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FACULTY OF GRADUATE STUDIES

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of

GARY McINTYRE BOYD

B.Sc., Carleton University, Ottawa, 1957

M.Sc., University of Saskatchewan, Saskatoon, 1962

IN ROOM 207, CHEMICAL ENGINEERING BUILDING

FRIDAY, NOVEMBER 17, 1967, AT 3:30 P.M.

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External Examiner: Dr. Kenneth Davies
Institute for Telecommunication Service
and Aeronomy
Environmental Science Services Administration
Boulder, Colorado

Research Supervisor: J.A. Jacobs

GEOMAGNETIC RAPID VARIATIONS AND ASSOCIATED IONOSPHERIC PERTURBATIONS AT MID LATITUDES

ABSTRACT

Observations using HF radiometers, a sensitive riometer, and near vertical-incidence Doppler sounding on three widely spaced frequencies, were made to determine the kind and frequency of occurrence of overhead ionospheric perturbations, at sub-auroral latitudes (L = 3.5), associated with magnetic variations, during the sunspot minimum period (1963-1966). It was found that F layer and sporadic E. layer (electron) ionisation density (and possibly collision frequency and velocity) perturbations, but not except during "storms" energetic particle precipitation, are associated with all types of magnetic rapid variations. The maximum association is for 'Pt' micropulsations, the minimum for daytime magnetic bays.

Statistics on the percentage of events of various kinds observed and on the percentage of hours when related events occurred are presented.

The nature of the various associations is discussed in terms of the currently published theories of micropulsations and ionospheric perturbation. It is concluded that available theories require further elaboration before the experimental results can be interpreted to specify unique processes for the various kinds of events.

A new kind of event appearing to involve modulation of electrojet currents by E region waves of 90 seconds period was observed.

Magnetic events without Doppler perturbations were observed indicating that observed associations are not merely direct magnetic perturbation of the magnetoionic refractive index but rather require electron distribution perturbations.

GRADUATE STUDIES

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PUBLICATIONS

Boyd, G.M. The conjugacy of magnetic disturbance variations. J. Geophys. Res. 68, 1011-1013 (1963)

(cont.)

Boyd, G.M., H.J. Duffus and J. Kinnera. Radio fading and the natural electromagnetic background. Can. J. Phys. 43, 1951-1961 (1965).

Boyd, G.M. Solar eclipse magnetic observations and Pc 1 geomagnetic micropulsations. Earth. Plan. Sci. Letters 7, 333-334 (1966).

Boyd, G.M. and H.J. Duffus. The association between ULF geomagnetic fluctuations and Doppler ionospheric observations. J. Atmos. Terr. Phys, in press (1967).

GEOMAGNETIC RAPID VARIATIONS
AND
IONOSPHERIC PERTURBATIONS

by

GARY McINTYRE BOYD

B.Sc. Carleton University, 1957
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A THESIS SUBMITTED IN PARTIAL FULFILMENT
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We accept this thesis as conforming to
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THE UNIVERSITY OF BRITISH COLUMBIA

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The University of British Columbia
Vancouver 8, Canada

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GEOMAGNETIC RAPID VARIATIONS

AND

MID LATITUDE

IONOSPHERIC PERTURBATIONS

ABSTRACT

The object of this study is to determine the kinds and frequency of occurrence of direct associations between rapid variations in the geomagnetic field and ionospheric perturbations at sub-auroral zone latitudes.

Simultaneous observations of the magnetic field and of several characteristics of ionospherically propagated radio waves were made near Vancouver, British Columbia (54°N geomagnetic latitude) during the years of low solar activity 1962-1967.

The radio measurements were made utilising
i) HF CW Doppler sounders on 2.7 and 4.6 MHz at near vertical incidence ii) a riometer on 30MHz iii) VLF sky wave phase monitoring equipment on 18.6KHz and iv) a broad band HF radiometer on 10 to 16MHz.

The magnetic measurements were made using
i) Telluric potential lines ii) 3 component induction pick-up coils iii) A rubidium vapour magnetometer and
iv) Standard observatory magnetograms.

The principal new observations found were
i) Direct associations of times of occurrence and of disturbance 'waveform' between F layer and sporadic E layer HF Doppler records on the one hand, and magnetic records of Pc3, Pc4, Pc5, Pi1, Pi2 micropulsations, SI, SSC, and H and D component 'transition' magnetic bays on the other

ii) Long trains of sinusoidal oscillations of about 90 second period in the E region. Sometimes these were unaccompanied by any magnetic variations but when a magnetic bay also occurred, 90 second period micropulsations and 90 second period F layer pulsations were also observed iii) Direct association of normal E layer reflected Doppler signals with micropulsations of period less than 150 second (Pc3, Pi1) iv) Similarities in the spectra and times of occurrence of HF fading and micropulsation activity v) No association between any form of magnetic variation and the frequently observed 3-30 minute period daytime waves in the D, E, and F regions vi) Scintillation of cosmic noise on riometer records and Pi1+Pi2 type micropulsation events usually occur simultaneously at night vii) No examples were found of pulsating riometer absorption (i.e. energetic particle precipitation) directly associated with micropulsations.

It is concluded that i) Most motions in the F region with characteristic times shorter than three minutes are drifts resulting from electric fields as are some motions with longer periods ii) Most long period motions anywhere in the ionosphere (and even short period motions in the D and E regions) are not primarily caused by electric fields. The most common daytime oscillations which extend throughout the ionosphere appear to correspond to the Brunt/Väisälä resonance

iii) Some motions of the E layer appear to be sonic waves. These waves appear to modulate bay electrojets giving rise to the class of Pi2 micropulsations and pulsating drifts in the F region iv) The absence of observable long period magnetically associated motions in the E layer is probably due to the effects of recombination, and possibly wind action v) Vertical incidence Doppler sounding using several frequencies and observing sites is probably the most satisfactory way of studying motions of the electron gas in the ionosphere.

This abstract is approved

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Note table numbers are followed by an asterisk to avoid confusion with figure numbers.

Symbols Frequently Used :

(#) denotes section of Thesis where described.

AM	morning LMT (also a.m.)
B	ionospheric blackout condition
$\vec{B}_o$	Earth's magnetic field (unperturbed)
C	equipment failure
D	ionospheric region (1.3) or magnetic component (1.2).
E	electric field Vm^{-1}
EM	electromagnetic
E, F, F_1, F_2	ionospheric regions and layers (1.3)
GMT	Greenwich Mean Time (also UT or z)
H	magnetic horizontal N-S component (1.2)
HM	hydromagnetic
Hz	Herz or cycle per second (also ~)
IF	intermediate frequency (3.3)
J	current
L	magnetic (latitude) shell (1.2) or,
L	inductance
LMT	local mean time (Vancouver 120° WMT)
Pc, Pi, Pt	magnetic micropulsation classes (1.2)
PM	afternoon LMT (also p.m.)
Q	selectivity
QRM	radio station interference
QL, QT	magneto ionic abbreviations (6.5)

S	noisy record
U	uncertain value
UT	GMT
X, Y, $Y_{\parallel}$, $Y_{\perp}$, Z	magneto ionic variables (6.5)
a.g.c.	automatic gain control
a.m.	AM
c	3×10^{8} m sec^{-1}
e	exponential e (Napier), or electronic charge
f	frequency
f_c	ionospheric critical frequency (e.g. f_oE, f_xF_2 (1.3).
f_o, f_x	subscripts refer to polarisation (o is a R.H. helix for downcoming waves in the Northern hemisphere).
h	hour
i	$\sqrt{-1}$
j	current density amp m^{-2}
k_ℓ, k_p	local and planetary magnetic indices (1.2)
m	minutes or meters or mill (standard MKS units and pre-scripts are used throughout.)
pc, pi	see Pc, Pi or section (1.2)
p.m.	PM
s	seconds
t	time
v	velocity, v_z vertical velocity
z	GMT, or height

α	recombination coefficient (6.2) or varies as
γ	gamma magnetic (B) unit = 10^{-9} webers m^{-2}
ϵ_0	permittivity of space
μ	permeability or refractive index real part
ν	collision frequency (6.2)
τ	period of a wave or pulsation or characteristic (Napier) time
ω	angular frequency
~	Herz

CHAPTER I

Introduction

The purpose of this study is to investigate the association between geomagnetic rapid variations, and ionospheric perturbations at sub-auroral latitudes.

Geomagnetic variations, and micropulsations initially arise through the interaction of the solar wind and the Earth's magnetic field. The signals originating out in the magnetosphere travel inward through the ionosphere which alters their amplitude, phase and spatial distribution. The conductivity of the Earth's surface also affects the character of the observed signals.

In order to use the magnetic signals to obtain information regarding the solar wind and magnetospheric processes it is necessary to establish transfer functions to represent ionospheric and surface conductivity effects. The surface conductivity is a constant characteristic at a given location and may be determined from a long series of records. The ionospheric transfer function varies with time and the nature of the magnetic disturbance. Its determination therefore becomes a major problem. It could be obtained by simultaneous measurements using satellites and ground based detectors. This approach however would not shed much light on the ionospheric processes which are themselves of considerable interest. The formation and drift of ionospheric irregularities, the electric current streams, the winds and waves of the neutral gas component, and

the electric and magnetic fields in, above and below the ionosphere are all intimately related in ways which have not yet properly been delineated. By utilising ground based ionospheric sounding techniques together with ground based magnetic recordings, and satellite data when available, a full and satisfactory description of these processes may be developed. This thesis is an attempt to make a contribution toward such a description.

1.1 The Association of Geomagnetic Field Fluctuations With Ionospheric Perturbations at Mid-latitudes

The overall morphology and behaviour of the ionosphere and its association with the geomagnetic field has been under study for many years and is now well known. [Hines et alia (1965a)]. Recent work using satellites [Nelms and Lockwood (1967)], and work based on the IGY observations has led to an understanding of the morphology of the major equatorial, auroral zone, and polar anomalies; although the physical processes underlying the high-latitude anomalies are at present still uncertain [Hill (1963)]. There remain however many problems associated with the formation and motion of medium and small scale ionization irregularities. In particular the relative importance of magnetospheric, ionospheric, and mesospheric energy sources in the production of mid-latitude ionospheric perturbations is not known [Hines (1964)].

One of the major problems in the study of the association between ionospheric perturbations and geomagnetic fluctuations is the isolation of individual events. In the auroral zone, and particularly at sunspot maximum, so many disturbance processes are taking place simultaneously that it is quite difficult to decide whether the correlation between certain observations is significant or not, since the signal to noise ratio is poor because of overlapping events of differing types. The present study was conducted at a sub-auroral latitude, and near sunspot minimum, thus making possible a clear discrimination between events.

The character of upper atmospheric processes is such that direct experimentation under controlled conditions is rarely possible. The region is not a closed system, and it is not possible to maintain direct observing instruments in it. (Satellites burn up quickly at 100 km. altitude while balloons cannot reach such heights; only rockets and freefalling packages are available to obtain direct measurements.)

In order to identify the physical processes of the lower ionosphere it is necessary to combine the results of direct vehicle-sampled measurements with indirectly obtained results concerning temporal and spatial variations. These indirect results are obtained by a study of statistical associations between ensembles of ground based observations. It is first necessary to decide what kinds of observations are suitable on the basis of the known characteristics of the region and technical resource limitations. The second step in such an investigation is to run a number of observations and to determine those which exhibit any significant association. The third step is to refine whatever techniques appear hopeful, in the light of all available knowledge. At this point several conflicting theoretical models may be introduced and the observational techniqes refined to discriminate between them, progress being made by the usual method of successive refinements of theory and technique. This is the procedure which has been followed in this study. This thesis concerns experimental investigations of interactions between certain types of ionospheric motions and magnetic 'signals'. In order to make clear what is involved, a short summary will be given of:

a) mid-latitude magnetic pulsation observations,

b) mid-latitude ionospheric observations

c) previous observations and studies of associations between magnetic and ionospheric effects, and

d) theories of association.

1.2 Geomagnetic Field Fluctuations at Mid-latitudes

By mid-latitudes, we mean geomagnetic latitudes between approximately 40° and 60°, i.e. between the latitudes of the equatorial ionospheric anomally and the auroral zone latitudes. (Vancouver is located at 55° N. geomagnetic lat.)

Geomagnetic fluctuations having a time scale varying from a few tenths of a second to many hours, a horizontal spatial coherence scale varying from a few hundred meters to a few thousand kilometers, and an amplitude scale varying from a few milligammas to a few tens of gammas are observed. (The total ambient field is about 50,000 gammas.) The more rapid fluctuations have the smallest amplitudes and shortest spatial scale lengths for coherence. These fluctuations exhibit characteristic diurnal and seasonal variations, as well as particular associations with sunspot cycle, and auroral activity.

At present, the standard classification is that given in a resolution of IAGA at Berkeley in 1963 [Jacobs et alia (1964)]. This classification divides events into two classes--impulsive --"Pi", and continuous wave train--"Pc". These are further subdivided on the basis of the period of the principal spectral component :

IAGA Micropulsation Classification Scheme

Pc1	0.2-5 sec.	Impulsive Events	
Pc2	5-10 sec.	Pi1	1-40 sec.
Pc3	10-45 sec.	Pi2	40-150 sec.
Pc4	45-150 sec.		
Pc5	150-600 sec.		

A survey of micropulsation investigations in the 0.1-10 cps range is given by Jacobs (1962). A review paper by Saito (1967) dealing with all types of micropulsations has recently been published by ESSA/ITSA. Magnetic storms and other longer period variations are discussed by Chapman (1963).

The magnetic fluctuations which are of interest in connexion with this study are those which are observed during sunspot minimum at mid-latitudes, and which are thought to involve ionospheric processes. They have the following characteristics : Pulsations of classes Pc-2 and Pc-3, are observed for a large percentage of the time at mid-latitudes, and particularly during sunspot minimum periods and in the daytime. Although they probably originate through magnetospheric-ionospheric cavity resonances [Watanabe (1959)] it is thought that at sub-auroral latitudes ionospheric currents may be involved, [Campbell and Matsushita (1962)] or HM waves, [Kato and Tamao (1962)].

Pc-4 pulsations are frequently observed at night in mid-latitudes and exhibit some association with magnetic disturbance activity. In other respects, they are considered to be basically similar to Pc-5 [Saito (1966)].

The long period regular pulsations, Pc-5, are occasionally observed at mid-latitudes [Ohl, (1962)]. It is still an open question whether any ionospheric interaction is involved. However, these signals exhibit such excellent correlation at

conjugate stations [Nagata et alia (1963)] despite the existence of differing ionospheric conditions that one may infer ionospheric interaction is slight or negligible.

Short period pulsations Pc-1 are less frequently observed at sunspot minimum. They are subject to attenuation in traversing the ionosphere and although this may result in heating [Francis and Karplus (1962)] the heating effects are not likely to be detectable [Akasofu (1960) Fatkulin (1963)].

The irregular micropulsations Pi-1 and Pi-2 (together = Pt). consist of damped trains of pulsations lasting for a few minutes to tens of minutes. They have a broad spectrum but the largest components are in the 60-500 second period range. The amplitudes of Pi-2 in mid-latitude are about 1γ peak to peak [Jacobs et alia (1965)]. They occur mainly in the evening and night (14^h - 06^h LMT) and their onset frequently precedes a geomagnetic bay [Maple (1959)]. In the auroral zone Pi-2 are generally accompanied by Pi-1 pulsations, but at lower latitudes the Pi-1 are frequencly missing--probably due to attenuation on propagation paths from the auroral zone [Chapman and Akasofu (1964)]. In the auroral zones Pt's are sometimes directly associated with pulsating aurora [Campbell (1961)]. Pi-2 seem to occur simultaneously over the whole earth and certainly at conjugate stations [Campbell and Matsushita (1962)].

It has been suggested by Jacobs and Westphal (1962) and others [vid. also Radoski (1967)] that the pulsation periods of Pi-1, Pi-2 (and possibly some Pc) micropulsations are related to the eigen periods of geomagnetic field lines at

particular L values or latitudes. Such an hypothesis would account for the latitude and diurnal dependence of the dominent periods of these pulsations.

If this is the case then, for the long-period pulsations which originate on higher latitude field lines to reach mid-latitudes they must propagate across the field lines either in the magnetosphere, or horizontally in the ionosphere. There is some evidence that 5-10 minute period pulsations do not propagate across the field lines in the magnetosphere [Patel (1966)]. Horizontal propagation through the ionosphere is favoured by Rostoker (1965) (1967). Measurements using spaced magnetometers yield apparent horizontal propagation speeds in the order of a few tens of kilometers per second, [Herron (1966), Lawrie (1963)].

Magnetic bays and sudden commencements are also of interest in connexion with ionospheric perturbations, as ionospheric currents are believed to play an important role in their production at mid-latitudes [Chapman (1963)].

Stress has been placed on mid-latitude characteristics because a distinctly different mechanism is operative in the auroral zones. Ionospheric perturbations in the auroral zones are principally caused by particle precipitation from the magnetosphere. This precipitation may itself be caused by magnetohydrodynamic waves [Cole (1964)], giving rise to a correlation between magnetic pulsations observed on the ground and ionospheric irregularities not primarily resulting from electric currents induced in the ionosphere.

Magnetic micropulsations may be observed by using induction coils, earth-current electrodes, or sensitive magnetometers. A survey of techniques is given by Duffus (1966). Long period variations may be observed by regular suspended magnet variometers and other methods [Whitham (1960)].

Note : For classification purposes, the periods of the dominant spectral components in micropulsation events may be determined with sufficient accuracy by direct examination of wave-form records, without recourse to spectral analysis. [Fooks and Morgan (1967)].

1.3 Relevant Mid-latitude Ionospheric Characteristics

An excellent survey of ionospheric characteristics is given by Ratcliffe and Weekes (1960). A comprehensive review of F region theory is that of Rishbeth (1967). A survey of wave and drift motions is given by Hines (1963).

The ionosphere extends upwards from about 50 to 1000 km. The region between 50 and 85 km. is known as the D region; that between 90 and 130 km. the E layer; that between 130 and 200 km. the F_1 layer; and that from 150 km. upwards the F_2 layer. The figures are not exact as the heights of the layers vary with time and place. Ionisation in the D, E, and F_1 layers is produced by solar UV radiation, and disappears at sunset due to rapid recombination rates. F_2 layer ionisation is produced partly by photoionisation and partly by precipitation from the magnetosphere; recombination and diffusion rates are

slow and as a consequence the layer is present all night. The height of the maximum (i.e. the principal maximum in the F_2 layer) electron density is about 250 km. in the afternoon rising to about 350 km. at midnight. The total electron content in summer is about twice that in winter, but the peak electron density is greatest in winter when most of the ionisation is concentrated in a compressed layer.

The conductivity of the ionosphere [Obyashi (1963)] is a tensor quantity depending on the ion and electron densities and their mobilities parallel and perpendicular to the ambient magnetic field. Detailed calculations of conductivity for various ion density models have been made by Maeda (1953) and by Fatkul in (1964). At Vancouver, the dip angle of the Earth's magnetic field is about 70° and it is therefore reasonable to consider parallel conductivity as being synonymous with vertical conductivity , and transverse (Pedersen or Hall) conductivity as synonymous with horizontal conductivity. Also, at about 120 km. altitude the E-W and N-S horizontal conductivities are about the same at these latitudes. (At 120 km. altitude.)

At all heights in the E and F regions parallel conductivity is very high and currents may readily flow vertically. The horizontal conductivity is a maximum in the region between 100 and 130 km. where it is about equal to one tenth the vertical conductivity; both are approximately equal to the conductivity of sea-water. Below 100 km., the conductivity falls off very rapidly. In the daytime it is negligible at 70 km, while at night, it is not important below 90 km. [Fatkul in (1964)].

In general one may picture a conducting sphere separated from an anisotropically conductive medium by a very thin dielectric shell of air. The inductance of such large conductors is great, and may result in time constants as long as one day for some current paths [Wescott and Mather (1964)]. Although such a model may be of some use for the study of long period world-wide magnetic changes, it is inadaquate where rapid (1000 sec. period or less) and localised fluctuations are concerned. Instead, we must consider the conductivity of a partially ionised gas in a gravitational field, which depends on the currents flowing, and on the motions of the neutral gas, as well as the overall geometry of the conducting regions.

In the D region below about 75 km., the collision frequencies of both electrons and ions are greater than the gyro frequencies. Thus the magnetic field has little effect on motion either electrons or ions, and neutral winds move both [Poeverlein (1967)].

In the E region the electron gyro frequency is greater than the collision frequencies, thus the electrons are constrained by the magnetic field. On the other hand, below 140 km. the ion neutral collision frequencies are higher than the ion gyro frequency and the ions are not so constrained, but rather are coupled to the neutral gas. For example, positive ions suffer about 100 collisions per second with neutral molecules [Nicolet (1962)]. Neutral gas winds and atmospheric wave motions will therefore set up currents by moving the ions relative to the electrons. Electric fields also readily set up currents in this region, which will result in secondary perturbations of the

electron density, and also in dissipative (Joule) heating which in turn alters collision frequencies. Both these effects in turn alter the conductivity.

Above 300 km. in the F region, both ions and electrons tend to be 'frozen' into the magnetic field. The time constant for reaching velocity equilibrium with the neutral gas varies from about 400 sec. at 250 km. to about ten hours at 550 km. [Ratcliffe (1959)]. Consequently, in the F region, rapid changes in the charge distribution are less readily produced by winds than by electric fields. However steady F region ionisation drifts with speeds of about 20 m/sec. associated with neutral winds are observed [Rosenberg and Edwards (1964)].

Although vertical currents may flow everywhere, the E region and lower F region, where the largest horizontal currents must flow, contain complex wind systems. These winds have a large horizontal scale of hundreds or even thousands of km. although their vertical scale is quite small. Wind shears involving a complete reversal of direction with a change in height of only 10 km. are occasionally observed in the E layer. In the F layer the vertical scale of wind shear is about 40 km. [Rosenberg and Edwards (1964)]. Rocket-borne observations of electric [Mozer and Bruston (1967)], and magnetic [Burrows and Hall (1965)] fields in the E region indicate that appreciable changes may occur in passing through a height range of 20 km. It is possible that a number of current-lamina stacked on top of one another sometimes occur in this region, particularly in the daytime, and in the auroral zones [Cahill (1959)].

The driving energy to maintain ionospheric currents may come from the lower atmosphere through wave and wind motion [Hansen et alia (1964)], [Lauter (1967)] as well as from the magnetosphere through hydromagnetic waves and particle precipitation.

These varying electric fields and currents in the ionosphere are the phenomena most likely to be associated with magnetic fluctuations observed at ground level. But, they are not directly observeable, for example, rocket experiments are transient, making it difficult to distinguish between temporal and spatial variations. On the other hand, electron density irregularities and their motions are readily observeable. Insofar as these irregularities and motions are related to electric fields and currents the latter can be determined. Irregularities are observed by recording the characteristics of radio waves passing through the ionosphere. Signals originating from radio stars, satellites, or ground-based transmitters may be used. See for example, Ionospheric Radio Propagation [Davies (1965 a)].

At mid-latitudes, irregularities of a few percent of the ambient electron density and with a scale size ranging from a few meters to many kilometers are generally present. Above the peak of the F_2 layer, Allouette and other satellite experiments have shown [Willmore (1966)] that well-developed irregularities are of common occurrence. F region irregularities tend to occur in large collocations, having a horizontal scale size between 200 and 2,000 km., containing irregularities whose

horizontal scale size varies from a few hundreds of meters to a few tens of kilometers. These collocations of irregularities occur during magnetically quiet periods as well as during disturbed periods. There are also transient irregularities and travelling ionospheric disturbances (TID) [Heissler (1967)]. Many of the former are associated with magnetic storms and auroral, but TID's and ordinary mid-latitude sporadic E tend to be associated with quiet conditions.

It has been shown by Maturra (1959) and Grigor'Yev (1964) that irregularities below a certain horizontal scale size should move with the general ionic flux, and retain their shape over distances of a few horizontal scale lengths. In the E region, irregularities smaller than about 100 km. will move with the wind. In the F region, irregularities smaller than a thousand km. will move with the ion flux, and thus be governed by electric fields rather than by (neutral gas) winds. Consequently, the motion of medium and small scale irregularities in the ionosphere can provide information about the currents, or ionisation drift velocities, present in the E and F regions [Kato (1964)].

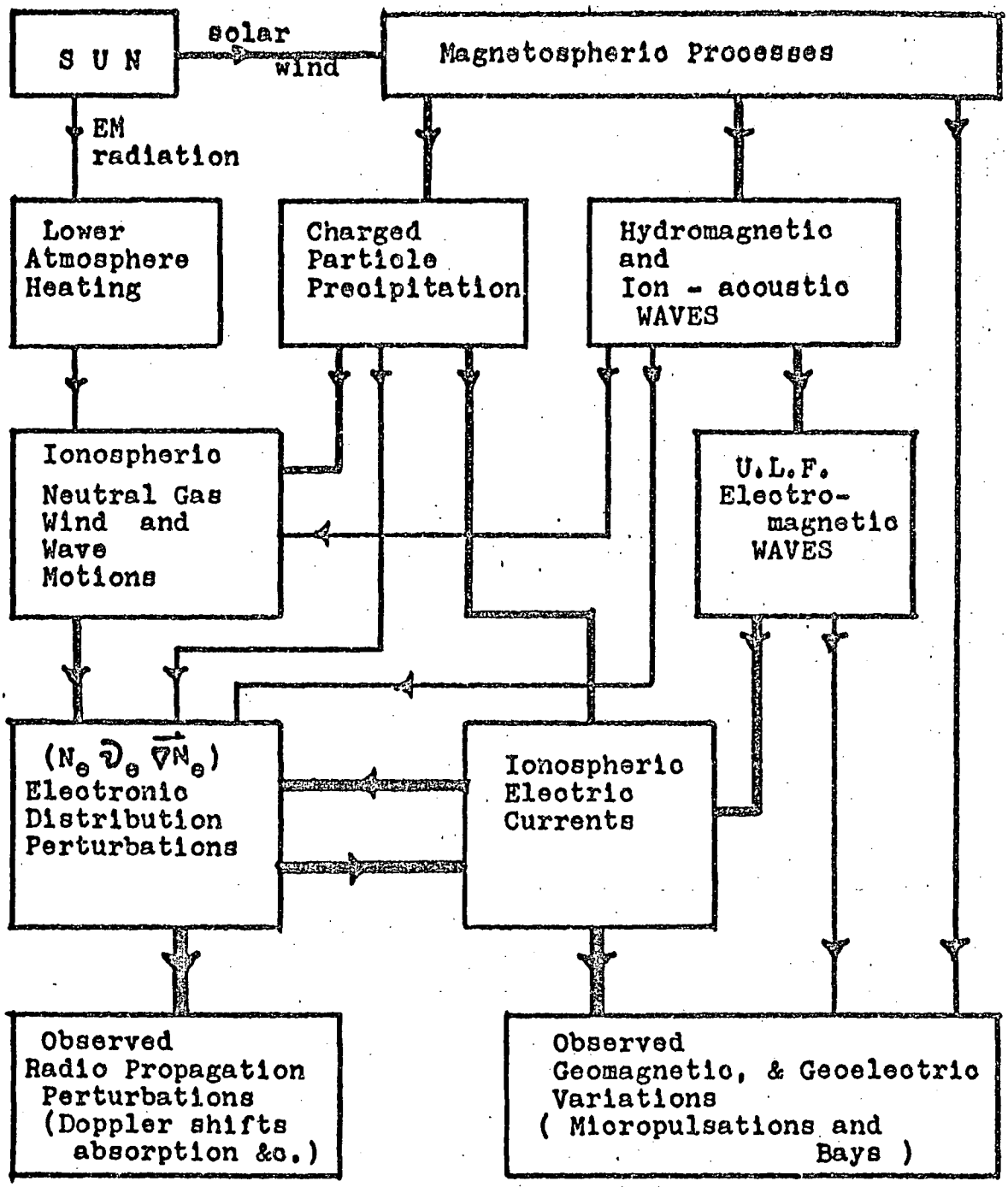


Fig.1.4.1. Disturbance Energy Flow Diagram

The principal processes relating solar disturbances to associated ionospheric and geomagnetic perturbations and the most important connexions between them as far as mid-latitude phenomena are concerned are shewn.

