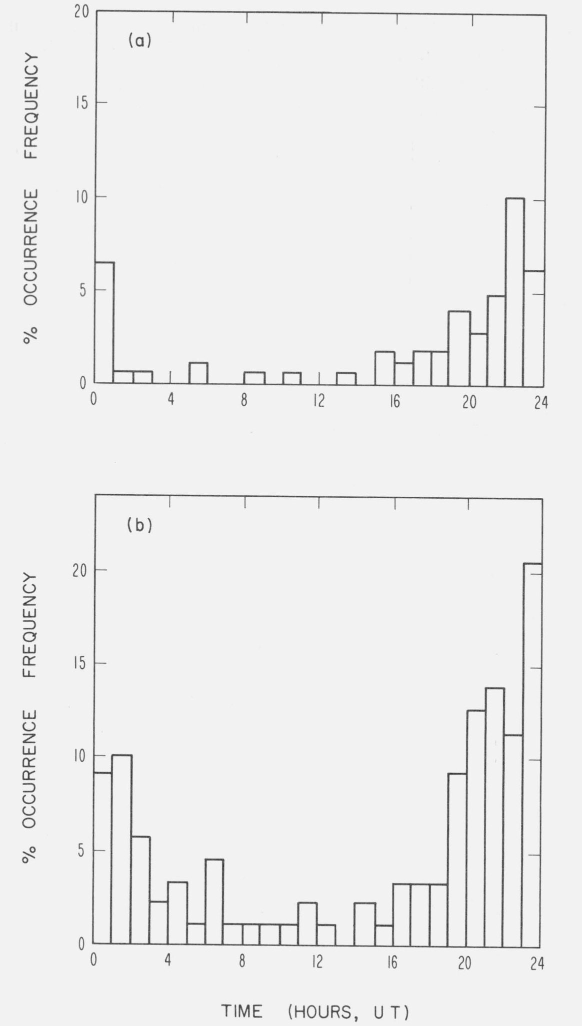


FIGURE 15. *Daily variation of occurrence of pi 2 pulsations at Legon, Ghana, during (a) 1957–8 and (b) 1961–2.*

(4) During sunspot maximum, an anomalous occurrence of pc 3 was found at equatorial stations during early evening hours. This appeared to be related to rapid changes taking place in the equatorial ionosphere at that time of day. More detailed study of this anomaly should now be made, using sensitive magnetometers, or preferably magnetometers in conjunction with the earth current technique.

(5) More attention should now be paid to frequencies of 1 Hz and above; except at Canton Island and in Peru no suitable recording equipment has been available at equatorial stations.

(6) It has been suggested that, as a result of the relative constancy of the ratio of the amplitudes of the *Z* to *H* fluctuations for fluctuations of period greater than 8 min, the position of the responsible currents must be more or less fixed. There is, however, some evidence from other work that there might be a seasonal change, or even a day-to-day change in the mean position of the electrojet axis. Thus further study of this question also is required.

Fortunately, it may be possible to examine a few of these problems during the next few years. Until very recently, the only equipment of sufficient sensitivity and recording speed at equatorial stations has been of the earth current type, but now suitable induction magnetometers are already in operation at Lima and Huancayo, in Peru, and within the next few months, as a result of a grant from the National Science Foundation, Washington, and assistance from the National Bureau of Standards, ultra-low-frequency investigations will be undertaken at Zaria, Nigeria. It is also hoped that a rapid-run magnetometer will be installed at Ibadab.

A much more ambitious and more coordinated program of research will, however, be required, before many of these problems can be resolved. This would involve a N–S chain of stations across the electrojet region each fully equipped with identical magnetometers, both normal and rapid-run. In this way, instantaneous values of the electrojet parameters could be related to the occurrence of any particular type of micropulsational activity.

The author is indebted to Sydney Chapman for reading the manuscript and making many helpful suggestions.

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