1.4) Theory of Ionospheric Perturbation Dynamics

This section contains a brief discussion of the pheonomena occuring in the ionosphere which can involve associations between ionospheric perturbations and magnetic variations. Only a broad outline of the phenomena and the way in which they relate to each other is given here. Discussions of particular phenomena and quantitative evaluations of their importance are given in appendix II, sections A, B, and C. The theory of measurement is given in Chapter II in connexion with each particular type of measurement.

A flow diagram showing the various ways by which solar energy may result in simultaneous ionospheric perturbations and mangetic variations is shown in Fig.1.4.1. The processes which are related to particular ionospheric variables such as : electron density (N_e), electron velocity ($\vec{v}_e$), electron-ion and electron neutral collision frequencies (ν_{ei}, ν_{en}) and ionospheric disturbance current ($\vec{J}$).

Here we are concerned with the disturbance source processes, and the interaction processes involving the ionospheric variables and the limiting processes such as attachment and recombination, which in time alter the electron density perturbations. There are (at least) six important 'source' phenomena; that is, processes which transfer disturbance energy from distant (magnetosphere, auroral zones, lower atmosphere) regions to the region of the ionosphere overhead which is observed.

TABLE 1.4.1*	see Appendix II B						
INTERACTION PROCESSES / SOURCE PHENOMENA (see Appendix II C)	1) DIRECT CHARGED PARTICLE INJECTION	2) MODULATION of IONOSPHERIC CURRENTS	3) PARALLEL and PEDERSEN DRIFTS	4) HALL FIELD INDUCED DRIFT	5) INDUCTION $\frac{\partial \vec{B}}{\partial t} \rightarrow \vec{E}$	6) DYNAMO EFFECT $\vec{v}_e \rightarrow E$	7) JOULE HEATING (I^2R)
a) IONOSPHERIC CURRENTS (with remote sources)	NO	NO	YES	YES	NO	NO	YES
b) PRECIPITATION FROM THE MAGNETOSPHERE	YES	YES	NO	NO	NO	NO	NO
c) WIND-BORNE IONISATION IRREGULARITIES	YES	YES	(VIA 6)	(VIA 6)	NO	YES	NO
d) NEUTRAL GAS etc. WAVES without magnetic fields	YES	YES	(VIA 6)	(VIA 6)	NO	YES	NO
e) ULF.EM.WAVES etc. HYDROMAGNETIC WAVES	NO	YES	YES	YES	YES	NO	YES
f) COMPRESSIONS of the scç,Si) magnetosphere by the solar wind	NO	(VIA 5)	(VIA 5)	NO	YES	NO	NO

Then in the overhead region there are six major interaction processes which involve ionospheric perturbations directly associated with local magnetic variations.

A scheme of the relationships between the source phenomena and the various local interactions which they may excite is given in the table Fig. 1.2. All these processes are subject to limitations due to recombination and diffusion.

The source phenomena in table 1.4.1* are as follows :

a) Ionospheric Currents

All currents driven by electric fields which originate at some location remote (auroral zone, etc.) from the volume of ionosphere being observed : electrojets, D_s currents, and currents flowing from the magnetosphere to the ionosphere (not locally induced currents.)

b) Particle Precipitation

The precipitation of electrons and ions (with energies of a few KeV or greater) directly into the observed (over-head) volume of ionosphere (usually during magnetic storms, etc.)

c) Wind-borne Irregularities

Horizontal irregularities in electron density carried across the field of view by ionospheric (neutral component) winds.

d) Neutral-gas Waves and Ion-acoustic Waves

All classes of waves not directly involving magnetic fields: infra-sonic waves, Brunt period oscillations, internal gravity waves.

e) Hydromagnetic and ULF Electromagnetic Waves

All classes of waves directly involving magnetic fields : Alfvén waves, hydromagnetic waves of both the fast and slow modes, electromagnetic waves propagating as surface waves on the Hall conductivity layer in the E region etc.

f) Magnetospheric Compressions

Very large scale magnetic field disturbances such as magnetosphere compressions due to solar wind fluctuations which lead to magnetic sudden impulses and sudden commencements. (These are, however, sometimes treated in terms of HM waves.)

The interaction mechanisms in table 1.4.1* are as follows:

1) Direct Charge Injection

The introduction of more electrons into the observed volume by transport due to coupling with neutral winds or waves, or by direct precipitation from the magnetosphere, or by secondary ionisation due to precipitation, (or solar flare U.V. induced ionisation.)

2) Modulation of Quasi - steady Currents

If an Sq current or other steady electric current is flowing in the ionosphere, then any process which alters ionospheric conductivity (by altering N_e or $\vec{V}_e$) can perturb the current and lead to magnetic variations.

3) Pedersen and Parallel Electric Field Drifts

These are drifts of electrons parallel to some applied electric field. Pedersen drift occurs across the magnetic field lines if the collision frequency is appreciable compared to the electron (or ion) gyro frequency, Drift parallel to the magnetic ambient field may occur at any altitude above the D layer.

4) Hall Electric Field Drift

Electron drifts normal to an applied electric field and normal to the ambient magnetic field can occur anywhere (above 80 km) where the electron gyro frequency is greater than the electron (ion and neutral) collision frequency.

5) Induction

Changes in the ambient magnetic field (due to compression of the magnetosphere by a verying solar wind say) induce electric fields in the conducting ionosphere leading to electron density perturbations.

6) Dynamo Effect

Electrons (and ions) borne across the magnetic field by neutral gas motions give rise to a Lorentz electric field which

can be mapped up the field lines to effect ionisation movements elsewhere.

A comprehensive theory including all these processes, and also heating effects, is not within the scope of this thesis.

However, in appendix IIA, the continuity equation for the electron gas is discussed quantitatively in order to establish decay times for irregularities.

In appendix IIβ, the interaction mechanisms (1 to 6 in Fig 1.2)are discussed.

In appendix IIc, the characteristics of the various source phenomena (a to f in 1.4.1*) are reviewed.

The discussion of the continuity equation (Sect. 5.4) leads to the conclusion that : transport with a characteristic time of 10 sec. or less is virtually unaffected by the loss processes. Transport of irregularities with a characteristic time (or period) of 100 sec. or longer will be somewhat attenuated at E and F_1 layer heights in the daytime. Transport with a period of one thousand seconds or longer will be severely affected in the F_1 layer in the daytime, and somewhat attenuated in the E and F_2 layers.

Finally, transport with a characteristic time longer than an hour will be damped everywhere in the ionosphere in the daytime, and in the lower ionosphere (E region and below) even at night.

Current experimental techniques permit the observation of coupled perturbation phenomena in the ionosphere which are not adequately described by presently available theories. In particular a theory taking into account non-linear interaction and mode-coupling in the propagation of ULF electromagnetic and hydromagnetic waves in the ionosphere is required to account for the observed phenomena.

1.5 Previous Work on the Association Between Magnetic Fluctuations and Ionospheric Perturbations

During the past decade a number of refined techniques have been developed for the study of ionospheric irregularities and their motions. Likewise, sensitive methods of recording natural magnetic fluctuations have been developed.

Nonetheless, remarkably few direct comparisons between ionospheric drift records and micropulsation records have been published. What has been done has been reviewed by Matsushita (1965). It is found that from time to time periods of very high correlation seem to occur. Most of the time, however, there appears to be little or no association [Watt (1964)]. Most ionosphere observers have made comparisons with K indices, and many have looked at regular magnetograms in connexion with scintillation and wind studies. These comparisons have yielded a few valuable results [Allan, Aarons and Whitney (1964)].

That the major effect of the ionosphere on magnetic field variations is caused by currents flowing in the E region rather than by properties of diamagnetic irregularities in the F region, was asserted by McNish (1937), [see also Davies (1966)]. This was the first concrete evidence that currents, hypothesized by Chapman (1940) and others, do in fact flow. The result was based on the time constants of solar flare effects on the magnetic field. These died out too quickly to have been produced by F_2 region ionisation enhancement, it was thought. The relationship between ionospheric electric currents and the motion of irregularities has been discussed by Maeda (1959), Hewish (1952) found an association between the horizontal velocity of irregularities in the F region, causing radio-star scintillation, and the magnetic K_p index. The presence, alone, of irregularities, in the F region is not significantly correlated with K_p, it is only their motions which are [Kokurov (1963)]. The occurence of some E region irregularities

however, is correlated with magnetic variations at mid-latitudes [Thomas (1962)].

The F_2 irregularities which cause scintillation also cause one class of 'spread F' on ionograms when they are not shadowed by lower layers of 'smooth' ionisation distribution. Spread F [Briggs (1965)] is observed both during magnetically quiet and disturbed periods. No direct information is obtained from a single ionogram regarding the motion of irregularities. However, Becker (1961) has found that sequences of ionograms, taken a few minutes apart, do exhibit vertical motions correlated with magnetic declination changes.

A relation between micropulsation occurrence and F region electron density was suggested by Duffus (1960).

A technique for measuring ionospheric irregularity drifts, using a pulse transmitter and spaced receivers, was originated by Mitra S.N. (1952), and has subsequently been improved to yield full 3 component vector drift velocities [Kiyaovsky (1963)]. Using this technique, F region drifts have been found to correlate in a general way with dynamo current patterns deduced from magnetograms [Kazamirovsky (1963)]. As yet, no studies of the association between rapid magnetic variations, and spread F, or 'wind' experiments, have been published, although such associations have been looked for.

A more sensitive method of measuring the motions of ionospheric irregularities has been developed by Findlay (1951)

and by Thomas and McNichol (1955). They recorded the phase shift of the carrier frequency of ionospherically reflected pulse signals. When radio wavelengths of twenty to forty meters are used, very small ionospheric motions produce appreciable phase changes. The principal drawback to the Findlay technique is radio interference caused by continuous pulse transmissions, and the wide receiver bandwidth required with consequent susceptibility to interference. If absolute height information is not required, continuous-wave transmissions can be used. The simplified CW approach has been followed by a number of workers, notably Ogawa (1960) and Miroktan and Drachen (1959). Davies (1962a) developed a technique using an offset reference frequency and frequency change, rather than phase change, measurement. This technique is very straight-forward and has proved exceptionally reliable [Davies and Baker (1966)]. The principal use to which Davies' Doppler frequency sounders have been put is in the study of solar flare effects [Agy, Baker and Jones (1965)].

Chan, Kanellakos, and Villard (1962) found that phase path recordings, made from WWV and other signals, correlated with certain features on magnetograms. Between October 1960 and September 1961, twelve magnetic sudden commencements which correlated directly with abrupt phase path changes were observed. Excellent correlation was also obtained during four magnetic storms with K indices ranging from 3+ to 8. One good example of a Pc-5 micropulsation event which was directly associated with periodic phase-path variations, was found.

Similar examples exhibiting close association between regular magnetograms and 'Dopplometer' records have been reported by Agy, Baker and Jones (1965). Davies and Baker (1966) report that a 'ringing' Doppler signal is observed associated with magnetic sudden commencements both day and night, and that occasionally frequency variations very similar to variations in one or more components of the earth's magnetic field are observed.

A detailed study of NBS F region 'Dopplograms' was undertaken by Lewis at the instigation of this author. [Lewis (1964)]. Records of vertical and oblique incidence paths covering the period 1961 to 1964 were compared with magnetograms at Boulder, Colorado. It was found that rapid variations, of less than four minutes period, were frequently well correlated; a Doppler frequency shift due to phase-path changes, of between 0.1 to 0.4 cycles per gamma of magnetic variation being observed. The correlation for longer period variations proved more difficult to assess. Sometimes changes in the H component and sometimes changes in the D component were well correlated; but the frequency shift only amounted to about 0.01 cycles per gamma, and events were sporadic.

This work is reported in Lewis (1967):

"Doppler frequency changes are suitably divided into two classes: rapid variations and slow changes according to whether or not the time scale of a change is shorter than about 4 minutes. The overall coincidence between

> geomagnetic variations and Doppler frequency changes is poor. However it is found that rapid geomagnetic variations such as sudden impulses and Pi-2 micropulsations accompany Doppler frequency change with a high degree of probability. The correspondence between the two is activity-wise in most cases. Peak to peak correspondence has been observed, however in some cases, when the Doppler frequency changes amount to a few tenths of a c.p.s. for magnetic variations of unit strength (one gamma in the south-north component). The coincidence is also very good for sudden commencements of magnetic storms. ....The correspondence is, in most cases indefinite for magnetic bays. When a clear coincidence is seen the ratio of the change of frequency to magnetic variation is of the order of a few hundredths of a c.p.s. per gamma."

No actual statistics of occurrence are given. A number of events of different sorts are illustrated by tracings from sonograms, and magnetograms. He stated that:

> "For every rapid event seen on the boulder magnetograms, a rapid Doppler shift occurs simultaneously." p.1552

(This implies a magnetic event of at least three gammas amplitude and two or three minutes duration, since regular-run Boulder magnetograms were used.) Lewis also exhibits (sunrise event) evidence that:

> "As the height of reflection decreased the amplitude of Δf decreased."

An attempt was made by Watt (1964) to obtain correlations between phase-path changes and rapid-run micropulsation records during an experiment carried out in the summer of 1963 at Suffield, Alberta. He concluded that, although positive correlation was observed only on one isolated occasion, this lack of association was due to the equipment characteristics.

Ionospheric soundings using the CW HF Doppler technique have been made by a number of other workers: Fooks (1962), Jones (1964), Georges (1967), Weaver et alia (1967). These workers have not published reports of associations with magnetic variations, [Donnelly (1966)].

In summary of the observational findings it may be said (a): clear-cut associations between ionospheric HF radio propagation perturbations and magnetic rapid variations have been observed from time to time by a number of workers; and (b) : the order of magnitude of the perturbations (in frequency and phase) associated with magnetic sudden-commencements, and bays has been measured.

1.6 Theories of Association Between Magnetic Rapid-variations and Ionospheric Perturbations

Some theoretical work has been done directly relating HF Doppler shifts to magnetic variations: Rishbeth and Garriott (1964), Jacobs and Watanabe (1966). (This work is treated more fully later.) The predicted Doppler shifts are found to be much smaller than many of those actually observed. [Duffus and Boyd (1967)].

A great deal of work has been done on the motion and formation of various E and F region irregularities in conjunction with electric and magnetic field variations. [Matsushita (1965)].

The most notably successful theory is that of Farley (1963). He relates two-stream instabilities caused by the equatorial electrojet current to the formation and motion of field aligned irregularities in the F region. His predictions have been confirmed by incoherent backscatter studies Bowles et alia (1960). A similar process is expected to occur involving the auroral electrojets.

Dungey (1955) proposed that hydromagnetic waves generated in the exosphere, and propagating downwards through the ionised medium might account for F region irregularities having associated magnetic perturbations. Cole (1964) proposed that hydromagnetic waves in the magnetosphere may be responsible for the acceleration and hence precipitation of charged particles. In this case the HM waves would produce ionospheric irregularities and also magnetic field perturbations.

Martyn (1954) postulated that dynamo (electric) fields associated with E region current systems would be mapped to the F region along the magnetic field lines and would lead to the formation and drift of F region irregularities. Farley (1960) however, has shown that this mechanism would not produce F region irregularities although it could result in F region drift motions. [vid. also Kamiyama (1956)].

Magnetic field variations are implicit in the wind-shear theory of sporadic E formation, but they are thought to be rather small. [Axford et alia (1966)].

Various theories which do not specifically implicate magnetic perturbations concerning the formation and motion of ionisation irregularities may indirectly be related to magnetic perturbation theory if the ionisation irregularities result in changes of conductivity. In such cases any (electrojet) currents flowing will be modulated by the plasma motions.

Various atmospheric wave motions and wind-borne irregularities could result in magnetic perturbations. In particular :

i) infra-sonic waves, Maeda and Watanabe (1964)
ii) ion-acoustic waves, D'Angelo and Michelsen (1967)
iii) Helmholtz (shear) waves, Jones and Maude (1965)
iv) Brunt/Vaisala waves, MacDonald (1963)
v) internal gravity waves, Hines (1967)

In summary, it may be said that it is very unlikely that any single mechanism accounts for all the types of association observed between magnetic variations and ionospheric perturbations.

All types of interaction do, however, suffer from constraints imposed by atmospheric conditions in the ionosphere. These constraints are discussed at some length in the following chapter, as are the possible interaction processes.

The theory involved in interpreting specific kinds of experimental results is given in chapter 3 in conjunction with the descriptions of the experiments.

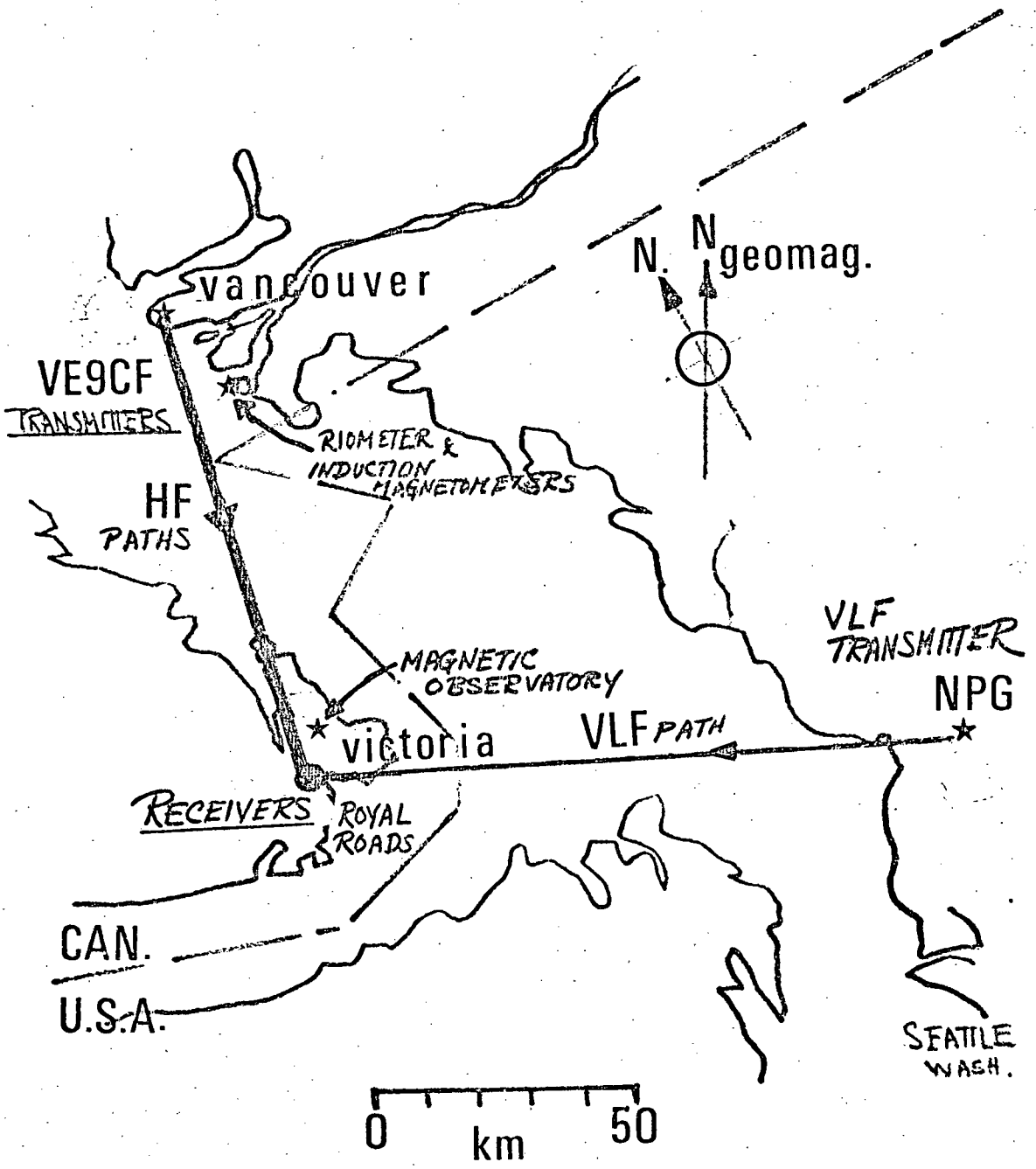


Fig. 2.1.1. Map of the Vancouver Victoria region shewing the location of the experiments, and the radio propagation paths.

CHAPTER II

Experiments

2.1 General Account of the Experiments Performed

With the exception of the eclipse experiments, all the experiments were conducted in the Vancouver - Victoria vicinity. Fig. 3.1.1 is a map of this area showing the locations of all the observing equipment from which data have been obtained. The geomagnetic latitude at Victoria is 54° N and LMT = UT $- 8^{h}$.

The initial experiment was conducted during a four-month period in the spring of 1963. A 25 MHz radiometer was operated in conjunction with induction magnetometers at Westham Island. On at least one occasion a signal level enhancement occurred in direct association with a night-time Pt micropulsation event. However, interference, receiver noise, and gain drift, made it desirable to seek other methods of continuing the study of the association found.

In order to determine whether the signal enhancements were due to a decrease in cosmic noise absorption or to scattering from ionospheric irregularities, two further experiments were implemented. A radiometer to measure absorption changes was installed at Westham Island, and a broad-band radiometer to observe ionospherically reflected signals was designed and built at Royal Roads.

An Aerospace ARII 30 Mc. riometer, borrowed from the Stanford Research Institute, was installed at Westham Island, a very quiet location in the Fraser River Delta. Two separate records were made; the regular servo-diode records, and a record of rapid variations in the a.g.c. voltage. The a.g.c. record had a full scale range of about one decibel for variations in signal strength with a period between five seconds and five minutes. The regular servo-diode record showed longer period and diurnal variations at much lower sensitivity. The riometer was operated in direct conjunction with the induction and fluxgate magnetometers at Westham Island. The period of operation extended from November 1964 to March 1965.

Simultaneously, at the Canadian Services College, Royal Roads, (just West of Victoria) a broadband HF radiometer was constructed and operated to monitor ionospherically reflected signals.

A broadly zenith-directed antenna composed of a dipole and an orthoganally oriented loop was used to discriminate against groundwave signals from Victoria and pick up circularly polarisedwaves. A bandwidth of about 4 MHz centered on 14 MHz was customarily used. The purpose of this radiometer was to detect wide-band-coherent components in the fading spectra of a large number of signals at frequencies near the maximum-useable-frequencies for their respective paths. It was thought that this should provide a sensitive continuous measure of the

presense of F region irregularities of the type that cause 'spread-F' on ionograms.

In conjunction with the radiometer at Royal Roads, a pair of telluric potential recording lines (E W and N-S) were constructed and operated. The broad-band radiometer was operated from the fall of 1963 until the fall of 1964. A number of examples of associated events were obtained.

From another point of view it was considered desirable to know as much as possible about the role of E region electric currents in the transmission of micropulsation signals through the ionosphere. One means of studying these effects is to make use of the 'hole' in the conducting E and F_1 layers which occurs during a solar eclipse. Consequently participation in the Defence Research Board Pacific Naval Laboratory eclipse expedition was arranged. During the July 20, 1963 eclipse, induction and rubidium vapour magnetometers were operated at Hay River, N.W.T. by P.N.L. staff, and a rubidium vapour magnetometer at Fort Vermilion by the author. The path of totality in the E region lay above Hay River while F region totality occurred above Fort Vermilion. Records were taken for several days before, during and after the eclipse, and were compared with magnetograms obtained from Meanook and other locations. Pc-1 and 1 - 5 Hz micropulsations appeared to have been attenuated by the eclipse. Some evidence of an S_q current effect was also obtained [Boyd (1966)].

By the summer of 1964, it was apparent that neither the riometer nor the broadband radiometer were capable of providing an unambiguous set of data for ionospheric motions associated with magnetic rapid variations. Although both experiments provided many examples of associated events, and although the riometer records indicated that (scintillation) scattering rather than decreased absorption was probably responsible for the enhancements observed, it was felt that a more definitive experiment was required [Duffus, Boyd and Kinnear (1965)]. Dr. K. Davies (E.S.S.A.) suggested that vertical incidence HF Doppler sounding, a technique which he had developed, might prove most suitable.

A preliminary survey, utilizing E.S.S.A. Doppler records was made by Mr. T. Lewis of U.B.C. He uncovered a dozen or so examples of Doppler frequency variations paralleling magnetic variations, after looking through about three years of the Boulder, Colorado records.

On the basis of this survey, it was decided to conduct a Doppler sounding experiment, utilizing the short N-S path between U.B.C. and Royal Roads. Frequencies of 2.7 and 4.6 MHz, or 5.3 MHz. were transmitted from Vancouver and received on polarisation discriminating antennas at Royal Roads. This experiment was operated more-or-less continuously from March 1965 to June 1966.

The Doppler experiment is the principal one on which this thesis is based. In addition to the HF Doppler sounding it was possible to obtain VLF Doppler records by differentiating the output of a sky-wave phase moitoring receiver. The NPG phase receiver was provided by Dr. J. Belrose of the Defence Research Board, Telecommunication Establishment, Ottawa. The NPG transmitter is located about 120 km. East of Royal Roads, near Everett, Washington. Consequently, as may be seen in Fig. 2.1, the VLF Doppler path is an E-W path, while the HF Doppler path is approximately N-S in geomagnetic co-ordinates.

In addition to data obtained by the author in association with Professor J. Duffus at Royal Roads, data were also obtained from a number of other local sources. The Westham Island (U.B.C. - P.N.L.)micropulsation data have already been mentioned. Extensive use was also made of rapid-run fluxgate records supplied by Mr. B. Caner of the Department of Energy Mines and Resources magnetic observatory, near Victoria, and of ionograms from the University of Washington.

In the following sections of this Chapter, each of the experiments is described in detail. Theoretical models relating measured variables to ionospheric parameters are given. These are followed by reasonably detailed specifications of the equipment actually used.

2.2 Geomagnetic Rapid Variations in the Ionosphere

2.2.1 Theory of Measurement

For the purposes of this study a continuous record of the vector magnetic disturbance field in the ionosphere would be most desirable; such records are not yet attainable by any known technique. The best that can be done is to record magnetic variations and electric potential at locations on the earth's surface in the immediate vicinity of the radio experiments and to estimate the field prevailing in the ionosphere from these records.

The disadvantages of this method are those arising from the fact that the ionosphere is an anisotropic conductor and the earth is an inhomogeneous one. Also, currents and associated fields may exist at different heights in the ionosphere, yet only the net effect of all these is measureable at a distance.

The ground is not in general uniform and consequently induced currents tend to have a preferred direction, characteristic of a given station. These currents are important as they account for about one third of the observed disturbance field. [Price (1965)]. The ground conductivity is, however, invariant with time for the range of frequencies and skin depths involved. The net effect of the ground is to distort the vector field by increasing the horizontal component perpendicular to the 'strike' of the earth conductivity, and by decreasing the vertical component.

Studies conducted in this locale involving observations at a number of closely spaced stations have shown that earth effects typically perturb the amplitude of a disturbance by an order of magnitude, and the apparent orientation by ten or twenty degrees [Duffus et alia (1959) ,Lambert & Caner(1965), Rostoker (1966) and Wescott and Hessler (196)].

Although ground conductivity is time invarient, ionospheric conductivity is a complex function of time. Consequently the changing currents induced in the E region will vary greatly with time of day, season, and with the occurrence of sporadic E ionisation. These changes will alter the relationship between the field observed at the ground and the magnetic field in the F region.

For these reasons, a precise theory relating magnetic field measurements at the ground to ionospheric fields is not practical : nor is there much point in very accurate quantitative field measurements at the ground stations.

Two rather simple theoretical models will suffice : if it is assumed that an infinite sheet current flows in the ionosphere then the horizontal disturbance ΔH is given approximately by : $|\Delta H| = 2\pi J \times 10^3 \gamma$ (3.1) [Heppner (1958)] where J is in amperes M^{-1}. The electric field induced in the earth's surface is given approximately

by :

$$| \Delta E | = \frac{0.6}{T} | \Delta H | \text{ volts km.}^{-1} \qquad (3.2)$$

where $| \Delta H |$ is in γ and T the scale time or period is in sec. (for T within an order of magnitude of 60 sec.) [Heppner (1958)].

If, on the other hand, it is assumed that hydromagnetic waves are being transmitted through the lower ionosphere then it would be desirable to know what relationship holds between the incident magnetic field in the F region, the induced current strength in the E region, and the magnetic and electric fields at the earth's surface.

If the electric field of the incident wave is $\perp$ to the meridian plane (N-S) and the plasma motion lies in the meridian plane, then for a wave with a period of 60 - 600 sec. and an E-W scale of about 1,000 km., the incident magnetic field is not significantly modified in its passage through the ionosphere [Nishida (1964)].

On the other hand, if the incident wave electric field lies in the meridian plane, but the plasma motion is perpendicular to it, both attenuation and phase-shift occur. The ratio of the magnetic field B_y^I (D), incident in the F region, to the magnetic disturbance horizontal component observed on the ground, B_h (C), is given, in c.g.s. units (after Nishida) by :

$$\frac{B_y^I \ (D)}{B_h \ (C)} = \frac{c^2}{8\pi v \Sigma_2} \left(1 + \frac{4\pi\Sigma_1 v}{c^2 \sin\psi}\right) (1 + |k| \ d) \qquad (3.3)$$

where $c = 3 \times 10^{10}$ cm. sec.$^{-1}$.

v is the Alfvén velocity $\approx 10^8$ cm. sec.$^{-1}$,

$|k|$ is the E-W scale of the HM wave $\approx 10^{-8}$ cm.$^{-1}$ $= \frac{1}{\lambda}$ (wave number),

ψ is the magnetic dip angle $= 72^\circ$,

$\Sigma_{1,2}$ the integrated conductivities from bottom of the ionosphere ($d = 100$ km. $= 10^7$ cm.) to the top ($D = 300$ km. $= 3 \times 10^7$ cm.),

Σ_1 is the Pedersen conductivity,

Σ_2 the Hall conductivity both $\approx 10^{13}$ c.g.s. units.

Substituting these values

$$\frac{B_y(D)}{B_h(0)} = \frac{1}{800} \qquad (3.4)$$

-- a very appreciable attenuation. The phase shift for this case is about 90°.

In general, the observed (Pt) magnetic pulsations are found to be elliptically polarised in this vicinity, [Rostoker (1966)] and consequently it is rather difficult to estimate what the incident fields may be. It is also possible that evanescent waves transmitted horizontally through the ionosphere, rather than vertically incident waves, are involved. In any case, the disturbance field in the ionosphere will not be less than two-thirds of the disturbance field observed on the ground.

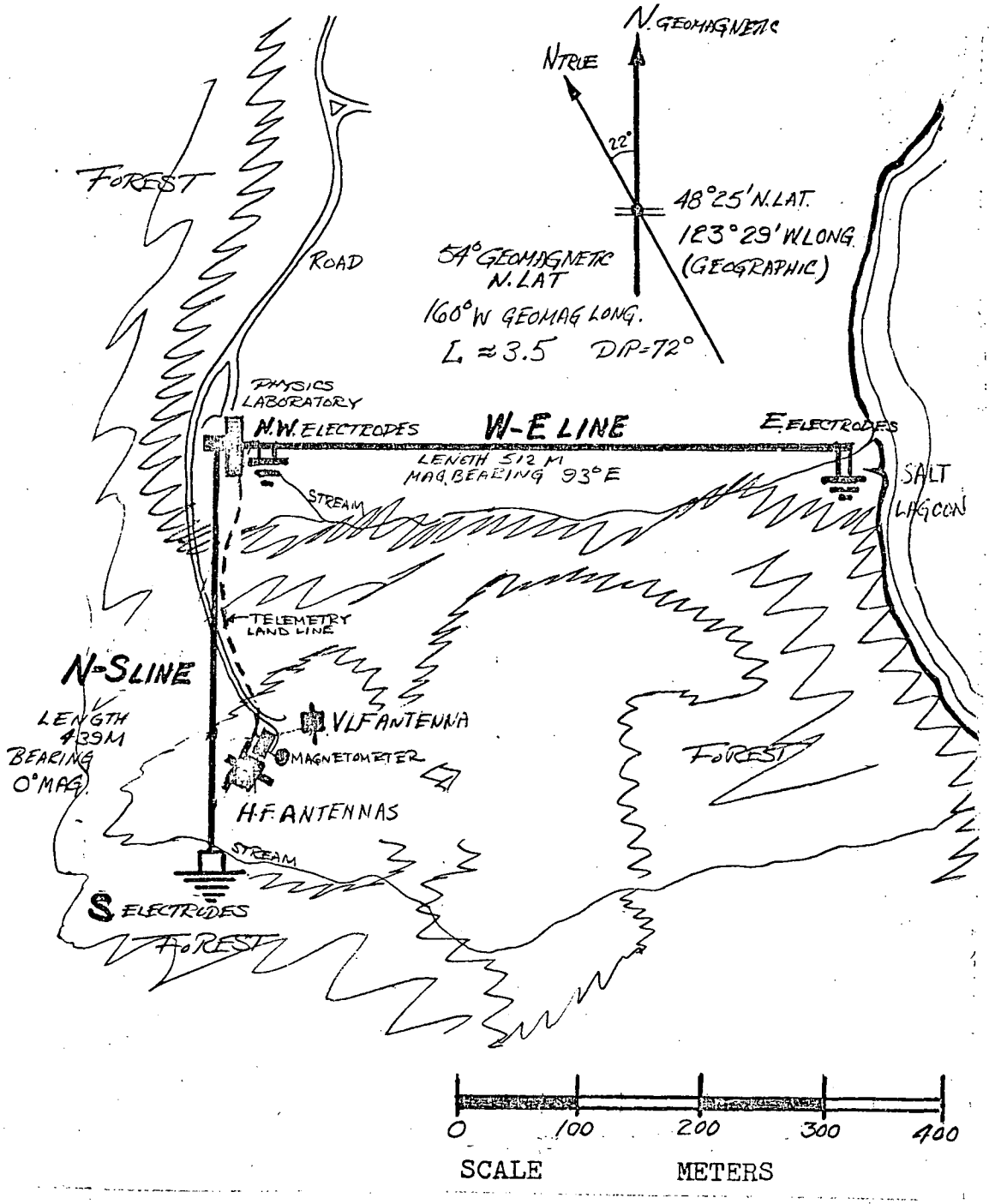


Fig.2.2.1. SITE PLAN ROYAL ROADS MILITARY COLLEGE
Shewing : Telluric potential measuring electrodes and line, and the HF and VLF receiving antennas.

Unless particular assumptions are made the ionospheric disturbance fields are uncertain by one or two orders of magnitude. However, assumptions regarding sources and propagation modes can be made for specific classes of events.

It is apparent from the foregoing that, a good signal-to-noise ratio and a flat (or known) frequency response are more important than absolute amplitude calibration in the design of a magnetic monitoring system.

2.2.2 Equipment Used for Magnetic Disturbance Recording

Telluric Potential System, Royal Roads

Figure 2.2.1 is a map of the Royal Roads experimental site showing the locations of the telluric potential lines and electrodes, and also the location of the rubidium-vapour magnetometer and radio equipment. The only power lines in the vicinity are buried cables and do not utilise a ground return. The site is a quiet valley in a forest about a mile from the nearest road.

Figure 2.2.2 is a block diagram of the telluric potential recording system, including one channel of the slow speed FM recorder and the total field magnetometer.

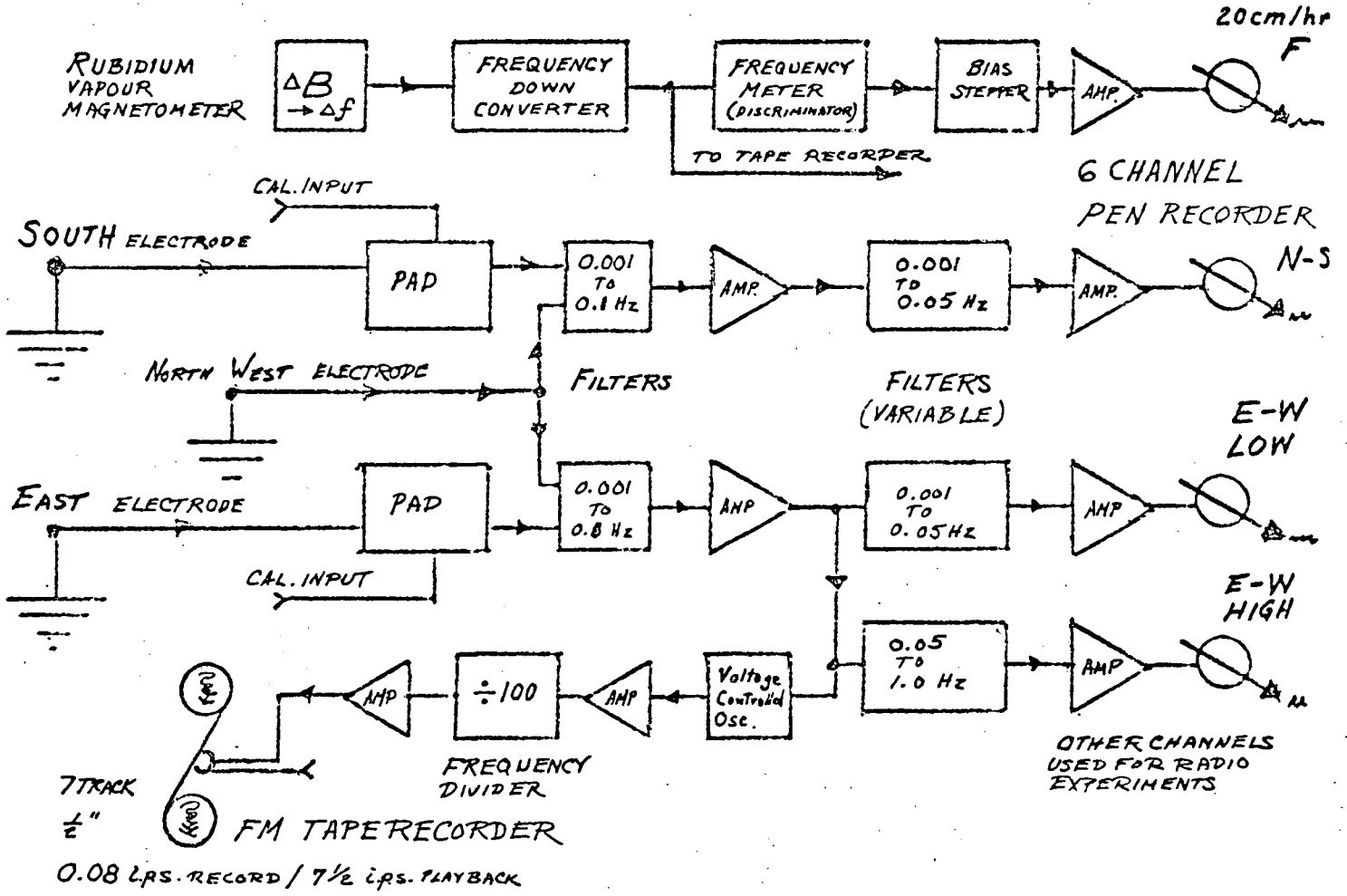


Fig. 2.2.2. Telluric Potential and Geomagnetic Total Field measurement and recording system CANSERVCOL Royal Roads Victoria BC.

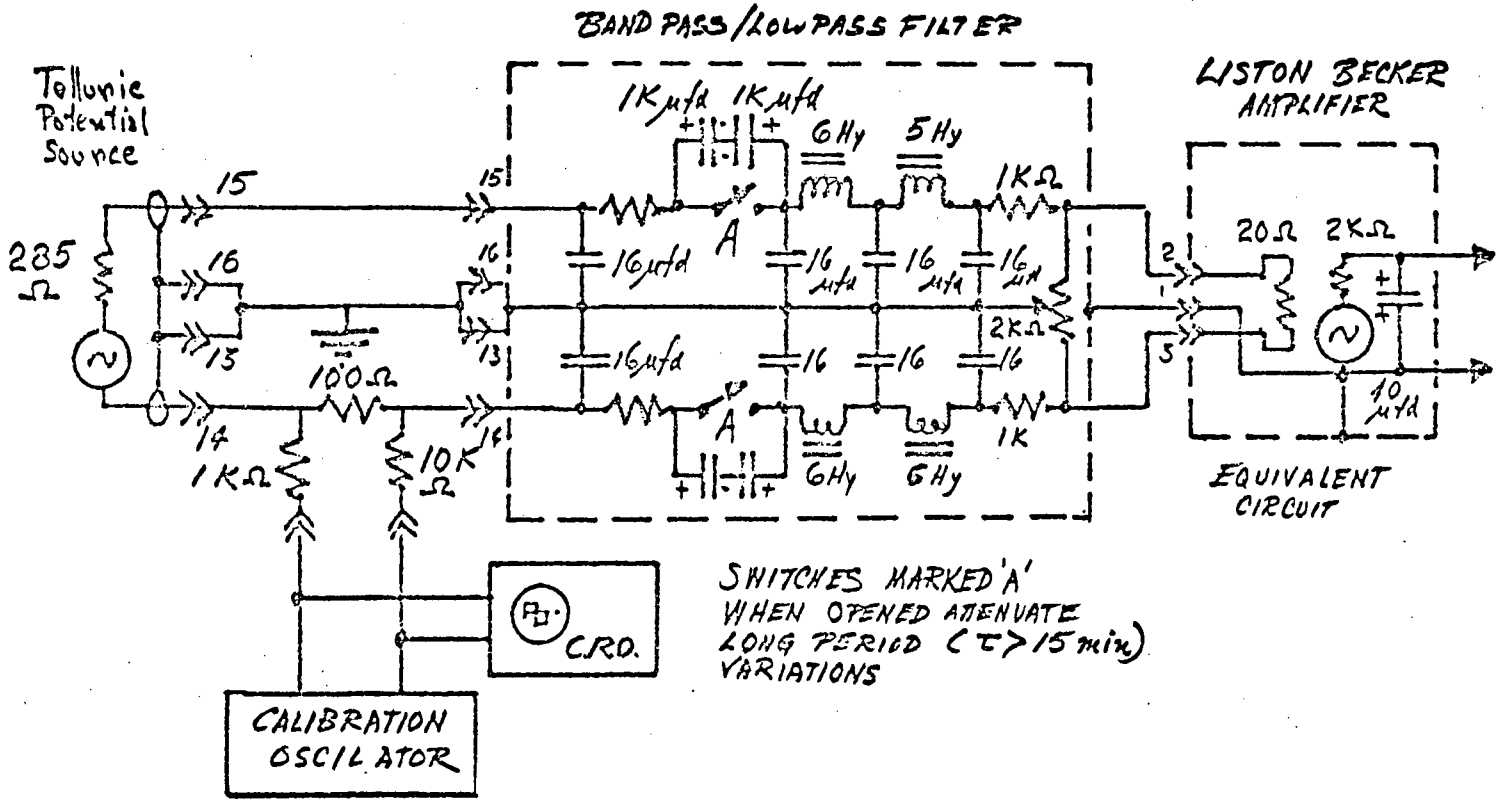


Fig. 2.2.3. Telluric Potential Measurement Channel , shewing actual circuits of calibration pads and filters, and equivalent circuits for the source electrodes and the breaker amplifier.(Liston Becker)
(Double Vee symbols represent connectors and associated numbers are contact numbers.)

The pick-up electrodes are ten foot cadmium copper ground rods driven into stream beds. Connexion is made to shielded lines and then through calibration 'pads' to low-pass filters, and finally to 8 cps. chopper amplifiers which feed low-pass and band-pass filters which in turn, feed the recording units.

The equivalent circuit of the telluric pick-ups and the actual circuits of the calibration pads and low-pass filters are shown in Fig. 2.2.3. The high-band bandpass output filters are Krohn-hite adjustable filters, which are fed through a series capacitor to minimize ringing effects when very large long-period signals occur.

Nearly every event seen on the N-S telluric line was also recorded with larger amplitude on the E-W line (Figure 2.2.4), consequently after an initial test period of several months, continuous chart and tape recordings were made using only the output of the E-W line. A similar predominance of E-W signal has been found on the Dominion Observatory telluric potential lines located about 10 miles north of Royal Roads [Caner, (1966)].

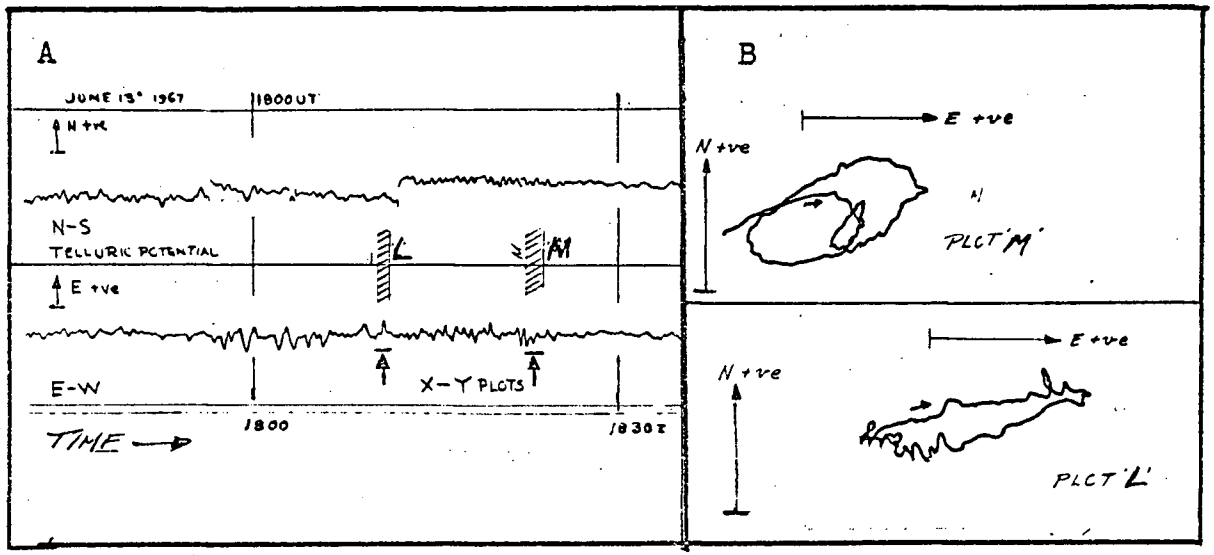


Fig. 2.2.4. Telluric Potential chart records A , and corresponding Polarisation plots B. On the polarisation plots the ordinate is N-S potential and the abcissa is E-W potential. The length of the arrows represents 0.5 mV/Km. The record is of a Pc 4. event June 13, 1967.

2.3.1 General Nature of HF Radiowave Propagation

The ionosphere is an anisotropic doubly refractive medium as far as HF radio-waves are concerned. A linearly polarised EM wave incident on the ionosphere is separated into two elliptically polarised waves, of opposite rotational senses which propagate along differing paths in the medium. The elliptical mode which describes a right-handed helix when it is downcoming in the northern hemisphere is called the ordinary mode, and that describing a left-handed helix the extra-ordinary mode. Providing the radio wave frequency is greater than the electron gyro-frequency in the earth's magnetic field. (Other conventions are sometimes followed [Davies (1965)].)

The highest frequency which can be reflected coherently from the ionosphere is called the maximum usable frequency or MUF. As this frequency varies with the angle of incidence a horizontal path projection length is usually specified. The maximum useable frequency for a 3,000 km. path involving one reflexion from the F_2 layer is called the '1 hop f_2 MUF 3000'. The MUF usually refers to the extra-ordinary mode since the (X) MUF is usually greater than the (O) MUF by at least half a megacycle. The MUF's for zero path length are the so-called 'critical' frequencies of the ionospheric layers.

$$f_o \approx \left(\frac{e^2 N_{max}}{\pi m} \right)^{1/2} = \left(80.6 N_{MAX}\right)^{\frac{1}{2}}$$

where : f_o is the ordinary mode critical frequency

N_{max} is the maximum electron number density in the layer

e is the electronic charge

m is the electronic mass

Above the critical frequencies, waves pass through the ionosphere into space. Below the critical frequencies they are reflected from the ionosphere. At the critical frequencies, waves are retarded severely, and sometimes deviated into horizontal paths. The net effect is one of strong so-called 'deviative' absorption, at the critical frequencies and low group velocities at frequencies just below the critical frequencies.

In addition to its refractive properties, the ionosphere, and particularly the D region, has absorptive or dissipative properties. Waves of frequency higher than a few hundred KHz are strongly absorbed in the daytime D region. This absorption occurs because the electrons set in motion by the EM wave, frequently collide with heavy particles, before they can re-radiate the EM energy. The EM energy is thermalised or absorbed. This type of absorption is called non-deviative, as it occurs below the heights where refractive effects are important. The extraordinary wave suffers greater non-deviative absorption than the ordinary wave.

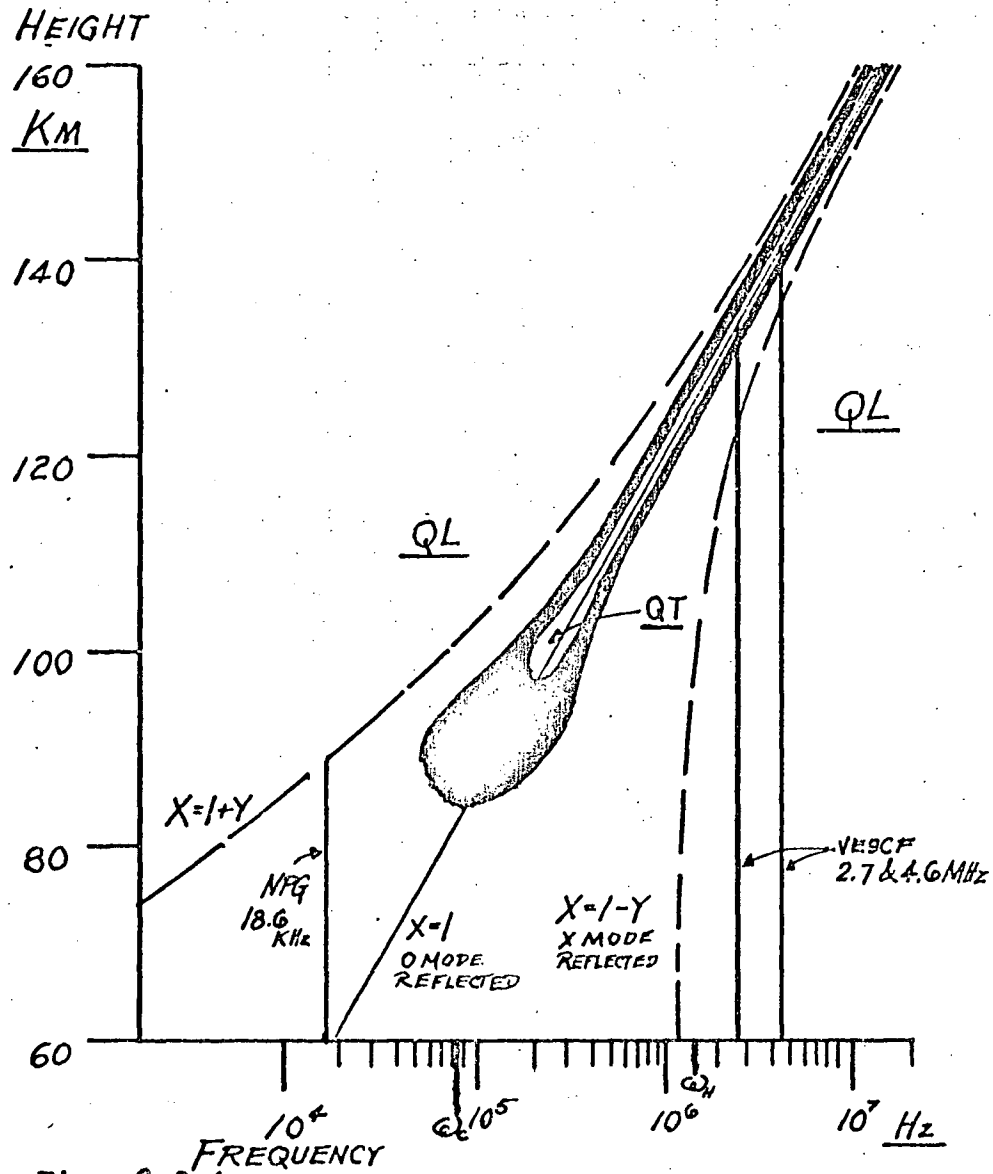


Fig. 2.3.1. Domains where the QL and QT approximations to the Appleton Hartree ionospheric refractive index equation are applicable. In the blackened region neither approximation holds. This figure is for a particular mid-latitude ionosphere model used by Ratcliffe (1959)/.

Four radio experiments were performed. In three of them the amplitude of received radio signals was measured in the fourth, the Doppler shift was measured. Further discussion of radio propagation is given in connexion with the discussion of each of the measuring techniques. A full formal treatment of HF radiowave propagation is given by Budden (1961), a less formal but more comprehensive treatment is given by Davies (1965).

2.3.2. RADIOMETERS

a) Narrow band Radiometer Amplitude fluctuations in HF radio waves transmitted through or scattered from the ionosphere are(statistically and often directly) related to ionisation perturbations . The narrow band radiometer at Westham islan was operated on a clear channel ,at first 20.1 MHz, later 25.0 MHz . Since the antenna was a half wave dipole ten feet above the ground low-angle skywave signals were somewhat discriminated against ,while the high frequency eliminated high angle specularly reflected waves, hence most of the signal was cosmic noise or scattered radiation. Occasional discrete events were caused by aircraft transmissions. The antenna fed a cascode pre-amplifier directly, It in turn fed an HRO 50 receiver through a hundred feet of RG9/BU cable. The A,G.C. voltage of the receiver was recorded on a strip chart. The receiver bandwidth was about 3KHz.

b) <u>The Broad band Radiometer</u> Instead of looking at cosmic noise there is some advantage in looking at (lower frequency)specularly reflected signals since these are more strongly perturbed by ionospheric irregularities. If a passive system is to be used either standard transmissions such as WWV , or an ensemble of many signals may be monitored. Since overhead ionospheric conditions were of most interest the distantly reflected signals from WWV (then in Maryland) were not suitable. The signal from a single hearby station was not considered desireable since the station's modulation characteristics would predominate over ionospheric amplitude perturbations. But if an ensemble of many stations is received then the individual modulation characteristics should average out while the effects of ionospheric focussing and/or absorption should add up and be more prominent.

The broadband radiometer located at royal roads consisted of a directional antenna (broadbanded as much as possible) feeding a receiver with an input bandwidth of about 4MHz which was usually centered somewhere in the twelve to fifteen MHz region. The signal level averaged over the 4MHz bandwidth and over a 10 second period, was recorded on a strip chart .

2.3.3 The High Sensitivity Riometer

The design and operation of riometers is fully treated by Little, and Leinbach (1959). Riometers normally operate to give the maximum amount of information regardin typical absorption events having a time scale of about an hour, and involving 20 or 30 db. of absorption. Signal strength resolution is usually limited to 0.1 db. at best (commonly 0.5 db.). And the time resolution obtained with the usual recording parameters is about 30 sec. at best (commonly 60 sec.). (Sensitivity is about 4times kTB ambient.)

For the purposes of this study greater signal strength resolution, and more rapid response were required in order to study association with micropulsations in the Pi-2 class. On the other hand long term stability and high accuracy of calibration were not required.

The normal record is produced by a servo system, and the servo current is recorded as a measure of signal strength. By continuously adjusting the output of a noise diode to match the input from the antenna, problems due to gain changes and receiver noise are obviated.

The receiver was operated with automatic gain control to avoid overloading. The response time of the servo loop depends on the integration time of the servo null detector and on the thermal time constant of the noise diode (0.5 sec.).

The a.g.c. time constant is much shorter than the servo system response time but longer than the diode/antenna switching period (about 2 ms.). Typically, the a.g.c. time constant is about 0.5 sec., and the servo time constant about 100 sec.

In the riometer used, the Aerospace AR 100A, the a.g.c. voltage is directly proportional to signal power over the normal operating range. Hence, it was decided to amplify and record variations in a.g.c. voltage. The a.g.c. signal, however, exhibits rapid fluctuations due to multipath fading and to the limited bandwidth of the receiver. That multipath and polarisation fading rather than the effect of filtering itself was responsible for the slow fluctuations when narrow i.f. bandwidths were tried can be seen from the following considerations. Fading broadband noise has a correlation bandwidth of about 3 KHz, and for fluctuation periods longer than 10 sec., this is the determining factor, rather than the bandwidth limited noise. The apparent frequency of noise from a filter is given by Bendat as : $\overline{f_o} = 0.58\ f_b$, where f_b is the (upper) cut-off frequency of the filter. That is, for a 3 KHz filter, $\overline{f_o}$ would be about 1.6 KHz and far out of the range (0 - 0.1 Hz) of interest. On the other hand, the correlation bandwidth of ordinary HF fading is about 3 KHz and the fading rate may frequently be in the 0 - 0.1 Hz band. [Davies (1965)].

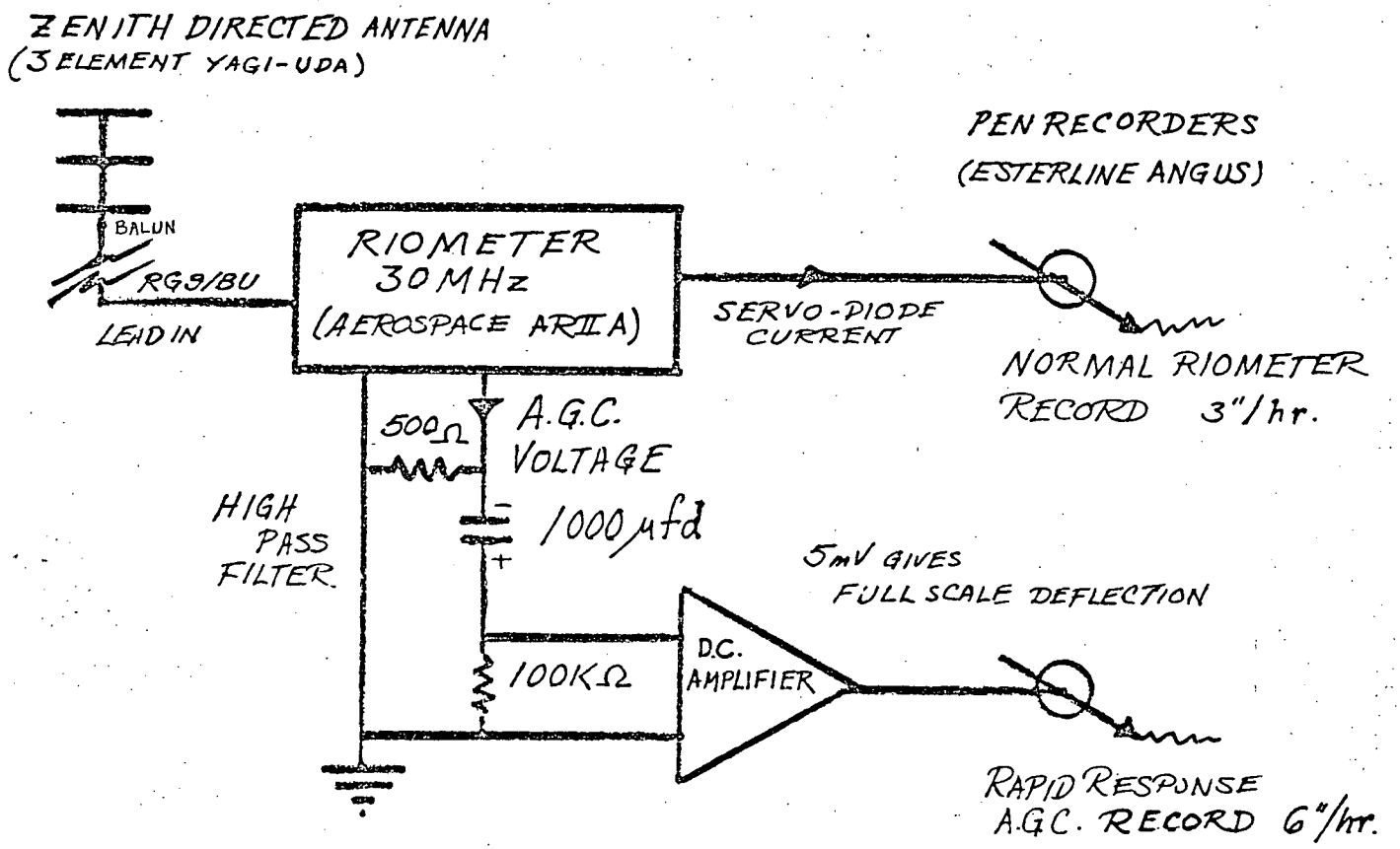


Fig. 2.3.2. Riometer with rapid response high sensitivity a.g.c. output channel.

It was found that by increasing the I.F. bandwidth from 3 KHz to 80 KHz fluctuations below 1 Hz were virtually eliminated from the amplified a.g.c. output during quiet periods. Fortunately, the ambient RF noise level at Westham Island was bery low, otherwise such a large bandwidth could not have been used.

The experimental arrangement used is shown in Fig. 2.3.2. A zenith directed wide-spaced 30 MHz yagi-uda antenna was used. It fed a simple balun and 200 feet of RG9B/U Cable, which fed the ArII-100A riometer. A Boonton Radio Admittance meter was used to set up the antenna and to match the line and the noise diode. The regular riometer record was taken on an Esterline Angus recorder operating at 3"/hr. The a.g.c. voltage was fed through a capacitor (high pass filter) resistor, network and into a Magnetic Instruments Corp. D.C. amplifier (model 759) which fed an Esterline Angus recorder operating at 6"/hr. and gave a sensitivity of 10 millivolts full scale; equivalent to about 3 db. of signal strength full scale.

2.4 HF CW Doppler Ionospheric Sounding

2.4.1 Theory

This technique simply involves illuminating the underside of the ionosphere with a fixed frequency continuous-wave radio source, and observing the frequency spectrum of the waves echoing back from the ionosphere. Ionospheric motions and changes in refractive index lead to Doppler shifts in the received signal [Davies (1962 a - d)].

If a plane radio wave represented by:

$E = E_o \exp i\,(\hat{k}\vec{s} - 2\pi ft)$ (s is a space co-ordinate) having amplitude E frequency f, and propagation vector $\hat{k}$, impinges upon a single electron in a neutral plasma, the electric field of the wave will set the electron in motion, and the moving electron will then reradiate a wavelet of frequency f, but advanced in phase by 90° in the forward ($\hat{k}$) direction with respect to the initial wave.

If the electron has some initial velocity v then the electron sees a wave Doppler shifted in frequency. The period of the wave as seen by the electron will be the length of time taken by one wave length to pass the electron: this is

$$t' = \frac{\lambda}{c - v.\hat{k}}$$

now $\lambda = \frac{c}{}$ and $f' = \frac{1}{t'}$

so that $f' = (c - \vec{v}.\hat{k}) \quad (\frac{f}{c})$

or $f' = f - \frac{f}{c}\,\vec{v}.\hat{k}$.

This is the frequency that the electron will re-radiate. The re-radiated frequency seen by a fixed observer will be again Doppler shifted.

$$f'' = f - \frac{f}{c}\,(\vec{v}\,.\,\hat{k} + \vec{v}\,.\,\hat{e})$$

where $\hat{e}$ is the unit vector in the direction of the electron from the observer. If the observer is at the transmitter $\hat{e} = \hat{k}$ and

$$f'' = f - \frac{2f}{c}\,\vec{v}\,.\,\hat{k} \qquad (2.4.1)$$

This is the simple moving mirror expression for Doppler shift.

If many electrons are involved many waves will be returned, each having a Doppler shift appropriate to the velocity of the electron, which re-radiated it; since successive re-radiations are possible a broad distribution of frequencies is to be expected if the electrons are not all in uniform motion. Moreover, the power spectrum received will depend on the geometry of the reflecting region, since the wavelets will be re-radiated with differing phases and will interfere with each other.

If the electrons possess thermal velocity components as well as an ordered velocity, the thermal components will simply broaden the Doppler spectrum provided density or temperature gradients are not present. If there is a density or temperature gradient, then more collisions will occur on one side of a lamina of electrons than on the other and the thermal velocities will not average to zero but will average to a net diffusion velocity opposite to the gradient. In this case the Doppler effect will involve not merely a broadening of the received frequency spectrum but a skewing of it or a net Doppler shift. In the presence of a magnetic field the effect is even more complicated since density or temperature gradients perpendicular to the magnetic field lead to drifts perpendicular to both the density gradient and the magnetic field.

Consequently, in discussing the ionosphere it is necessary to consider not merely the electron velocity due to applied accelerating fields but also the net velocity due to collisions in conjunction with density of temperature gradients and the magnetic field.

The microscopic problem is dealt with by summing up the waves radiated by the individual electrons. For the cases of interest there are many electrons in an ionospheric region small compared to a wavelength. Electrons in such a region move coherently when acted on by a wave, consequently the individual electron displacements r may be replaced by the bulk polarization matrix [P] defined by: $[P] = Ne\,[\langle r\rangle]$ where N is the electron number density and e is the electronic charge and $[\langle r\rangle]$ the average displacement in all the principal directions for electrons in a volume much smaller in radius than one wavelength, but large enough to contain many electrons. $[\langle r\rangle]$ is assumed to be determined by the electric field and by collisions and gradients in N and the ambient magnetic field so that [P] is a matrix of the form: $[P] = a\,[M]\,[E]$ where [M] is the susceptibility matrix for the medium, a is a scalar parameter and E is the electric field vector, then the displacement matrix $[D] = [\epsilon_0 E] + [P]$, may be used to replace E in Maxwell's equations, which may then be used to derive the matrix wave equations for $\vec{E}$ and $\vec{H}$.

The wave equations in turn may be used to obtain a dispersion equation, from which the phase velocity and attenuation for a simple harmonic plane wave travelling in any direction may be found in terms of the refractive index matrix. The refractive index matrix for a drifting magneto-ionic medium is derived by Unz (1965).

This approach is rather intractable and, alternately, a scalar wave equation may be derived by assuming that the vector

fields are deriveable from a scalar potential, and that they are 'slowly varying' in a distance comparable to a wavelength. This assumption is valid except in regions where reflexion or coupling occurs, where the wavelength tends to infinity. Assuming the scalar wave equation to be valid, simple harmonic plane wave solutions are considered. These entail the further assumption that the medium is not rapidly time varying.. Donnelly (1965) derives specific criteria for determining the validity of such solutions for vertical incidence propagation through a horizontally stratified plasma. Again these criteria are met everywhere except in coupling regions.

The next step in the derivation of analytic Doppler equations for ionospheric radio propagation is to specify some sort of propagation path between the transmitter and the receiver. The simplest concept is that of the optical phase path. This is a path which is everywhere tangential to the normal to the wave fronts. The usual differential equation for determining the optical phase path is derived on the assumption that $\frac{f}{c}$ is large [e.g. see the appendix to Gill's book, (1965)]. This assumption does not hold for HF radio frequencies and the differential equation obtained in the case of $\frac{f}{c}$ small does not have a unique solution.

Another approach is required. The path which a wave packet or group travels is uniquely defined, except in the coupling region, and the projection of the phase velocity onto this path at every point can be determined. Hence it is customary to employ the group ray path with a $\cos \alpha$ factor to take into

account the fact that the wave front normal does not generally lie along this path; α is the angle between the wave normal and the group path. The use of ray theory even for the coupling region where the assumption of a slowly varying medium does not hold has been justified empirically [Titheridge (1967)] and theoretically [Budden (1961) p. 145, "an investigation of the reflection or coupling process by 'full wave' theory shows that in general the ray theory can still be considered to hold with only trivial modification. An exception to this is the phenomenon of partial penetration and reflection for frequencies near the penetration (critical) frequencies of an ionised layer."]

Following the group ray path approach various authors [e.g. Davies (1962 c)] obtain expressions for the Doppler shift of the form:

$$\Delta f = \frac{f}{c} \frac{d}{dt} \left(\int^{s} \mu \cos \alpha \, ds \right) \qquad (2.4.2)$$

Various techniques may be used to approximate solutions to this equation. For instance, if vertical (normal) incidence is assumed together with a ray path symmetrical about the reflexion point h_r, then expanding the time derivative as two partial derivatives gives:

$$\Delta f = \frac{2f}{c} \left. \mu \right|_{h_r} \frac{dh_r}{dt} + \int_0^{h_r} \frac{d\mu}{dt} \, ds \qquad (2.4.3)$$

Since μ tends to zero as h_r is approached the first term is zero. For a uniform rate of variation of electron density with height the major contribution to the integral term occurs near the height of reflexion as Davies (private communication) pointed out with the following argument: Assume $\mu = \sqrt{1 - \frac{km}{f^2}}$, $k = 80.6$ then $\frac{d\mu}{dt} = \frac{-k}{2\mu} \frac{1}{f^2} \frac{dN}{dt}$ and this of course blows up as u tends to

zero. However the phase velocity $\frac{c}{\mu}$ also tends to infinity and so does the wavelength and the wave never reaches the point where $\mu = 0$.

Fooks (1962) refers to various results of drift measurements which gave velocities characteristic of a narrow range of heights near the calculated height of reflexion of the HF sounding waves, and concluded that for most E layer reflexions, and some F layer reflexions irregularities near the height of reflexion are most important in perturbing the phase path.

To put it in other terms: For many cases of reflexion, when the sounding frequency is away from critical frequencies, it may be shown that as the region of reflexion is approached the ratio of the wavelength to the scale height (for electron density variation) increases markedly, so that in effect reflexion takes place abruptly in a region small compared to a wavelength. This is the case to which the 'moving mirror' Doppler equation applies. It is: $\Delta f = \frac{-2f}{c} \frac{dh}{dt}r$ (2.4.4)

Equation 3.4.4 provides at least an order of magnitude estimate of the vertical ionospheric layer drift speed required to produce a given Doppler shift, when changes in height of a single reflecting layer are to be expected from a general knowledge of prevailing ionospheric conditions.

However since the wave equation itself fails when sounding frequencies close to critical frequencies are used equations 3.4.2 - 4 must be used with some caution. In particular it is frequently found that an appreciable contribution to the virtual height occurring near the height of reflexion can be accounted

for only by empirical formulae or by a full-wave theory approach. Titheridge (1967) The contribution to the Doppler shift corresponding to this additional path length, and ultimately attributable to time varying gradients of electron gas density and pressure near the height of reflexion, may occasionally be appreciable.

Another aspect of the Doppler shift determination which is particularly relevant to this thesis, is exemplified by the question: How much of the Doppler shift may be attributed to perturbation of the magnetic field parameter in the equation for the refractive index of the magneto-ionic medium? A conclusive theoretical answer, particularly for frequencies near ionospheric critical frequencies would be difficult to obtain. Experimentally, large magnetic changes are sometimes observed without related HF Doppler changes, which suggests the direct effect may be a small one.

This is borne out by ray-tracing calculations performed by Jones, and reported by Donnelly (1966). Simple quasi-longitudical and quasitransverse refractive index formulae were used where applicable taking into account the effect of perturbation in the earth's magnetic field lead to the conclusion that for a large magnetic disturbance ($\frac{d\Delta H_L}{dt}$ of 0.1γ and $\frac{d\Delta H_T}{dt}$ of 0.05γ sec $^{-1}$ constant for all heights) (ΔH_L is ΔH along B_o and ΔH_T is ΔH perpendicular to B_o) the Doppler shift due to direct magneto-ionic path perturbation is less than 0.01 Hz, which is negligible. [Most magnetic disturbances at Victoria (1965 - 1966) did not involve rates of change higher than 0.05γ sec $^{-1}$; while Doppler shifts of 0.5 Hz were frequently observed.]

If the ionosphere is fairly flat most of the echo will come from the first Fresnel zone, whose radius is about 5 km. for a 3 MHz wave reflected at a height z = 200 km. If the ionosphere is 'rough' the reflecting region is broadened so that the effective radius may typically be about 20 km. [Al'pert (1960)]. Occasionally 'tilts' of the reflecting layer may occur and displace the reflecting region horizontally.

Concavities and convexities many wavelengths across occasionally occur and lead to focussing and defocussing of the wave.

If the wave were simply reflected at a plane boundary the determination of the phase path would not be difficult, but in fact the wave is refracted and coupled to the electrons, which re-radiated characteristic waves determined by the magnetic field. Two modes are normally present, and may be coupled; the ordinary (O) and the extra-ordinary (X) modes of circular polarisation. These modes follow different paths.

Fig. 2.4.1 is a schematic representation of the day-time ray-paths between Vancouver and Victoria for the sounding frequencies used. B_o is the Earth's magnetic field. The up-going waves are linearly polarised in the (geomagnetic) E-W plane. The down-coming waves are elliptically polarised in the right handed (O) or left handed (X) sense. (Since by-and-large, propagation is quasi-longitudinal, the ellipses are nearly circular.) (The 'Spitze' or cusp in the ray-path occurs in the O ray only.)

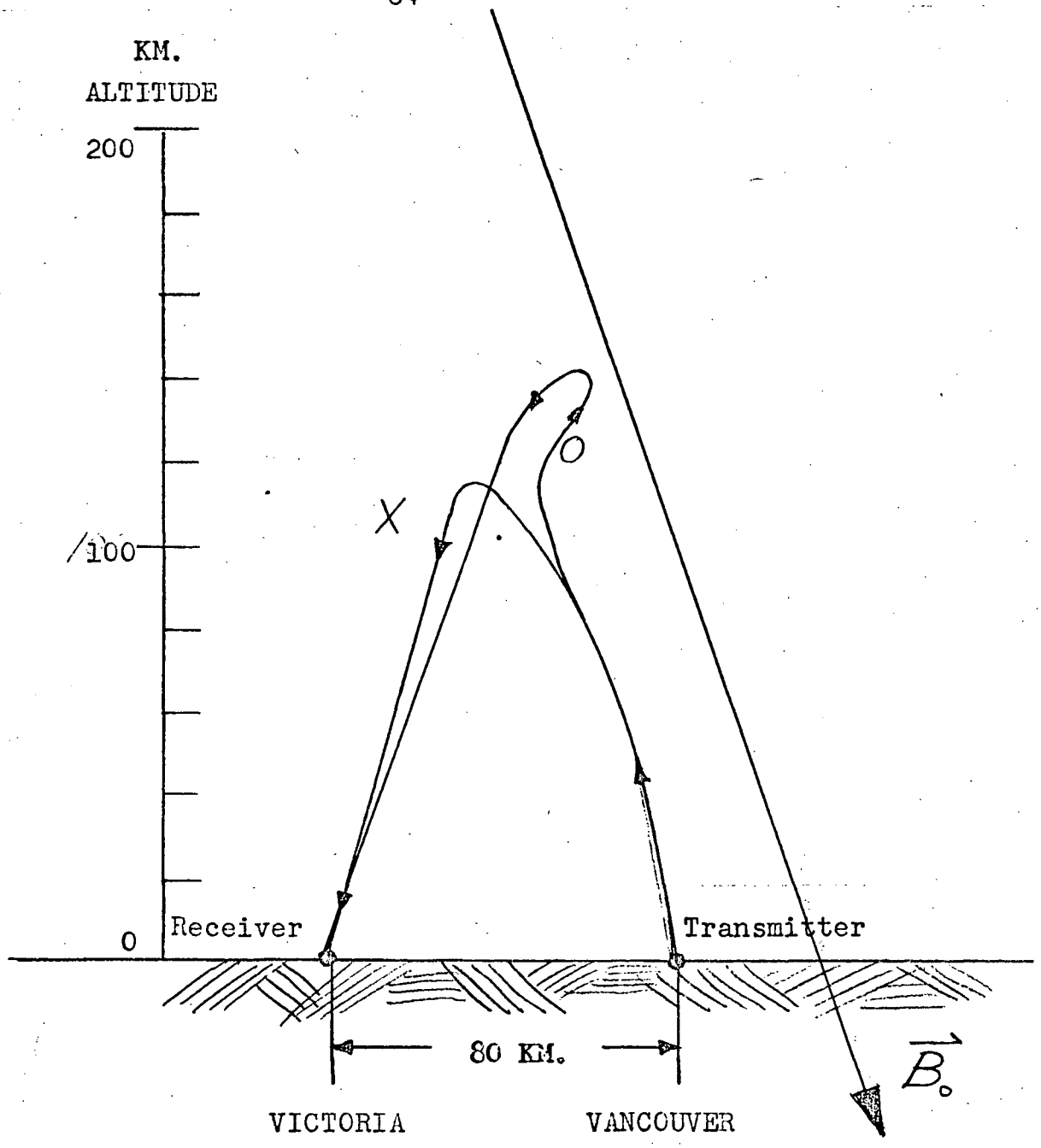


Fig. 2.4.1. SCHEMATIC DIAGRAM

HF ray-paths (2.7 MHz) between Vancouver and Victoria at about 1800 LMT (the paths lie approximately in the magnetic meridian plane.)

The principal refraction effects for the O and X components occur at different locations. This displacement varies from about two to fifty km. depending on the electron density profile present and the sounding frequency used.

When irregularities are present a multiplicity of ray-paths occur, and the various phase paths may differ by hundreds of wavelengths at times of severe 'spread F' occurrence. This leads to increased Doppler bandwidths.

The observed Doppler shifts represent the time rate of change of path-length for various paths, and the breadth of the spectrum or bandwidth indicates the velocity spread of the reflecting irregularities. Variations in path-length are the result of a number of causes :

i) Variation in the height (or location) of the reflexion (coupling) region (a large effect),

ii) variation in electron velocity at the height of reflexion,

iii) variation in electron density below the height of reflexion,

iv) variation in electron density gradient in the reflexion region,

v) variation in electron velocity in the reflexion region,

vi) variation in electron-ion and electron-neutral collision frequencies in the reflexion region,

vii) variation in the ambient magnetic field and hence in μ and in the O and X ray-paths.

In general, the electron velocity changes affect the ray-path less than the electron density changes (irregularity, drift). These mechanisms of phase path variation have been individually treated by several authors, but no comprehensive theory of Doppler shift due to reflexion from a moving anisotropic, inhomogeneous, dispersive, magneto-ionic medium is available.

The theory of the Doppler effect for waves transmitted in or through a dispersive and inhomogeneous medium has been developed by Gill (1965), and the problem of reflexion from a moving medium is treated by Unz (1965). Agy, Baker, and Jones (1965), vid. their appendices I - III, have extended Davies' (1962) treatment of Doppler shift for the vertical incidence reflexion problem, but they neglected the earth's magnetic field, and also dispersion and the effects of collisions near the height of reflexion. A discussion of previous work and of magnetic effects is given by Donnelly (1966). The oblique propagation case with a magnetic field has been treated by Tsedilina (1962) and a general discussion given by Davies and Baker (1966).

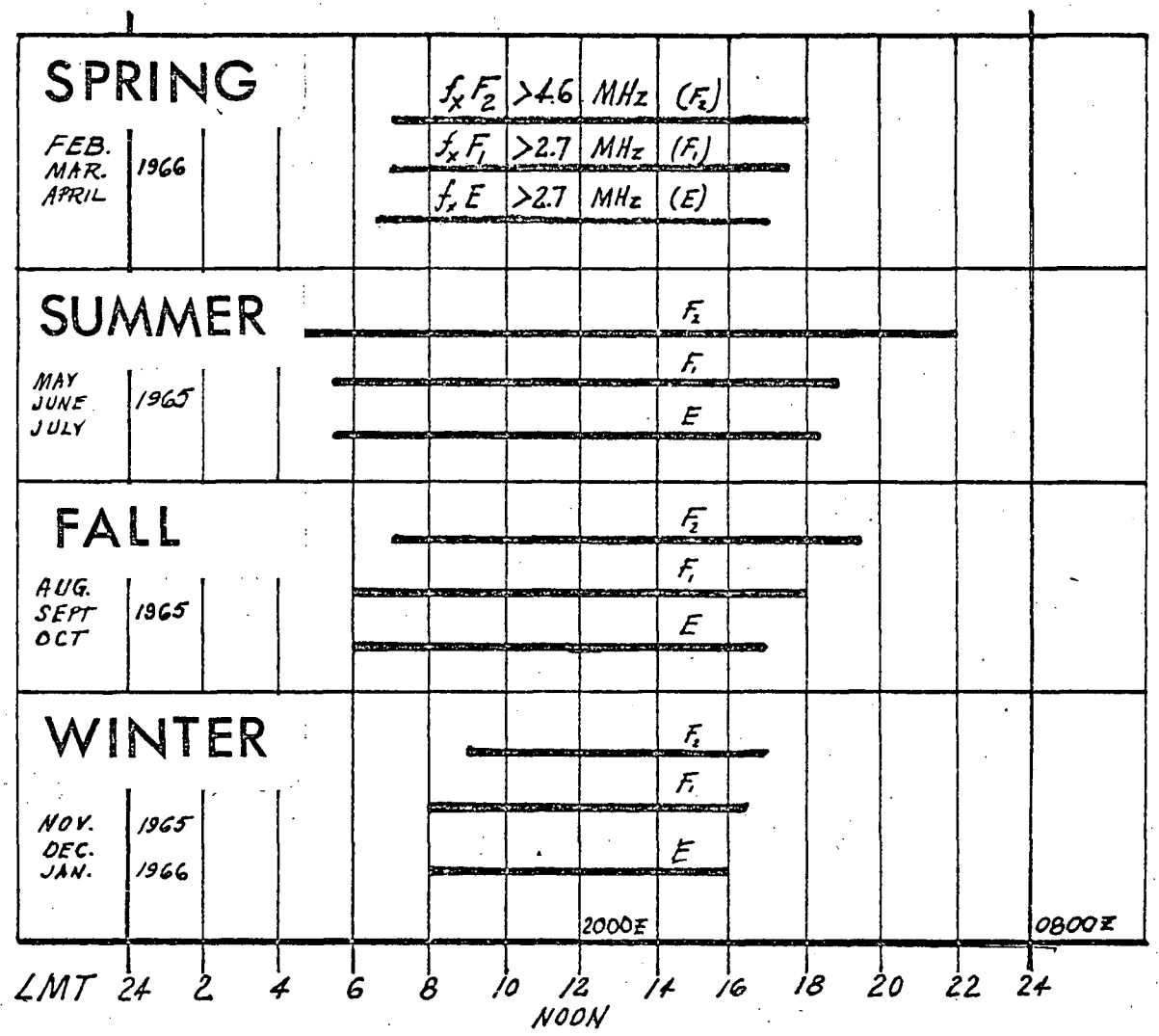


FIG. 2.4.2. DIURNAL AND SEASONAL VARIATION of IONOSPHERIC CRITICAL FREQUENCIES WITH RESPECT TO VE9CF FREQUENCIES

Since the interpretation of Doppler shifts depends strongly on how close the exploring frequency is to the ionospheric critical frequencies, estimates of this difference as a function of time of day and season were calculated for 1965. The f_oF_2 was estimated using the NBS/ITSA prediction system (tech. note 2, B151361). The f_oF_1 was estimated using data from Petrie and Stevens (1965). These results were then adjusted so that observed sunrise and sunset (4.6 MHz fade-in and fade-out times) fitted the predictions. The results for (1965) are plotted in Fig. 2.4.2. Ionograms were obtained from the University of Washington in Seattle and these results were also incorporated. However, the Ionosonde only operated intermittently, and few ionograms were obtained.

The nature of the dependence of ΔF on critical frequency and upon the height of the layer (h_m) is clearly illustrated by Agy, Baker and Jones (1965) in their figures : (2.1, 2.2, 2.3), see Figures 2.4.3 and 2.4.4. These figures were drawn on the basis of calculations made for parabolic ionospheric electron density distribution models, and assumed the ' phase-path' model for Doppler shift.

In Figures 2.4.3 and 2.4.4, p.69 and 70, the phase path which is defined by the integral term in eq'n.2.4.2 is represented by 'P'. h_o is the height of the 'bottom' of the parabolic ionosphere. h_m is the height of maximum electron density. f_c is the critical frequency (e.g. f_oF_2) of the layer. All three of these parameters are varied independently to give the three sets of curves.

DOPPLER SHIFT, Δf, FOR VERTICAL PROPAGATION WITH REFLECTION IN PARABOLIC F LAYER

$f_c = 10$ Mc/s, $h_o = 200$ km, $h_m = 300$ km

$$\Delta f = -\frac{f}{c}\frac{\partial P}{\partial h_o}\frac{dh_o}{dt} - \frac{f}{c}\frac{\partial P}{\partial h_m}\frac{dh_m}{dt} - \frac{f}{c}\frac{\partial P}{\partial f_c}\frac{df_c}{dt} \qquad (2.4.5)$$

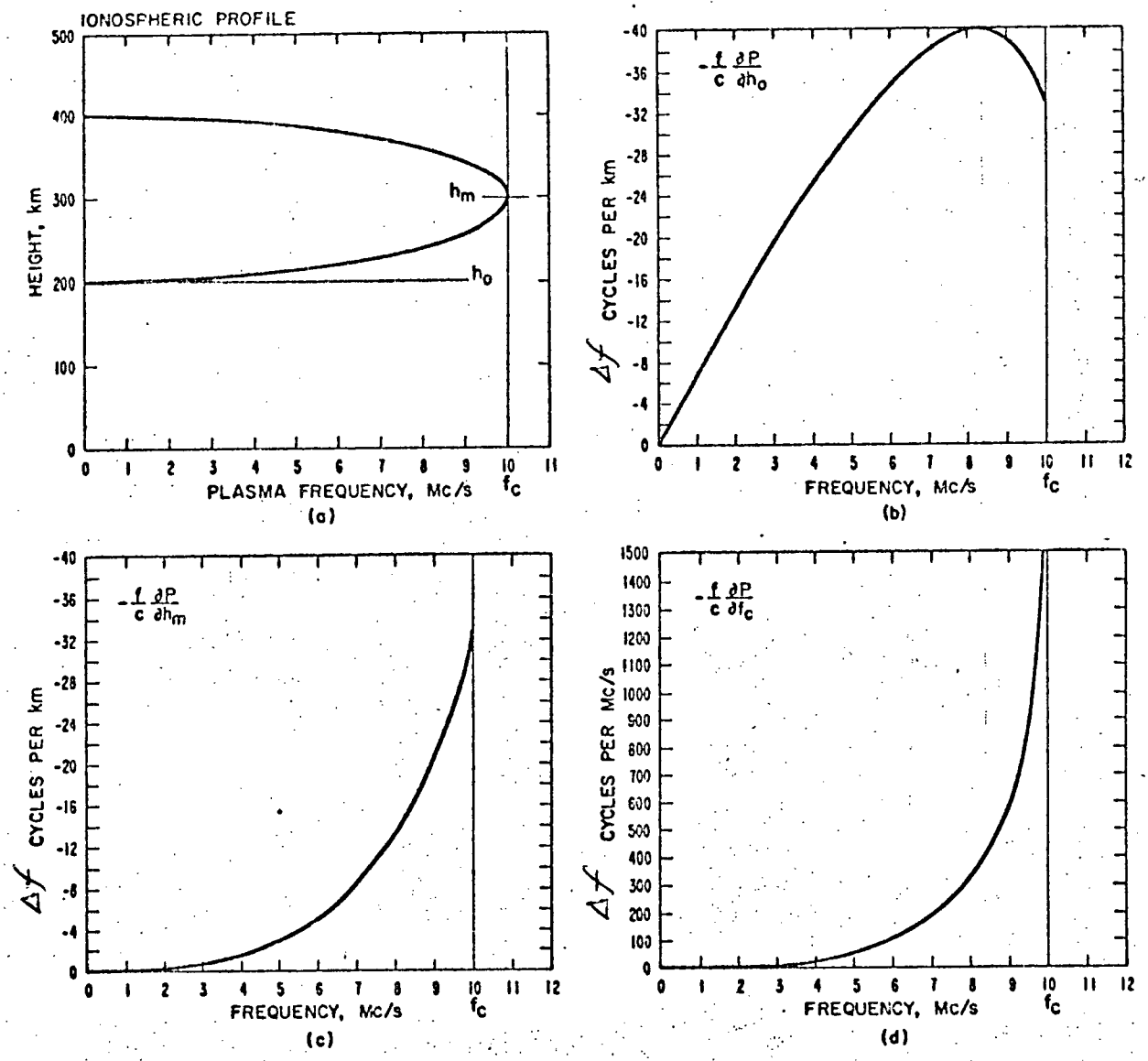


Fig. 2.4.3. Determination of Doppler shift.

After Agy, Baker & Jones, (1965)

$f_c = 10$ Mc/s, $h_o = 200$ km, $h_m = 300$ km

$$\Delta f = -\frac{f}{c}\frac{\partial P}{\partial h_o}\frac{dh_o}{dt} - \frac{f}{c}\frac{\partial P}{\partial h_m}\frac{dh_m}{dt} - \frac{f}{c}\frac{\partial P}{\partial f_c}\frac{df_c}{dt} \quad (2.4.5)$$

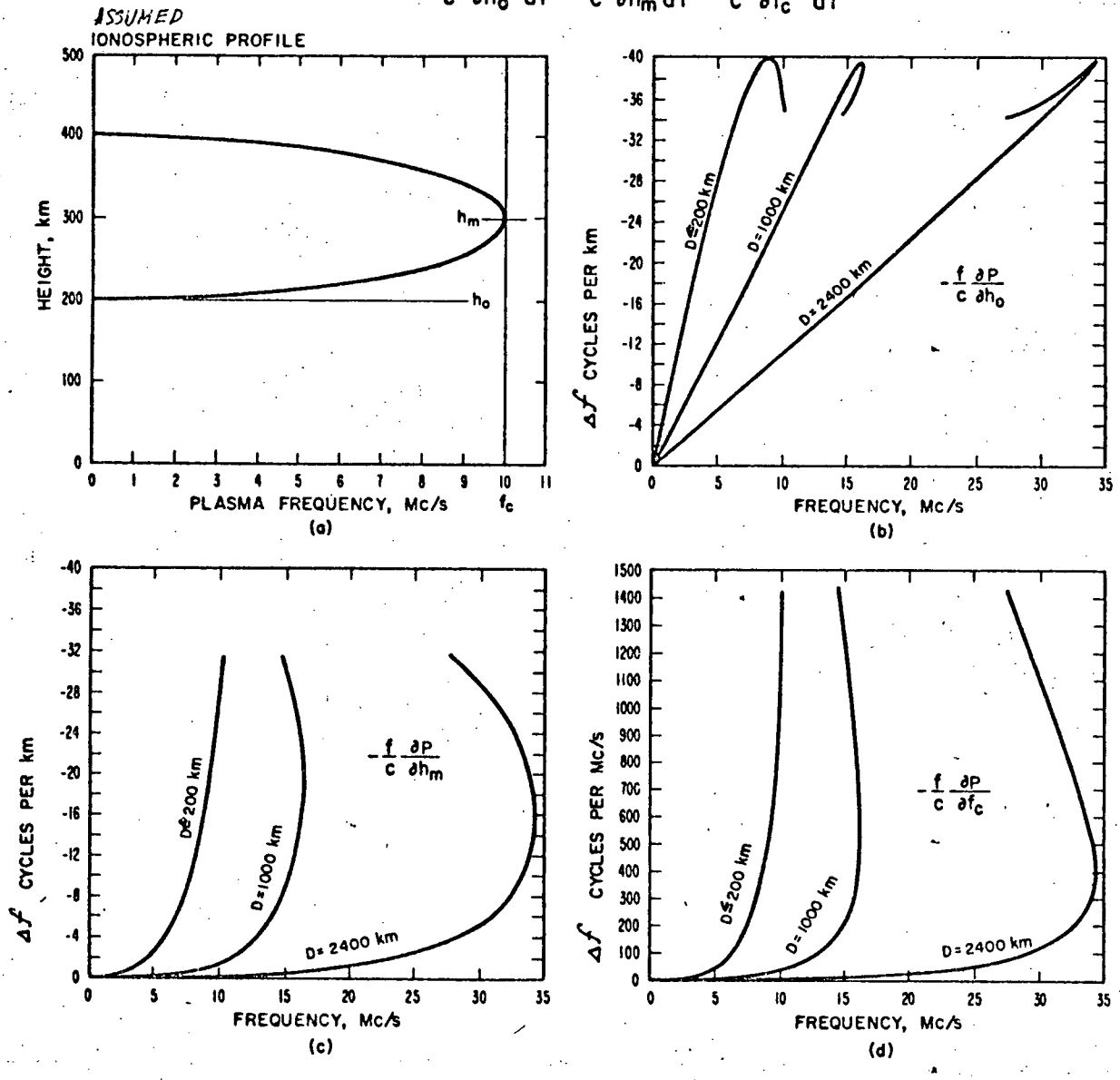


Fig. 2.4.4. Doppler shift, Δf, for oblique incidence propagation, with reflection in a changing parabolic F layer. (After Agy, Baker, and Jones, 1965)

As well as the vertical-incidence curves, curves for oblique incidence with 200 km. station spacing were given. By comparison, it is apparent that the 80 km. spacing used in this experiment may be considered as 'vertical' incidence with the introduction of only slight error.

Since the medium is time-varying, inhomogeneous, anisotropic and dispersive, an exact analytic expression for the Doppler shifts is not readily written. in order to make use of precise Doppler and wave propagation, equations detailed models of the ionosphere for the specific times of interest are required. Since ionograms were not available for the times when most of the important Doppler events occurred, quite simple Doppler shift equations were used.

When reflection from a single layer without perturbation in the intervening ionosphere was considered the simple moving mirror Doppler equation was used. It is :

$$\Delta f = \frac{-2f}{c} \frac{dh'}{dt} \qquad (2.4.6)$$

Δf is the Doppler frequency shift

f is the carrier frequency

h' is the height of reflexion assuming vertical incidence

c is the velocity of light in vacuo

On the other hand, when reflexion from a fixed layer with perturbations due to changes in a layer below was suspected, an approximate equation given by Agy, Baker and Jones (1965) was tried.

It is :

$$\Delta f = \frac{k}{c} \frac{1}{f} \frac{\partial N_e}{\partial t} (h^A - h_0) \qquad (2.4.7)$$

k is a constant

$\frac{\partial N_e}{\partial t}$ is the rate of change of electron density assumed constant over the height range from h_0 up to the height of reflexion h^A.

(To estimate the relative Doppler shift to be expected for the ordinary and extraordinary waves $1/f$ was replaced by $\frac{1}{f \pm f_{gyro}}$ in equation (3.4.2) where the + sign was used for the O wave and the - sign for the X wave.) These equations are only approximations; some of the assumptions underlying their derivations and the limitations to which they are subject are discussed in Appendix III

If the Doppler shift is found to vary approximately as f then it is likely due to vertical motions of the reflecting layer. If it varies as 1/ f, it is probably due to electron density variation below the height of reflexion. If the Doppler shift varies as a higher power of f , then it may be due to variations in the collision frequency, or height gradient, of electron density near the reflecting level.

2.4.2 Doppler Sounding

a) The Equipment

Vertical incidence CW Doppler sounding requires :

i) a stable carrier frequency source,

ii) sounding frequencies chosen to avoid ionospheric critical frequencies and to reflect from the layer of interest,

iii) vertically directed antennas spaced and oriented to eliminate direct ground wave transmission between transmitter and receiver, and preferably designed to separate magneto-ionic polarisation modes.

iv) narrow bandwidth receivers to eliminate interference problems,

v) stable reference oscillators,

vi) sensitive frequency meters and spectrum analysers to determine the Doppler spectrum,

vii) suitable recording systems.

The system used meets these requirements in large measure.

The equipment used in vertical incidence Doppler sounding consisted of transmitters on the U.B.C. Campus at Vancouver, and receivers at Royal Roads near Victoria, 80 km. to the south of the transmitters, (refer to Fig. 2.1.1.).

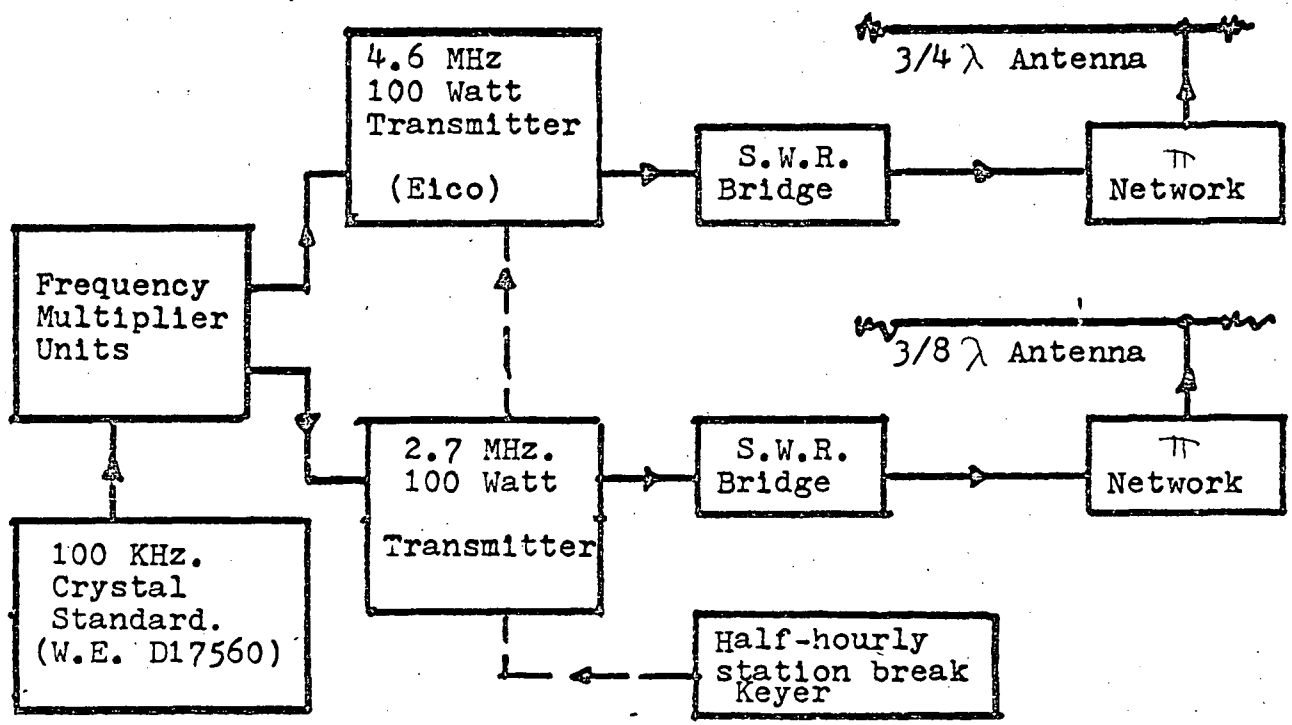


Fig. 2.4.5. VE9CF Transmitting system , U.B.C. Geophysics laboratory Vancouver B.C.

The transmitter installation is shown in block diagram in Fig. 2.4.5. A Western Electric D17560 100 KHz crystal frequency standard with a stability of $\pm$ 3 parts in 10^9 per day is the basic signal source. The 100 KHz is multiplied up by Class C frequency multiplier stages to obtain the required carrier frequencies 2700 KHz and 4600 KHz. These multipliers are well damped and the carrier frequencies maintain a stable phase relation with the primary frequency standard.

The frequency multiplier is followed by amplifiers and serves as an exciter for two Eico type 720, 90 watt transmitters. (These transmitters have been extensively modified for continuous operation on fixed frequency.) A keyer, utilising a perforated disc and photo-transistor, keys the transmitters for one minute every half hour with the call letters VE9CF. SWR bridges installed in the feedlines are used to adjust the π networks which feed the antennas, and are arranged to shut the equipment off if the SWR ratio exceeds a preset level (in the event of antenna failure).

The transmitting antennas are short inverted L antennas suspended 40 ft. above the ground. Consequently they radiate a large percentage of their signal vertically, and otherwise are oriented to have a null to the south-west, in the direction of the receivers. The π type matching networks were carefully developed and enable an SWR of 1.3:1 or better to be maintained at all times.

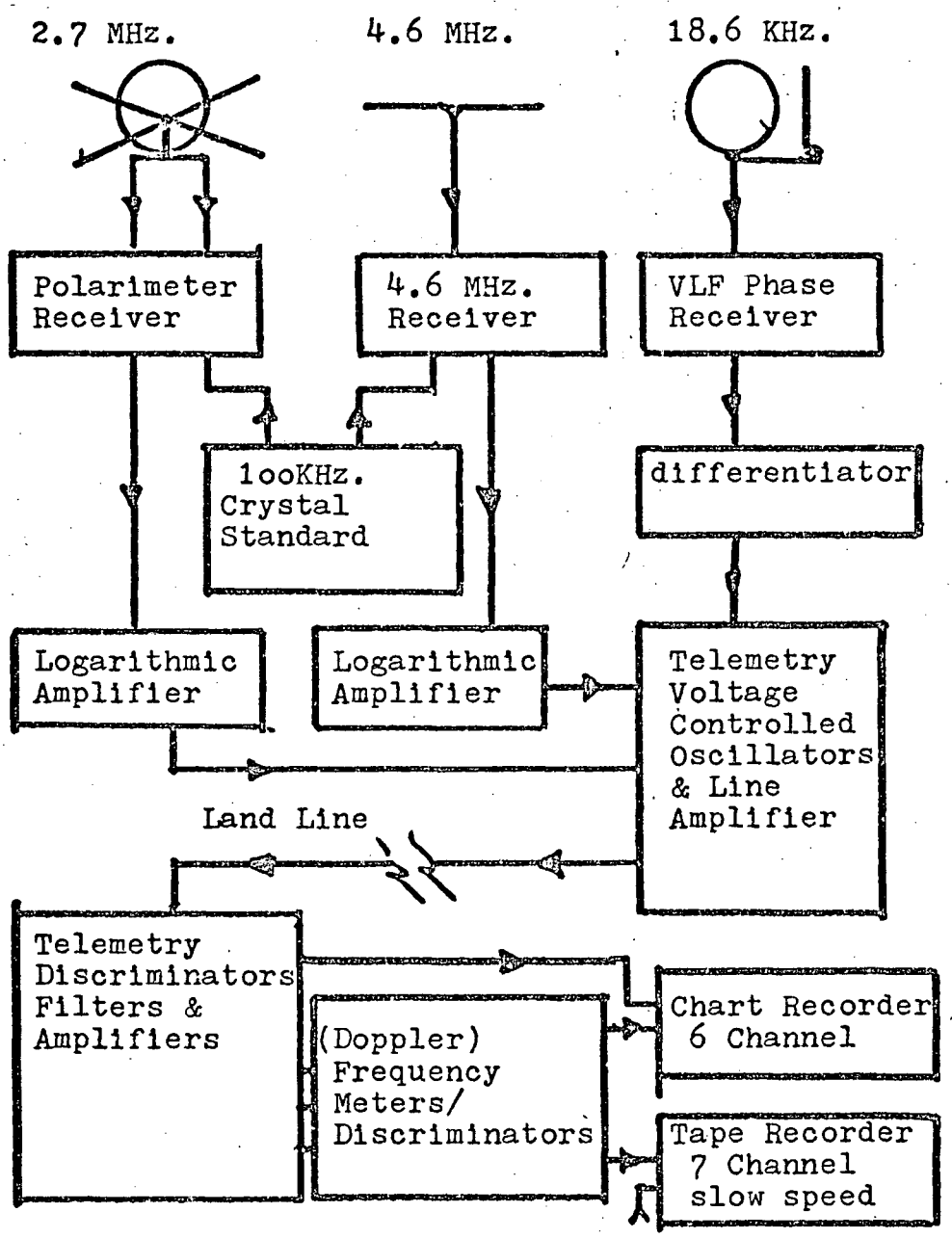


Fig. 2.4.6. Radio Receiving & Recording System
Physics Laboratory Royal Roads Victoria B.C.

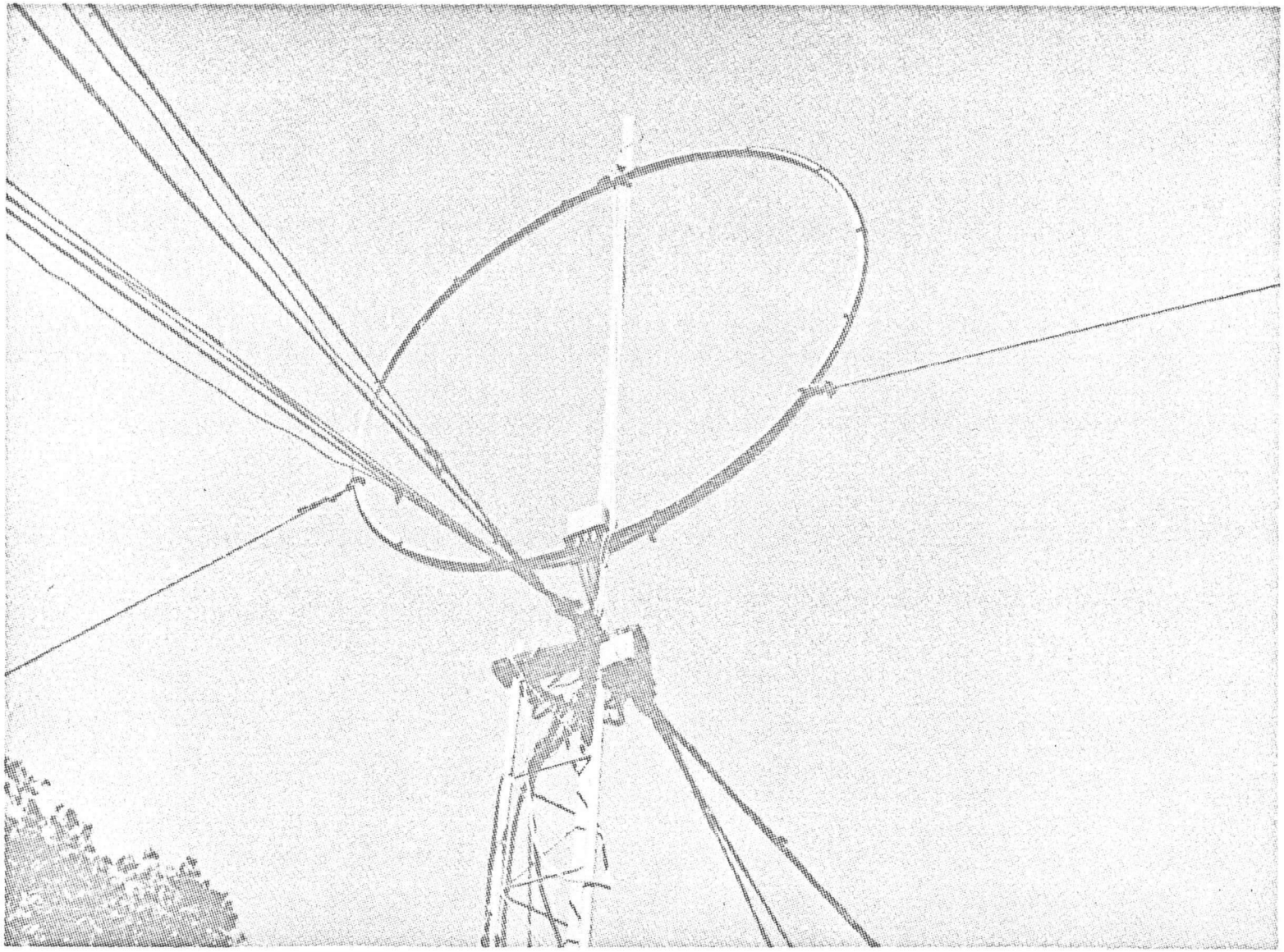


Fig. 2.4.7. 2.7 MHz. Polarimeter Antenna, shewing tuned loop with dual pre-amplifier, and multiple wire dipole with its preamplifier at centre.

The frequency standard's 100th harmonic is adjusted to zero beat with the 10.0 MHz WWV signal received on an RCA AR-91 receiver, which is also used to check for spurious radiation. The transmitter output frequencies are counted to the nearest 0.1 Hz once a month to check system operation.

The receiving installation is shown in block diagram in Fig. 2.4.6. The system consists of antennas, receivers, a reference oscillator, FM telemetry to the laboratory, frequency meters, a chart recorder, and a slow speed tape recorder. A photograph of the 2.7 MHz polarimeter antenna is shown in Fig. 2.4.7. This form of antenna is discussed in Jasik (1961).

The 2.7 MHz polarimeter receiver is shown in block diagram form in Fig. 2.4.8. Orthogonal tuned loop and dipole antennas feed tuned radio frequency (6AH6) pre-amplifiers which are matched to 50 Ω (RG9BU) coaxial lines about 200 feet long extending to the receiver trailer.

In the trailer the loop and dipole signals are combined with suitable terminating pads to obtain the ordinary and extra-ordinary circular polarisation components. (Two of the six possible Stokes components.) (The isolation between modes actually obtained is only about 15 db. because of difficulties in setting-up and phasing the antennas and feed system.)

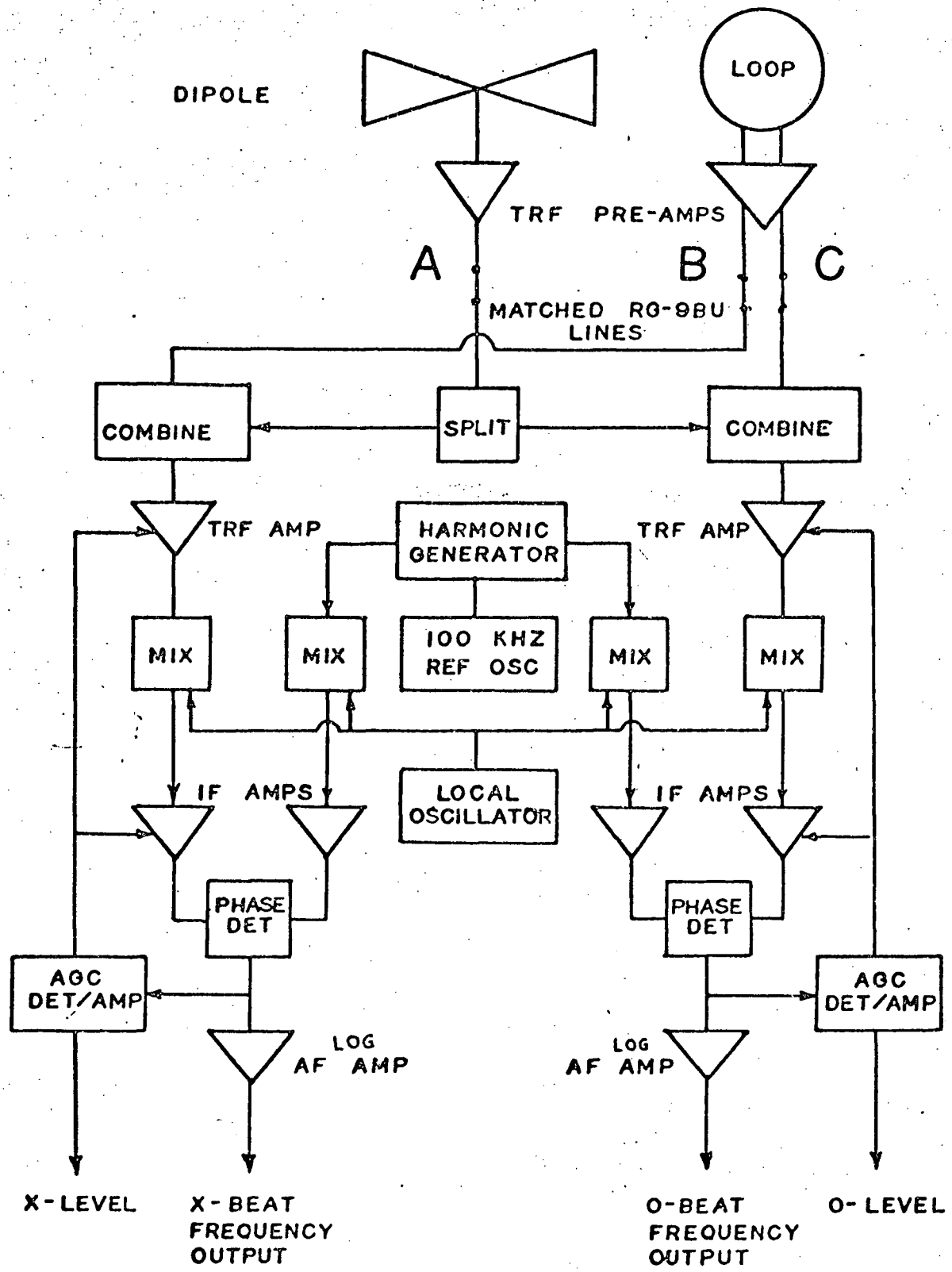


Fig. 2.4.8. 2.7 MHz. Polarimeter Doppler Receiver Block Diagram.

The combining networks feed two separate receivers with a common L.O. and reference standard. These receivers each consist of : an RF amplifier (cascode 6J4s) with large dynamic range, mixer units which convert the 2.7 MHz signal down to 455 KHz by mixing it with the output of a stable (double oven) crystal local oscillator. The mixers feed special narrow band Collins type 65010 six crystal, crystal filters (50 Hz bandwidth at 455 KHz) which were custom made for this experiment. The receiver is shown in photograph 2.4.9.

Because of the narrow bandwidth of the crystal filters the local oscillator has to be quite stable, but the filters were found to be necessary to eliminate radio interference.

In order to obtain beat frequencies another Western Electric 100 KHz frequency standard was used at the receivers to feed a harmonic generator. The 27th and 46th harmonics are selected and fed to the 2.7 and 4.6 MHz receiver reference channels. The reference signal is mixed with the same local oscillator output as the received signal in order to avoid instability problems. [Davies et al. (1962) The resulting 455 KHz is then amplified and combined in a phase detector with the received signal. The output of the phase detector is a beat frequency in the neighbourhood of 50 Hz (determined by the offset of the 100 KHz frequency standard.)

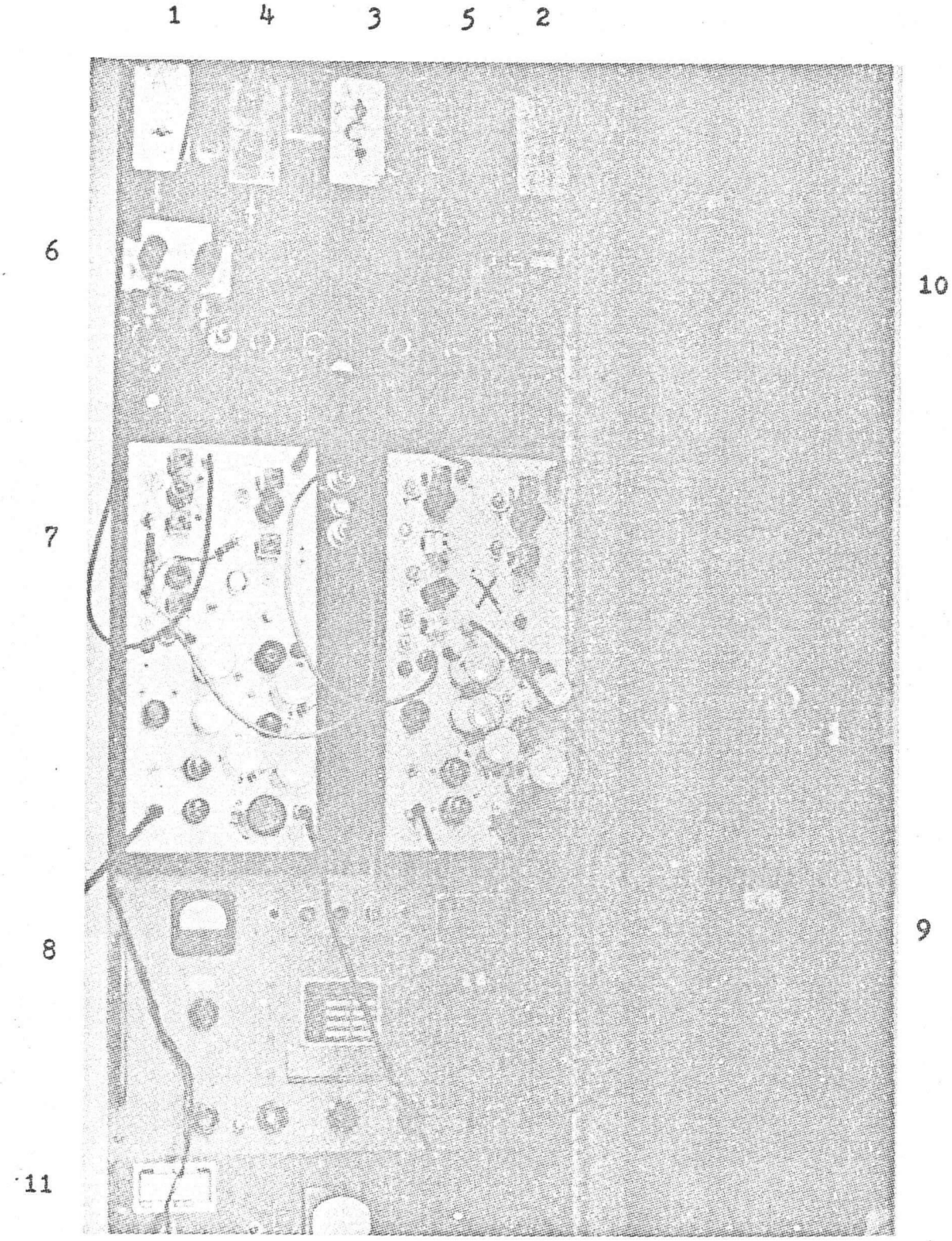


Fig. 2.4.9. 2.7 MHz Polarimeter Receiver; 1&2 Loop inputs, 3 Dipole input, 4&5 cascode RF amplifiers, 6 mixers with crystal IF filters, 7 IF amplifiers with a.g.c. and phase detectors, 8 Local Oscillator 3.155MHz. 9 Crystal standard 100KHz. 10 WWV receiver, 11 Power supplies.

A constant level beat frequency output is required for the FM telemetry modulators and is obtained by using a.g.c. and logarithmic audio amplifiers (Thompson BA-2) or zener-diode clippers.

The a.g.c. is obtained by rectifying some of the beat frequency signal. A time constant of about 10 sec. is used. The a.g.c. voltage is also provided as an output so that signal strength variations and hence the presence of absorption or deep fading may be recognized.

The 4.6 MHz receiver is similar to the 2.7 MHz receiver, except that a simple half-wave dipole is employed rather than the polarimeter antenna, and consequently only a combined (linear) polarisation mode is recorded.

b) The VLF 'Doppler' Equipment

VLF signals from NPG, 125 km. east (geomagnetic) of Victoria are received at Victoria using loop and dipole antennas and a special receiver provided by Dr. J. Belrose of D.R.T.E., Ottawa.

The sky wave is of the O mode and is reflected at about 80 km. in the daytime, and at a somewhat higher altitude at night. The wavelength is about 15 km.; consequently a vertical layer velocity of 100 m/sec. corresponds to a phase shift of 50°/sec. or a Doppler shift of 0.013 Hz. The receiver location is shown in Fig. 2.2.1

The D.R.T.E. VLF receiver compares the phase of the sky wave with that of the ground wave and provides a DC output varying from zero to plus 150 V as the phase difference varies from zero to 360°. [Straker (1955)].

This 'phase' output voltage is differentiated by a series capacitor and fed through a low pass filter into the FM telemtry system and thence to the laboratory, and to channel six of the Brush 20 cm/hr. chart recorder.

Three different series capacitors were used leading to three different response curves. This equipment was not operated on a continuous basis. A commercial phase tracking VLF receiver with a 10μ second Δ phase full scale output was used temporarily in the Fall of 1965.

c) Recording

At the laboratory the output of the Bendix TDA-2 FM telemtry demodulators is passed through Krohn-Hite 310 AB filters tuned to the signal (beat) frequency. These are set for a bandwidth of about 10 Hz. The output of the KH filters is fed to Hewlett Packard type 500 BR frequency meters operating on their 3 Hz full scale range.

The output of the frequency meters (a dc voltage 0-3V approximately) is fed to the Brush RD 1664 six channel thermal-writing recorder, along with the VLF signal and the outputs of the telluric potential amplifiers.

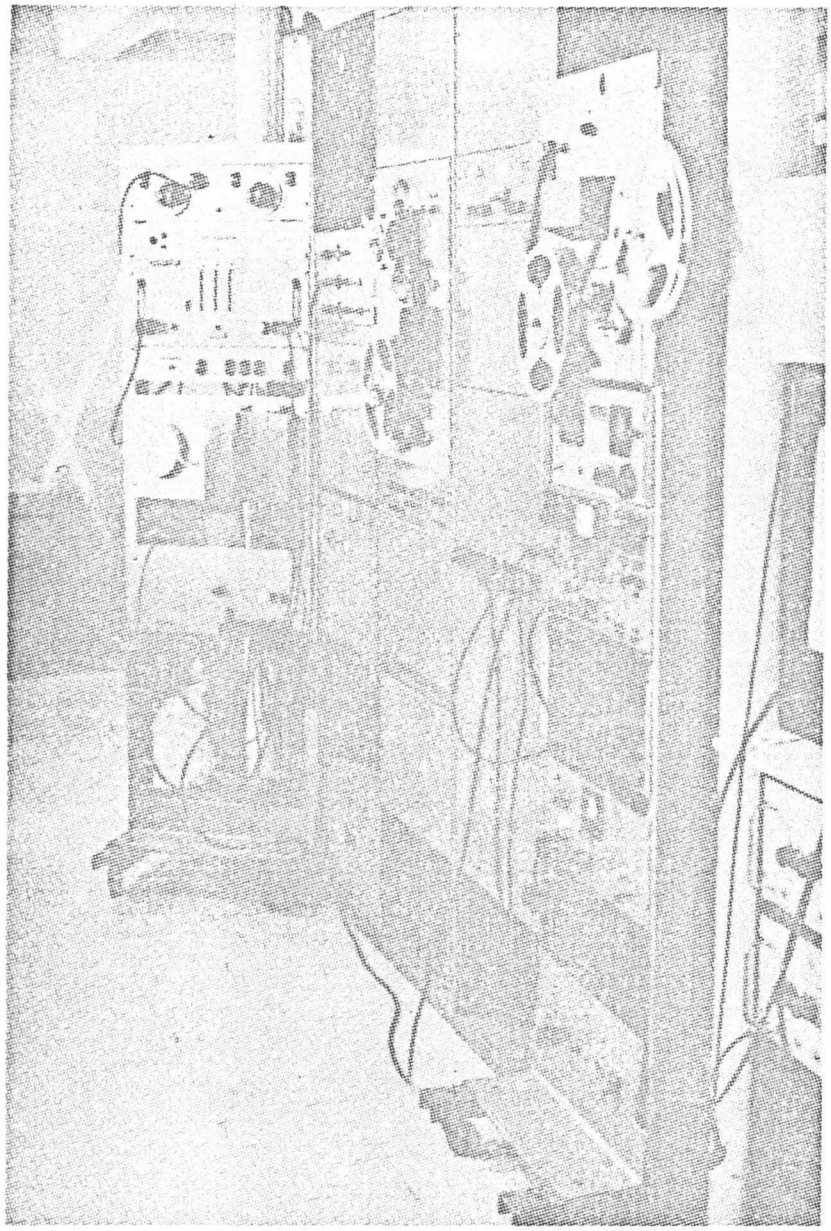


Fig. 2.4.10. Tape Recording and Digitising Equipment. Right to left 1/2" slow speed 7 track tape recorder, 1" multiple speed Ampex FM, 7 track tape recorder. Digital voltmeter and paper tape punch.

Time signals are impressed every 30 min. by a mains driven commutator, and the key-breaks of VE9CF show up as time marks every half hour. Manual time marks are applied daily using WWV as a reference source.

The signals are fed to a slow speed tape recorder as well as to the chart recorder. The slow speed tape recorder is a custom built seven channel 1/2 in. unit operating at 0.075 "/sec. on record, and 7-1/2 "/sec. on playback. (A speed-up factor of 100.) Other tape recorders and other speeds were sometimes used. The tape recorders are shown in Fig. 2.4.10.

The speeded-up play-back simplifies spectrum analysis and is also convenient for digitisation of long-period events.

The 'Doppler' shift noise level of the receivers is about 0.05 Hz. The full scale range of the Doppler chart records is normally 0.75 Hz (although 1Hz, 2Hz and 10 Hz full scale ranges were used from time to time). The full range of the tape system corresponds to about 5 Hz.

In actual practice the smallest Doppler shifts which can be resolved are 0.1 Hz. It was found that with the somewhat noisy RF signals available the frequency meters worked much better than digital counters set to count the period of the beat frequency in milliseconds.

The limiting factor in receiver performance is random phase fluctuation occurring in the various tuned amplifiers. These fluctuations have a bandwidth of about 0.02 to 0.05 Hz (i.e. about 10° phase angle.) The receiver noise level is well below the background noise level at the antenna due to sferics, QRM , etc.

A number of attempts were made to build a very high resolution spectrometer to display 1/100 Hz in 2.7 MHz and cover a 10 Hz band. Various crystal filters with frequency multiplication were used, but all the analogue techniques failed for one reason or another.

A digital analyser was therefore constructed to sample the 20 Hz heterodyned RF signal. This signal was used to gate a high frequency stable oscillator, which was counted. The staircase output of a conventional decade scale was displayed on the horizontal trace of a recording oscilloscope, and the intensity control was gated to show only the final value of the integer count for each cycle of oscillation of the heterodyned RF signal. A second oscilloscope-trace showed the position of the tens scale readout. The signal was averaged by the CRO camera film emulsion, so that a continuous record of Doppler shift frequency and bandwidth was obtained. As it turned out, the discrimination of this device was higher than needed. It showed that the bandwidth of the RF signal was of the order of 1/10 Hz in 2.7 MHz at quiet times, increasing to 10 Hz during severe

magnetic storms. The expanded scales of the Hewlett-Packard frequency meters are adequate for these bandwidths and make convenient records.

Conventional (Ampex 9221) FM recorder discriminators are used to reproduce the Doppler shift frequency from the tape recording. Because there is usually a hundred-fold increase from the recording speed to the playback speed, sufficient frequency multiplication is introduced to give 1/10 Hz frequency resolution. This is at the expense of greater time resolution on the records. It appears that a time resolution limit of about 10 sec. is adequate because only larger micro-pulsation and other magnetic disturbances are associated with Doppler shifts greater than 1/10 Hz, and these have relatively long periods.

A time constant of no more than 1/2 second was (generally) used on the frequency meter outputs, so that large noise spikes would not be integrated and spoil the record. Some integration was required however, to eliminate the fluctuations at the original beat frequency arising from the operation of the frequency meter.

It is found that if two frequencies are simultaneously fed into these frequency meters the output swings from the voltage representing one frequency to that representing the other, at a rate equal to the difference between frequencies. Hence the presence of two or more magneto-ionic components could be seen on the 4.6 MHz beat signal even after passage

through the frequency meter providing the difference in beat frequency was greater than 0.2 Hz and less than 5 Hz.

The 500 BR frequency meters have a noise level of about 0.02 Hz (with 1/2 sec. time constant) and a maximum drift rate (on regulated mains) of 0.1 Hz per day.

TABLE 2.5.1* SUMMARY OF OBSERVING TECHNIQUES AND IONOSPHERIC REGIONS OBSERVED

IONOSPHERIC LAYER	TIME OF DAY	OBSERVING TECHNIQUE AND PARAMETERS
F_2	DAY	-4.6 MHz Doppler - Broadband Radiometer
F	NIGHT	- 2.7 MHz Doppler - Riometer SCINTILLATION - Radiometers
F_1	sunrise & sunset	- 2.7 MHz Doppler (layer is present at midday but blanketed by the E layer for 2.7 MHz.)
E	DAY	- 2.7 MHz Doppler - (the solar eclipse experiment Boyd (1966))
E sporadic	summer evenings mainly	- ionosonde ,Seattle - 2.7 & 4.6 MHz Doppler
E	NIGHT	- VLF (NPG/NPN) skywave PHASE
D	DAY	- VLF skywave PHASE - Riometer ABSORPTION - 2.7 MHz AMPLITUDE

CHAPTER III

Results

3.1 General Notes on the Data Analysis Procedure

Two approaches were followed in the analysis of the records obtained from the simultaneous ionospheric and geomagnetic experiments. The first approach was to examine the overall statistics of occurrence and association of events. The object of this method of analysis was to determine what kinds of events are related, and when these associations occur. The second approach followed was to examine individual events which were typical of various classes of events. The purpose in studying the individual events was to determine quantitatively the particular nature of the associations.

In both analysis programs measures of confidence were obtained, and the final data was then plotted or otherwise displayed in whatever manner seemed best to facilitate comparison with theoretical predictions.

3.2 The Narrow Bandwidth Radiometer Experiment

A radiometer was operated on 20.1 or 25.0 MHz with a bandwidth of 3KHz at Westham Island in the spring of 1963. Several events occurred involving signal strength enhancements associated with evening and night time micropulsations activity. One of these events which occurred between 1830 hours and 2100 hours LMT on May 14th, 1963 is illustrated in Fig. 3.2.1. A fluctuating increase in signal strength of about 1μV occurs at the same time that micropulsations of about 100 seconds period, and 3γ p.p. (peak to peak) amplitude occur. (The pulsation record has been passed through a filter and a diode so that excursions in only one direction appear.)

On May 7, 1963 a series of enhancements of 20 MHz signal occurred in direct association with a series of pulsation events between midnight and three a.m. The event (0800 - 1100 U.T.) and the preceding quiet period (0500 - 0800 U.T.) are shown in Fig. 3.2.2. The records were smoothed, and amplitude-envelope indices were scaled at one minute intervals.

Correlation coefficients, power, spectra, coherence, and phase drift were computed for the control period and for the event period.

It was found that RF (Radio Frequency) signal strength enhancements were significantly correlated (1% level) with the 'X_B' (probably Pc-4) micropulsation bursts. The peak correlation 0.64 occurred with the RF bursts lagging the micropulsations by three minutes. Some of the parameters computed are plotted

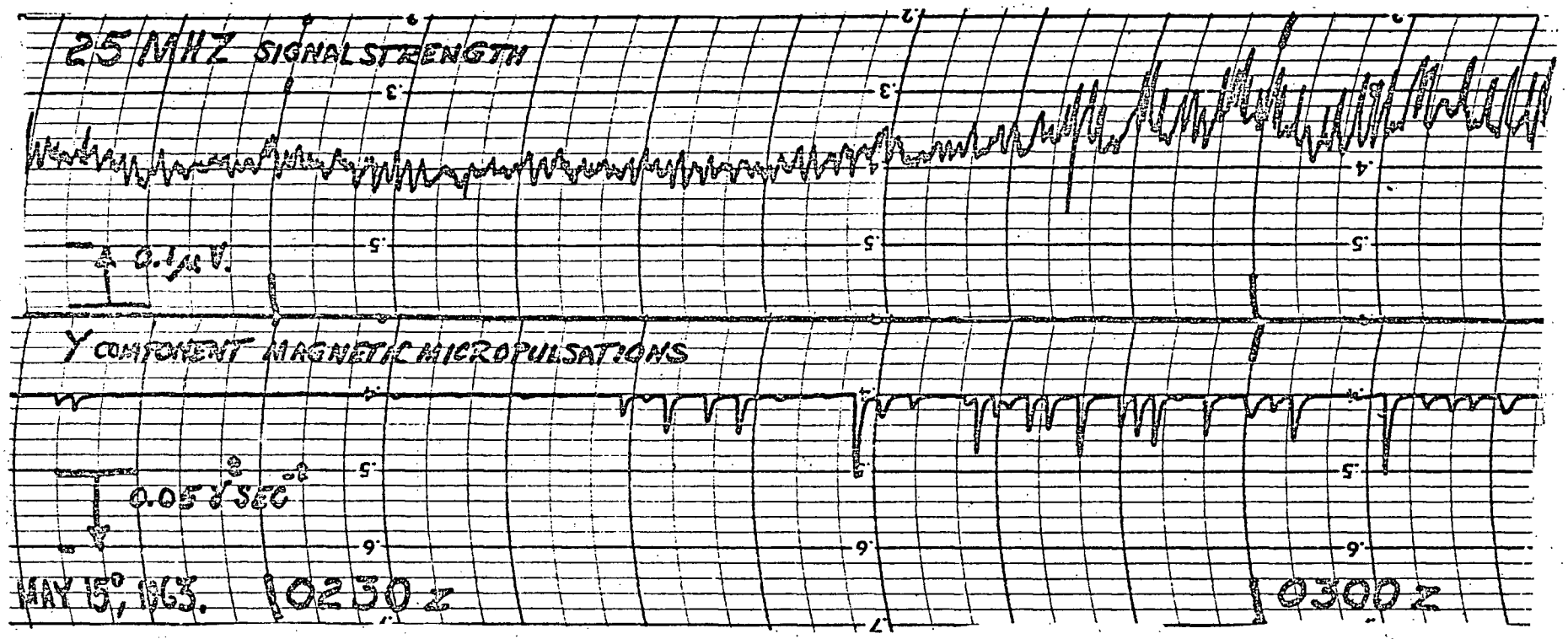


Fig. 3.2.1. Signal enhancement on 25 MHz narrow band radiometer commencing at the same time as evening Pi-2 micropulsations. The micropulsation signal was fed through a full wave rectifier and integrator.

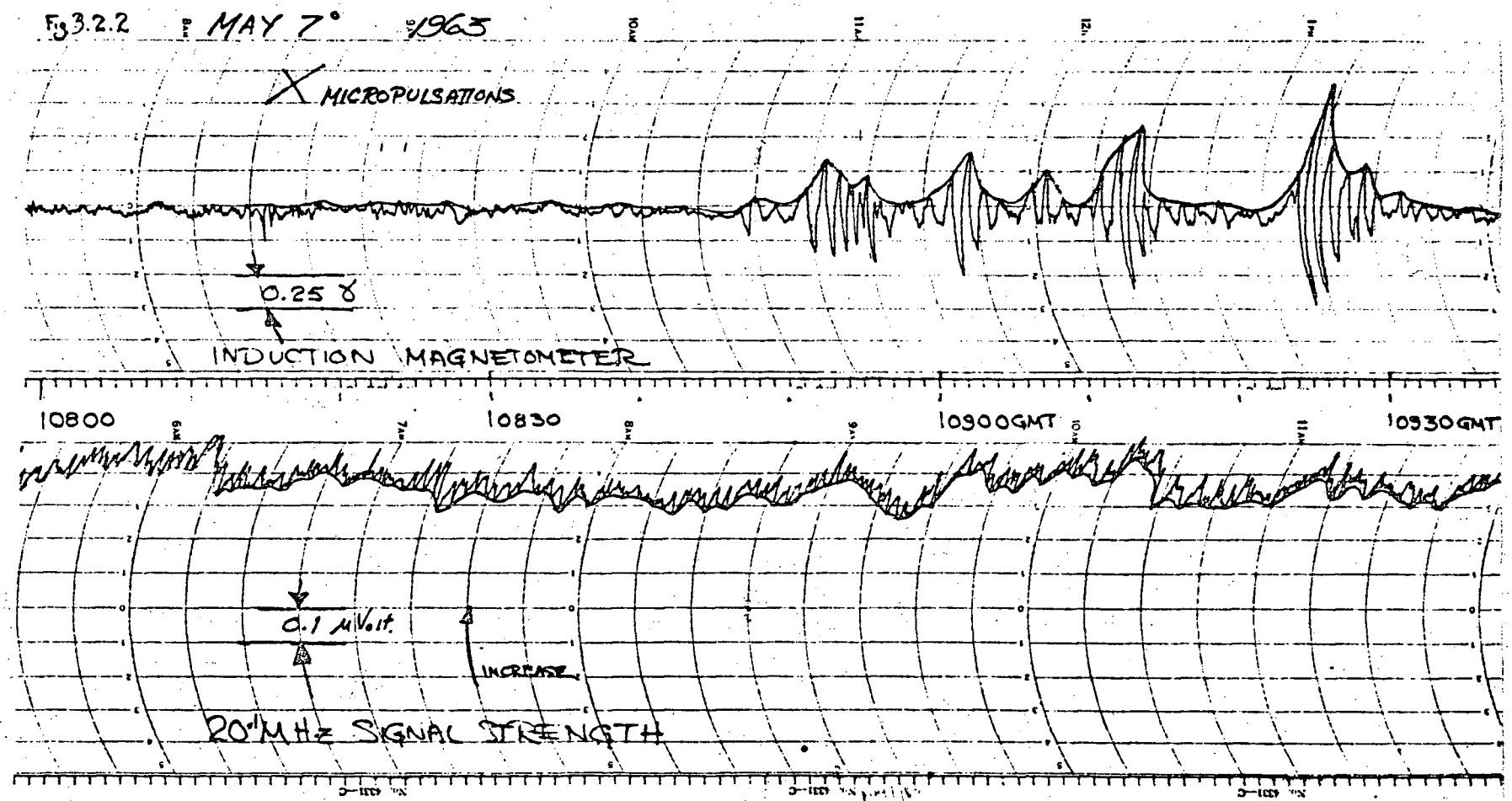
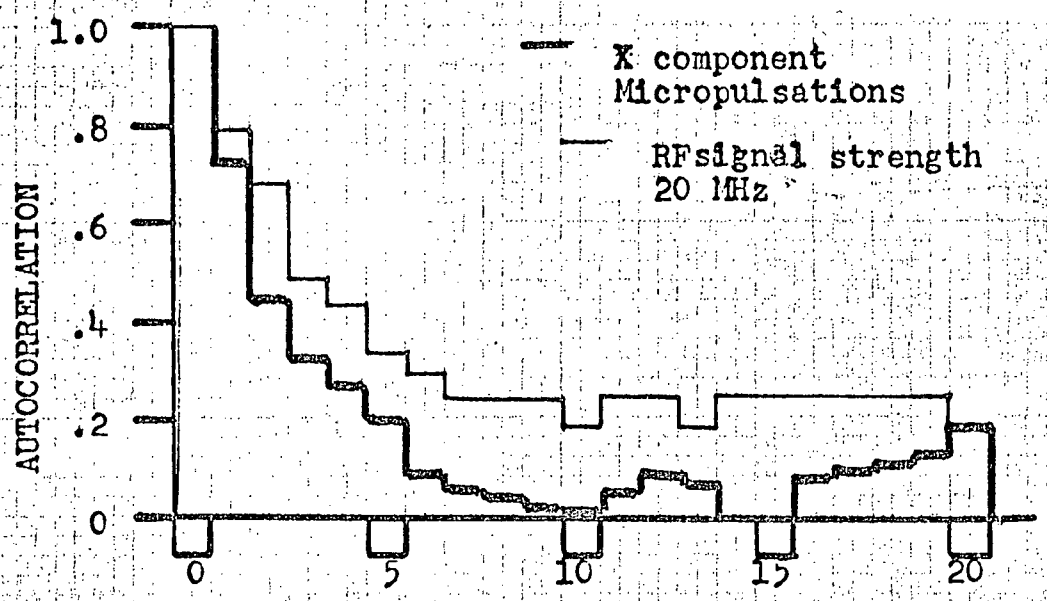


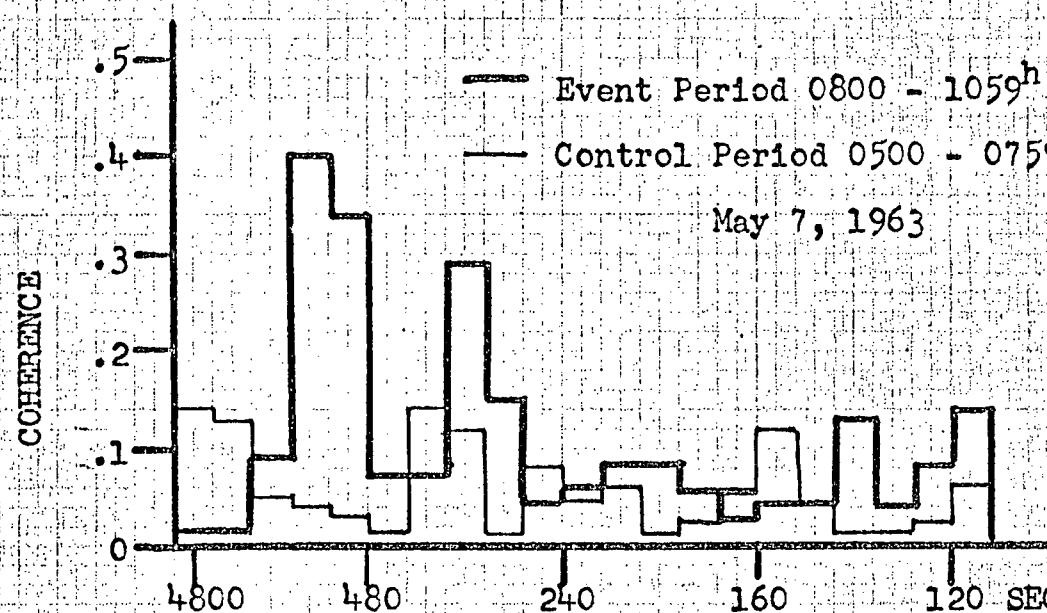
Fig. 3.2.2. Radiometer I signal strength enhancements associated with Pi-2 micropulsations. (Smooth curves have been drawn on the records, these were digitised and correlation coefficients were computed.)



A) Lags $\Delta t = 60^s$

AUTOCORRELATION PLOTS

0800 - 1059 GMT May 7, 1963



B) Pulsation Period Bands

COHERENCE PLOTS

Figure 3.2.3

in Fig. 3.2.3. It appears from the cross-spectrum (see appendix 6.3) that a component of about thirteen minutes period was responsible for most of the correlation.

A number of other events of a less clear-cut nature were observed before the radiometer was removed from service. (This instrument was considered a temporary expedient because of its susceptibility to radio interference.)

4.3 High Sensitivity Riometer Results

The riometer was operated from March 12, 1964 until Feb. 28, 1965. During this period, 230 days of good quality records were obtained. (Regular riometer records, high sensitivity a.g.c. records and 3 component induction magnetograph records were simultaneously recorded.)

The regular riometer (servo-diode) records yielded satisfactory quiet-day curves and exhibited a number of minor absorption events. However, no evidence of direct association between micropulsation events and absorption was found.

The high-sensitivity a.g.c. records did however, exhibit clear cut signal strength enhancements of a rapidly fluctuating character (probably scintillation) commencing at the onset of Pi-2 micropulsation events. A typical event is shown in Fig. 3.3.1 (Sept. 22, 1964). By tabulating the number of nights on which micropulsation events occurred (amplitude greater than 0.05 γ / sec.) and the number of nights on which scintillation (of at least 0.1 db amplitude with greater than 3 minutes

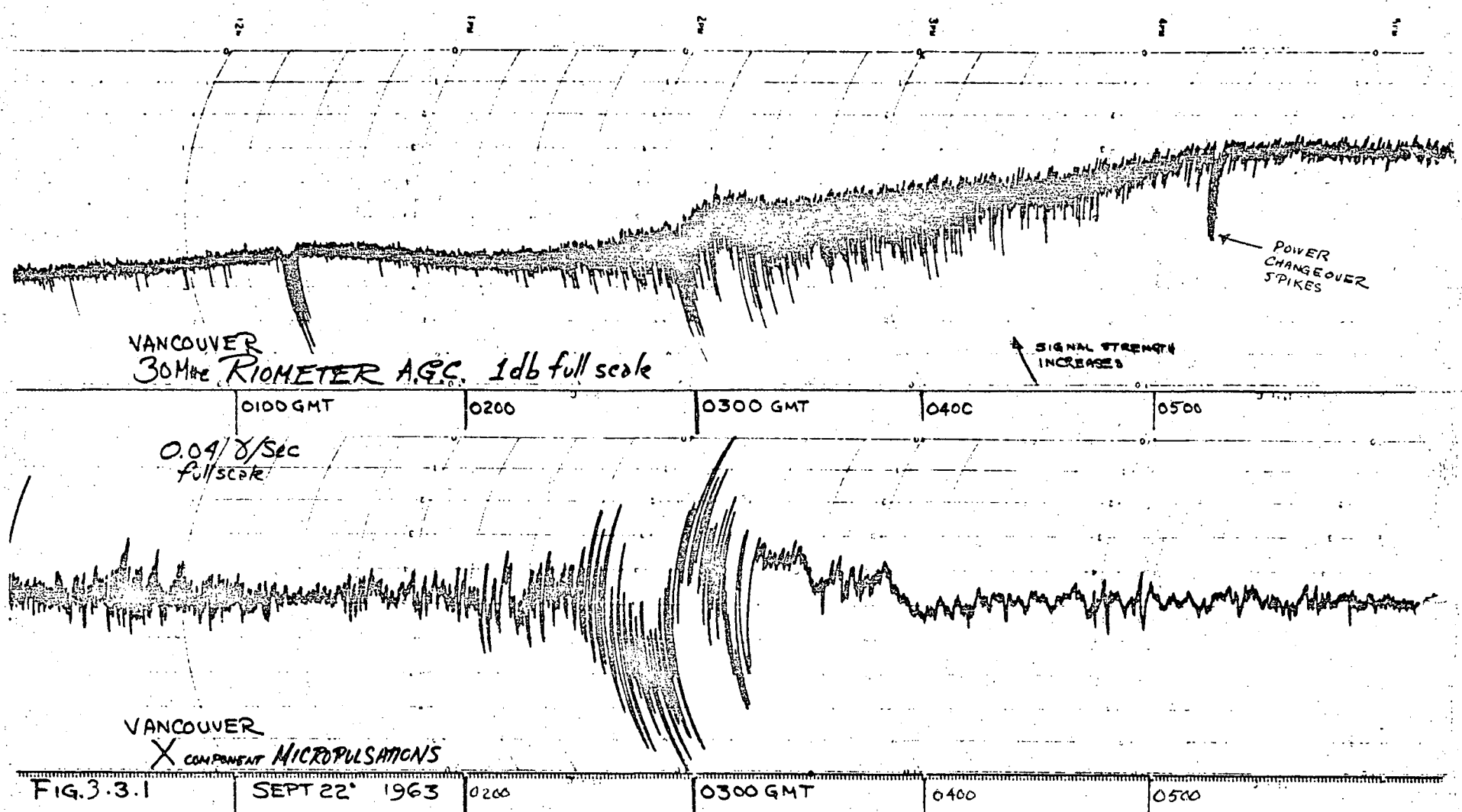


Fig. 3.3.1. Riometer A.G.C. 'scintillations' and signal strength enhancement occurring in conjunction with a Pi-2 micropulsation event. (The downward spikes on the riometer records resulted from the mains being transferred to and from an auxiliary power unit.)

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There is none
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duration) occurred, and the number of nights on which those events occurred together, a contingency table was obtained:

	SCINTILLATION PRESENT	NO SCINTILLATION
Micropulsations	11	12
No Micropulsations	7	200

(The χ^2 test indicates this association configuration has a probability of less than 0.1% of occurring by chance.)

Further examination of particular events indicated that either cosmic noise scintillation, or less probably (due to the smooth envelope of the noise) backscatter of HF radio signals, was being received, and that in general the average signal level increased rather than decreased during these events, although on some occasions slight dips of five minutes 'period' occured which may have been caused by absorption. On the rare occasions when magnetic storms occurred and where auroral type absorption was seen together with micropulsations, the complex nature of the events and the low chart speed masked any direct association. (Consequently little can be said concerning such periods.)

3.4 Broad-band Radiometer Results

Broad-band (6-16 MHz) radiometer records were made at Royal Roads from September 1963 until September 1964.

The radiometer records exhibited several events each month which appeared directly correlated with micropulsation events. In Fig. 3.4.1 a typical night time event (0300 LMT)

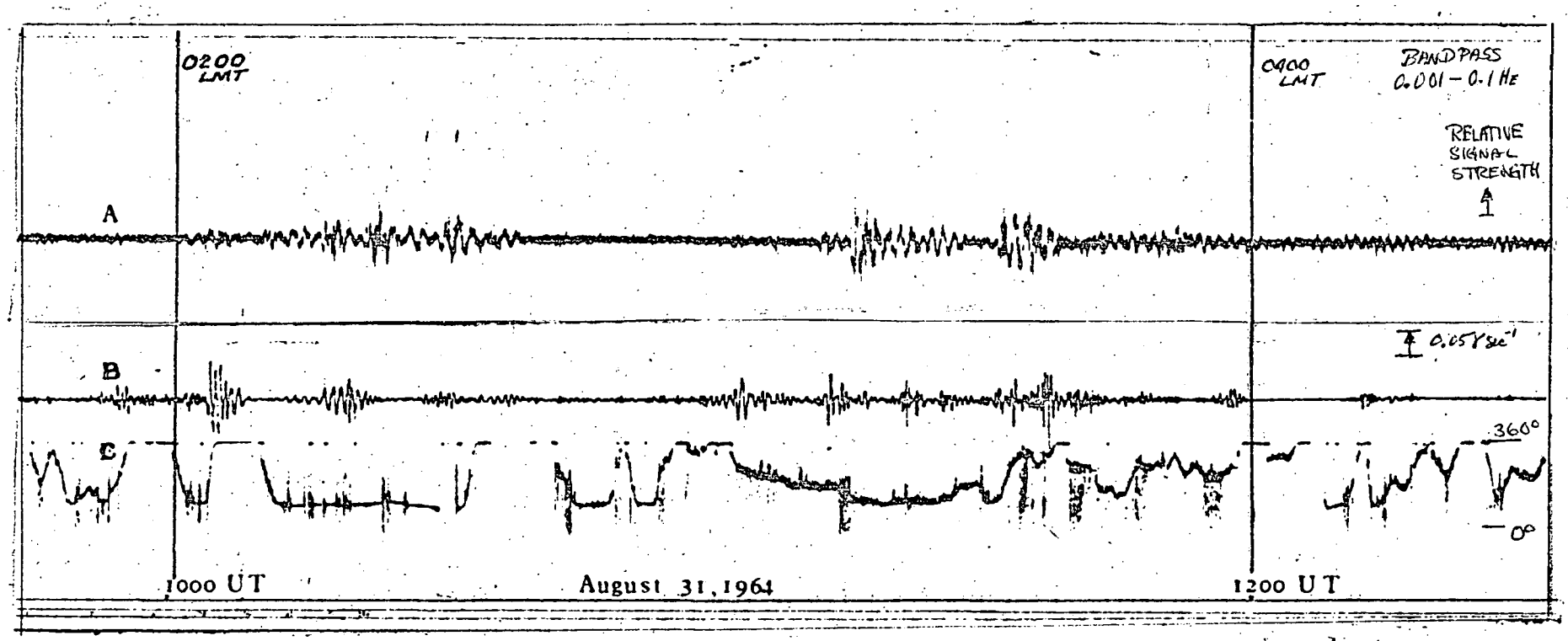


Fig. 3.4.1. Broad band HF Radiometer signal fluctuations (A), and Pi-2 magnetic micropulsations (B), (C) is the NPG, VLF skywave phase record.

is illustrated. Magnetic micropulsations of about two minutes period (Pc-4) appear in bursts on the telluric potential records, and are accompanied by rapid fluctuations in HF signal strength. (The 18.6 KHz sky-wave phase record is also perturbed but is without any direct association with the Pt's.) The HF signal and the telluric potential signal were recorded (FM) on magnetic tape. The tapes were played-back through a sweeping-filter type spectrum analyser and dynamic spectra were recorded on film. Figure 3.4.2 shows the spectra of fluctuations of RF (the difference between O and X vertically incident radio waves in the band 6 - 16 MHz) compared with the spectra of the geomagnetic fluctuations (telluric currents) at the same time. An idea of the resolution may be obtained from the faint but continuous line at 1.0×10^{-1} Hz on the telluric record which is due to 60 Hz pickup when the speeded up signal is re-recorded. Both spectra are therefore quite broad.

Both spectra fall off at the high frequency end. Also, the capacitor coupling of the telluric current amplifier makes it appear to fall off slightly at the low frequency end.

The diurnal variation of r-f and telluric fluctuations have rather similar regimes for the days studied : increasing about local dawn, rising to a maximum in the forenoon, passing through a slight minimum at noon. Slight activity starts about

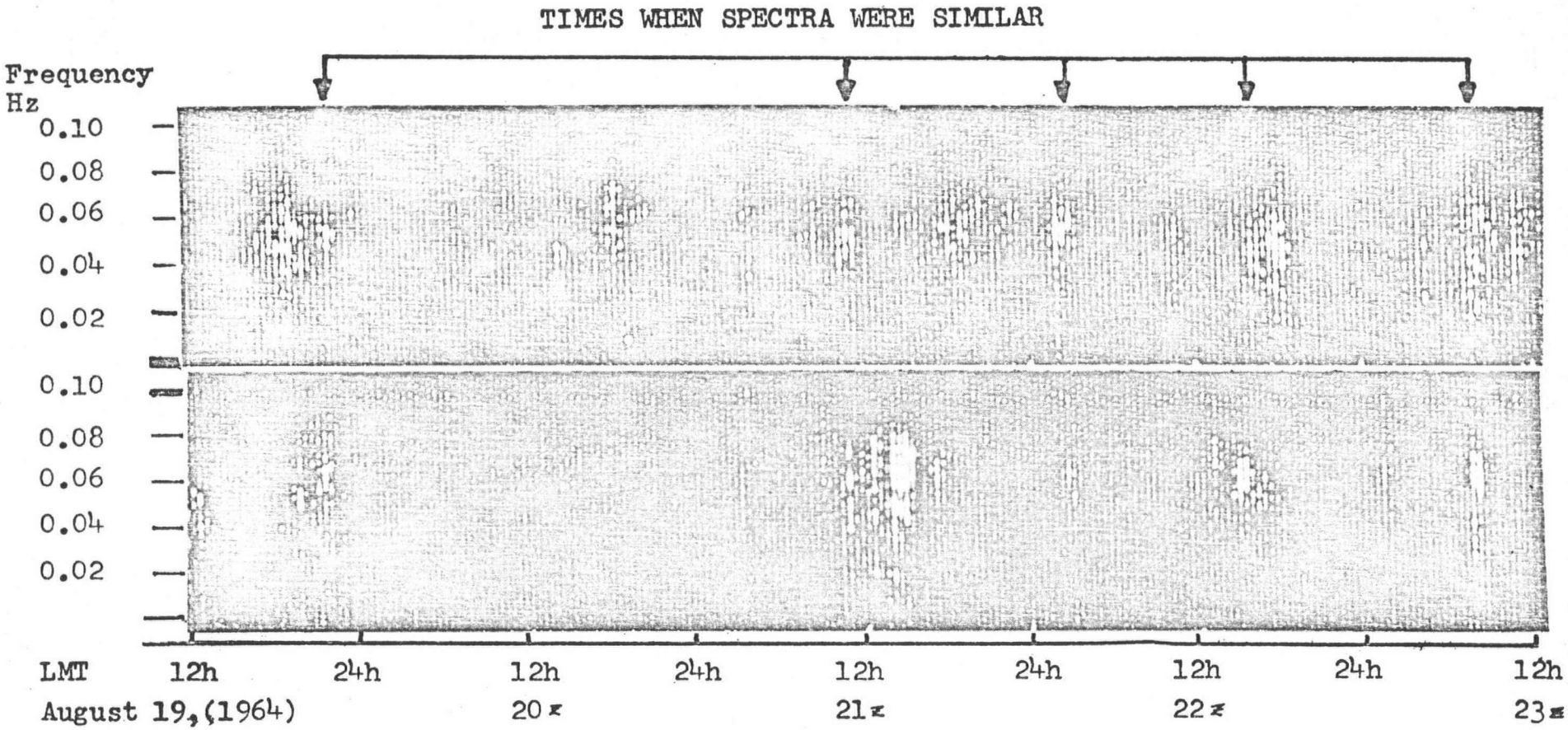


Fig. 3.4.2. Comparison of dynamic spectra, Top HF radiometer detected output, Bottom telluric E.W. potential output, for a four-day period. (White is strong signal, black no signal.)

1400 hours local time, and in the case of the r-f, increases steadily until a few hours before local midnight.

Records for 24 consecutive days were scaled into hourly average amplitude indices consisting of seven increments. Cross correlations of pairs of corresponding r-f. and telluric amplitude indices for a specific hour of each day were not significant except at 1400 local time (2200 U.T.). At 2200 U.T. the correlation coefficient r=0.71 is highly significant (1%). It reflects the normal increase of activity during the afternoon of both r-f. and telluric signals. Figure 4.4.2 was chosen as an example of signals having a similar frequency content. However, it also shows the typical increase of r-f. fluctuation about 2200 U.T. In this particular case the telluric signal was already fairly high and the change is less noticeable.

Taking data pairs from all hours of the day, and accounting for persistence, it is concluded that the hourly average r-f. and telluric amplitudes are significantly (1%), correlated with r=0.33. The large diurnal variation in signal amplitude obscures the relationship except for about one hour in the afternoon.

Neither the r-f. nor telluric signals were significantly correlated with the local K index during the period studied, and it is concluded that telluric current signal amplitudes in the range 0.006 - 0.6 Hz are a better indicator of r-f. fluctuation in this range than are larger slower changes in the geomagnetic field.

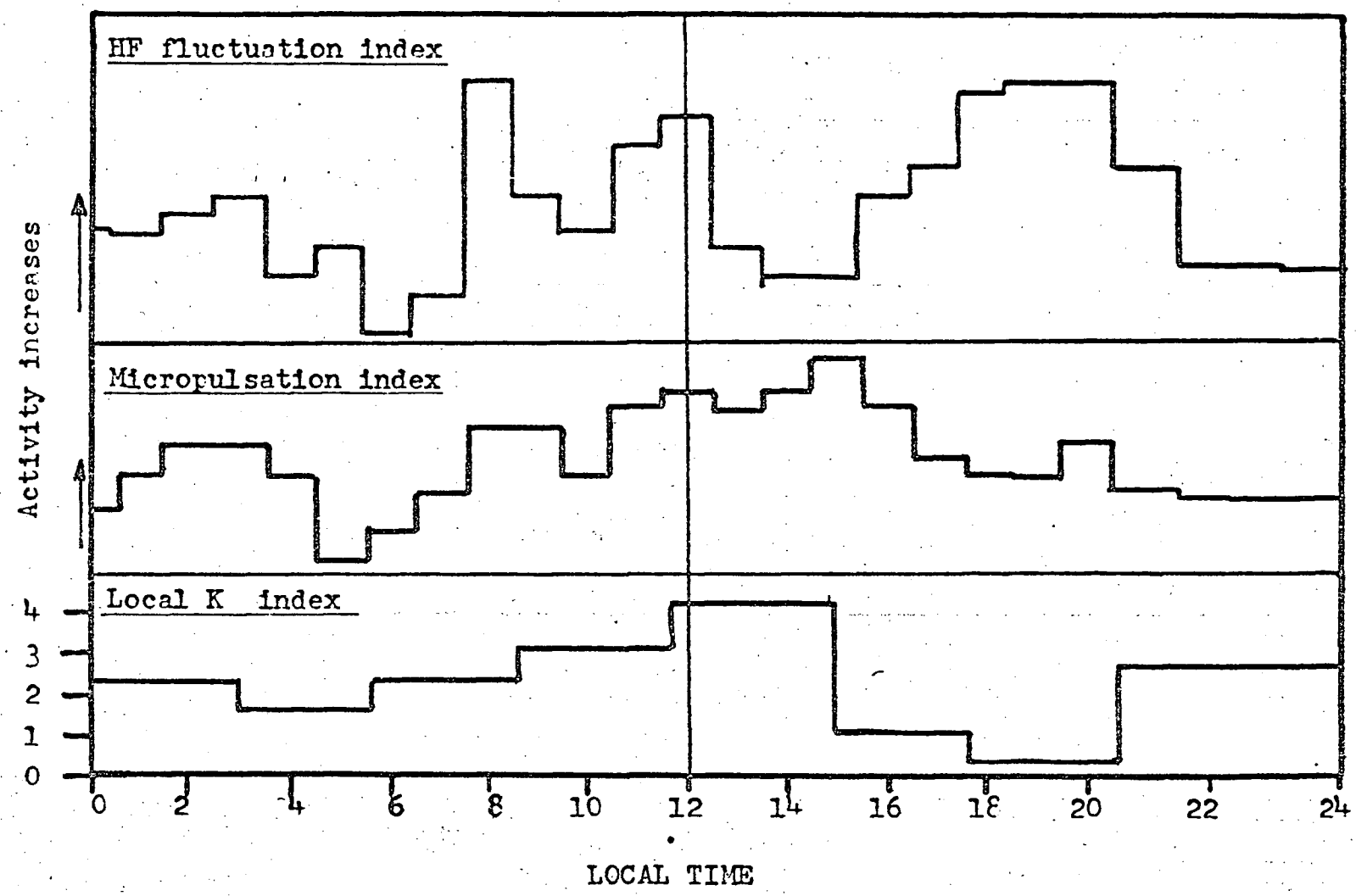


Fig. 3.4.3. shows the diurnal average of local K index for a 12 day period, and the same 12 days of geomagnetic and RF records. The micropulsation and HF fluctuation records were scaled using only three divisions of amplitude. They are significantly correlated to the 1% level from 0000^h to 1400^h, but the HF evening activity is not mirrored in the Telluric curve.

Figure 3.4.1 displays the relationship that exists between isolated events in the early morning hours, when r-f. and telluric signals are usually low. Such isolated events are de-emphasized by averaging amplitudes over an hour, and hence the lack of correlation noted above is not particularly surprising.

Figure 3.4.3 shows the diurnal variations of local K index, 100 days of geomagnetic record, and 12 days of simultaneous geomagnetic and RF records. In the 100 day histogram, taken in 1953, the P_t activity is suppressed by multiplying the average field change by its duration -- thus continuous daytime activity produces a larger value. The two 12 day records were scaled using only three divisions of amplitude. The results are significantly correlated to the 1% level from 0000 hours to 1400 hours, but the RF evening activity is not mirrored in the telluric curve.

The radiometer, as used, was not capable of providing accurate quantitative information. Consequently, once the association of HF fading and micropulsation activity had been confirmed, and their spectral similarities (dis-similarities) had been investigated this experiment was terminated. Further details of the results of this experiment are given by Duffus, Boyd and Kinnear (1965).

3.5 Vertical Incidence HF/CW Doppler Experiment Results

Near-vertical incidence sounding on 2.7 and 5.3 MHz was started in the spring of 1965. No us able records were obtained from the 5.3 MHz channel. In march, 1965, useable records

were obtained on the 2.7 MHz channel and this channel remained in use until April 17, 1966. In August 1965 a 4.6 MHz channel was added and continued in service until April 1966.

Six channel chart records (at 20 cm/hr) were made, of the output of sensitive frequency-meters measuring Doppler frequency deviation, of telluric potential and of VLF sky-wave phase. Slow speed FM tape recordings were also made throughout this period.

The Doppler bandwidth was generally 0.05 to 0.2 Hz increasing at times to as much as 15 Hz. The Doppler deviations recorded varied from 0.1 Hz to 10 Hz. The time resolution for changes was normally 5 - 10 seconds.

A) Type of Events

Various types of events were found to occur on the HF Doppler records, notably :

i) Cycle by cycle associations between quasi-sinusoidal frequency shifts and Pi-1 and Pi-2 micropulsations.

ii) Cycle by cycle Δf associations with Pc-3 and Pc-4 micropulsations.

iii) Direct associations between frequency shift and magnetic D or H bays.

iv) Increases in Doppler bandwidth associated with micropulsations and bays.

v) Impulsive frequency shifts associated with magnetic sudden impulses and sudden commencements.

vi) Sunrise and sunset events apparently involving magnetic variations, and frequency shift.

vii) Quasi-sinusoidal Doppler frequency variations not associated with any local magnetic disturbance.

B) The Period of Operation

The 2.7 MHz channel operated satisfactorily for about 233 days (± 8% depending on time of day) between March 1965 and April 30, 1966. The 4.6 MHz channel operated for about 113 days between Aug. 18, 1965 and April 30, 1966. Sunrise on 4.6 MHz generally occurred between 1400 hours and 1700 hours UT while sunset occurred between 0200 hours and 0700 hours UT .

When the HF sounding frequencies were near the critical frequencies of one of the ionospheric layers quite different propagation conditions prevailed than when they were below the critical frequency bands. In general, the transition periods occurred near sunrise and sunset. Fig. 2.4.2 indicates when these times occurred. It was prepared from local ionograms supplemented by prediction techniques.

The possible frequency locations of the sounding frequency are:

a) $f_{min} < f < f_oE$
b) $f_oE \leq f \leq f_xE$

DAYTIME (or sporadic E)

c) $f_xE < f < f_oF_1$
d) $f_oF_1 \leq f \leq f_xF_1$

DAYTIME ONLY

e) $f_xF_1 < f < f_oF_2$

f) $f_oF_2 \leq f \leq f_xF_2$

g) $f_xF_2 < f$ (no signal except during storms, etc.)

In bands a, c, e, the exploring wave suffers but little retardation and both circular polarisation modes are reflected. (Although the X mode is absorbed more than the O in the daytime.)

In the critical frequency bands b, d, f, severe retardation occurs. The X mode signal strength may be greater than the O ; and most important, the phase path is sensitively dependent on the electron distribution at the height of reflection. The sounding frequencies were chosen to lie in bands a, c, e, as much as possible. In band g no coherent reflections occur.

C1) Synoptic Statistics of Magnetic-variation-associated Doppler Shifts

The relative frequency of occurrence of the various types of event (on 2.7 MHz) as a function of time of day for the period March to October 1965 is shown in Fig. 3.5.1. The average local K_ℓ index for this period was 2.5. There were 125 days on which the 2.7 MHz channel operated satisfactorily. (In effect the numbers of hours on which events occurred at a given hour of the day may be looked upon roughly as percentages of occurrence.) There was some difficulty in distinguishing between some sudden impulses and Pi events. Also the distinction

between Pi and Pc events frequently was made mainly on the basis of the time of day, because even in the morning very few cases of long trains of pulsations were observed. Anything from 4 a.m. to 2 p.m. was considered to be Pc. Anything in the appropriate frequency bands, from 2 p.m. to 4 a.m. was considered to be Pi. By an 'associated event', cycle by cycle correspondence of the dominant period in the magnetic variation and of the doppler frequency shift is implied. Periods when both channels were merely active are not considered to constitute associated events.

C2) The Seasonal Variation in the Occurrence of Associated Events (Types i, ii, iii, page 114)

The seasonal variation is complicated by the diurnal variation and by the seasonal variation in magnetic activity. By considering only the night-time 1 to 4 a.m. period (0900 - 1200 U.T.) diurnal effects are minimized. Table 3.5.1* gives the percentage of 'good' (0900 - 1200 U.T.) operating periods on which associated pulsation events occurred for the four seasons, together with the sums of the K_ℓ indices for thesame periods.

Table 3.5.1*

1 to 4 a.m. 0900 - 1200 UT	SPRING Feb. Mar. Apr. 1965	SUMMER May June July 1965	FALL Aug. Sept. Oct. 1965	WINTER Nov. Dec. 1965 Jan. 1966
good operating hours on which associated events occurred	18	3	13	19
Local K index sums, the same hours	205	202	198	172

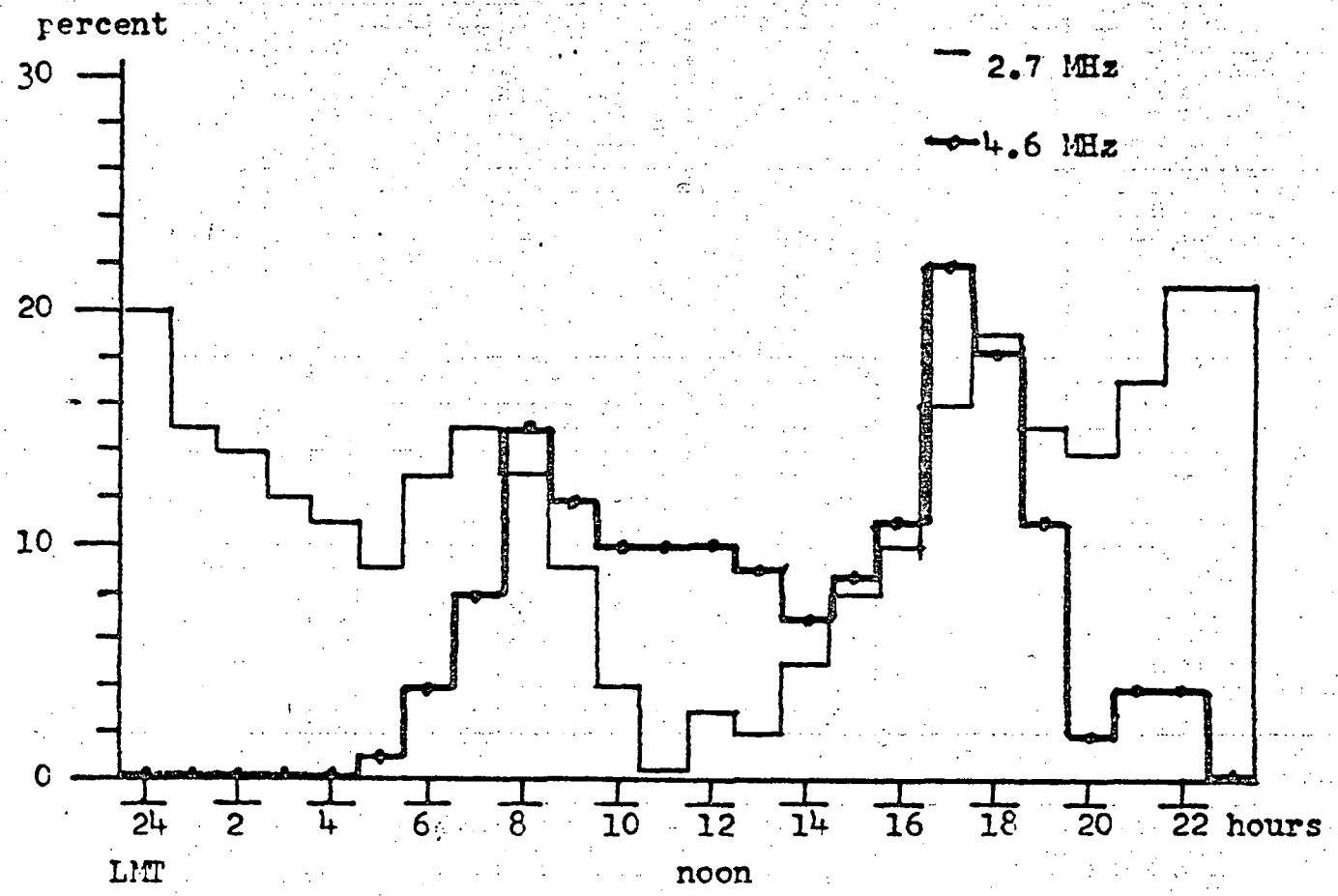


Fig. 3.5.1. Percentage of 'good' days when magnetically associated Doppler events occurred as a function of time of day. One year's results, April 1965 - April 1966.

It does not appear that variations in local magnetic (storm/bay) disturbance account for the seasonal variation in associated magnetic pulsation/Doppler events. A local micropulsation activity index (anything larger than 0.05 γ/sec. lasting longer than 5 minutes was assigned index 1; anything less, index 0) was compiled for the good operating hours for the (0900 - 1200 U.T.) period. For the spring months, the sum of this index (as a percent of the maximum possible sum) was 51%, for the summer months 49%, for the fall months 59%, and for the winter months 49%. That is, Pi-2's occurred about half the time throughout the year.

C3) The Diurnal Variation of Associated Event Occurrence

The diurnal variation of occurrence of 2.7 MHz associated events for the four seasons is shown in Fig. 3.5.2. The numbers of hours with events as a percentage of the number of 'good' hours at a given time of day is plotted as a function of time of day.

Similar dial plots for the 4.6 MHz channel are shown in Fig. 3.5.3 considering both sets of dials together it is clear that associated events occur throughout the twenty-four hour period, and particularly frequently (20% of the time) near the hours of sunrise and sunset, (compare with Fig. 2.4.2.)

In order to estimate how much of the diurnal variation depends on the presence or absence of micropulsations and how much on ionospheric conditions, a more detailed study was made of

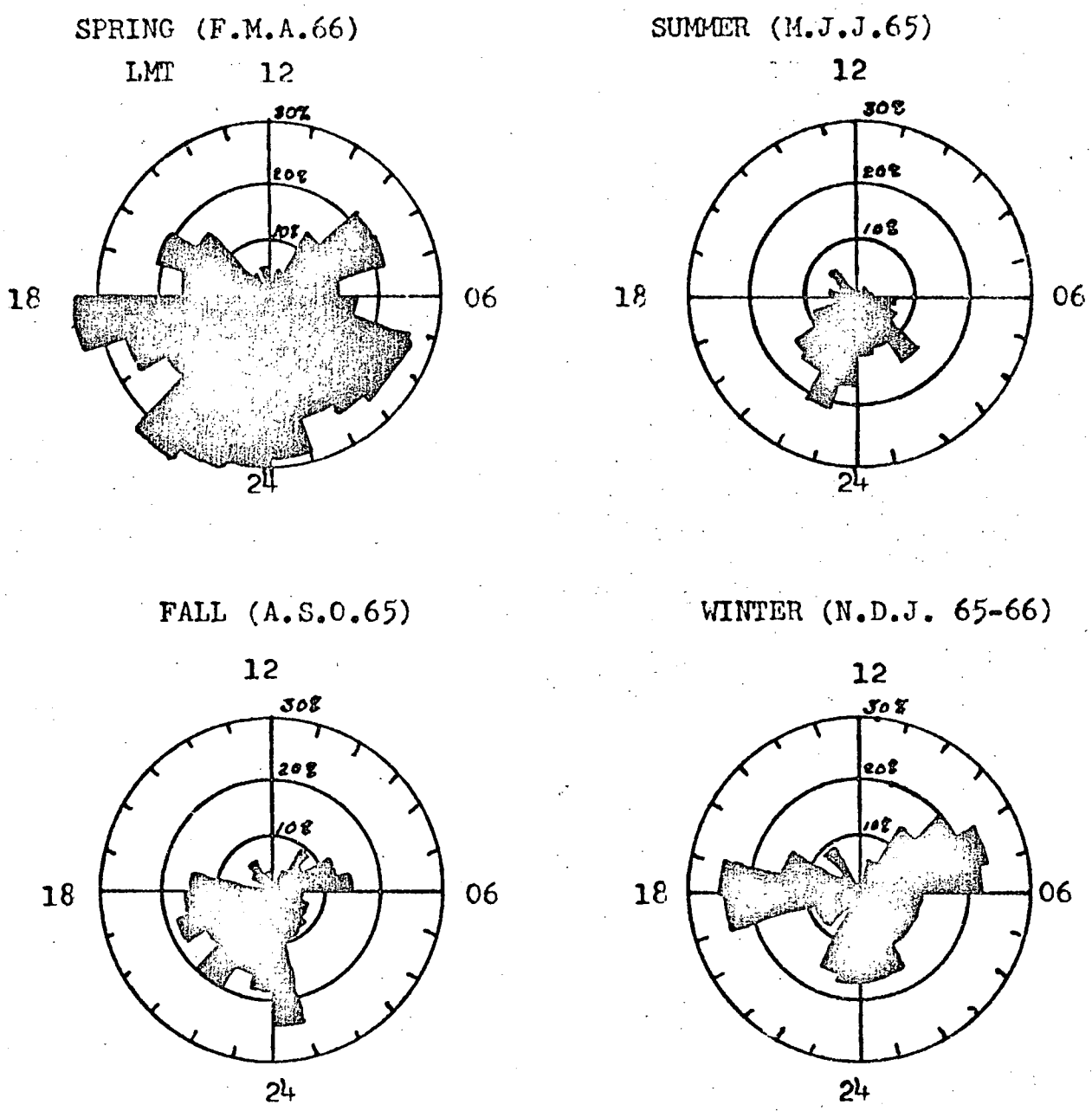
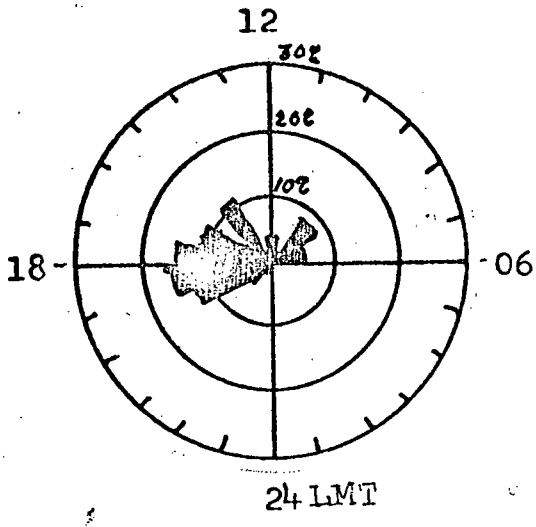


Fig. 3.5.2. Seasonal and diurnal variation 2.7 MHz Doppler events associated directly with magnetic micropulsations. Percentage of 'good' days when an event occurred in a given hour of the day is shown.

SPRING (F.M.A.66)

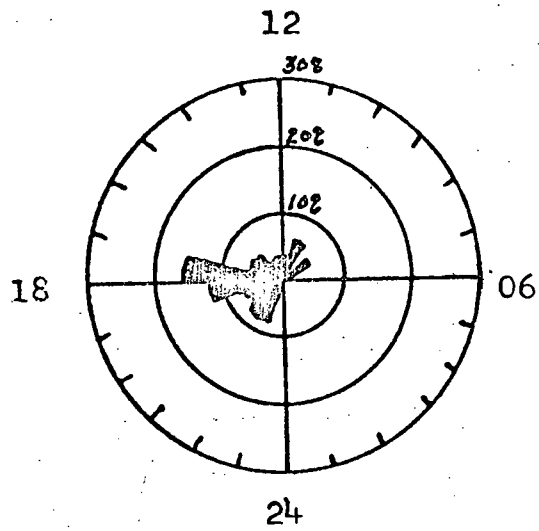


SUMMER --

No data available.

LMT = GMT - 8h

FALL (A.S.O. 65)



WINTER (N.D.J. 65-66)

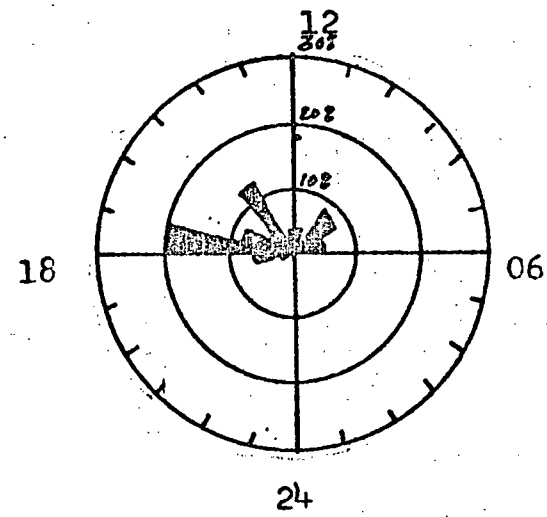
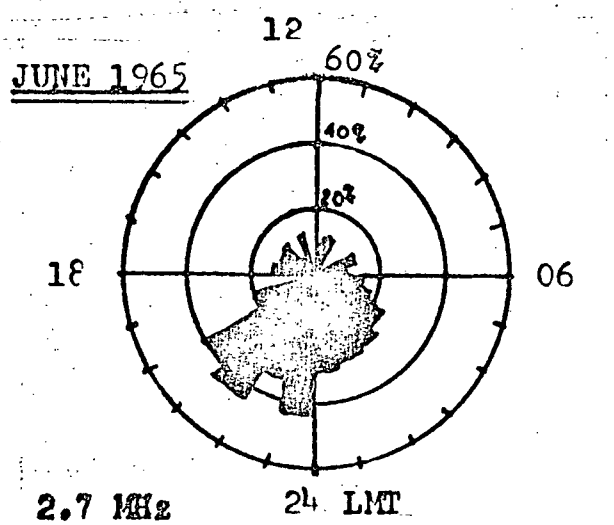
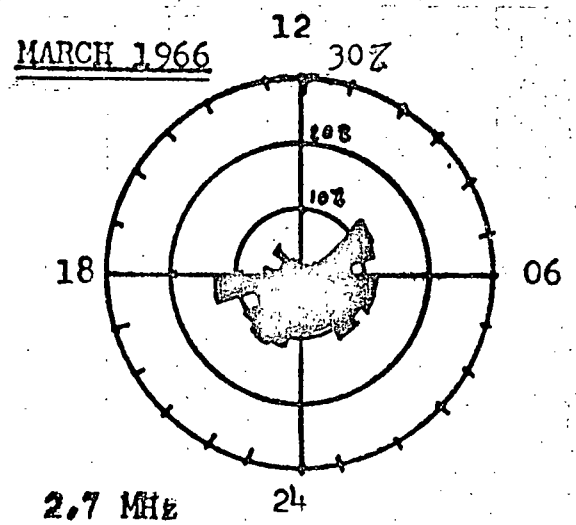


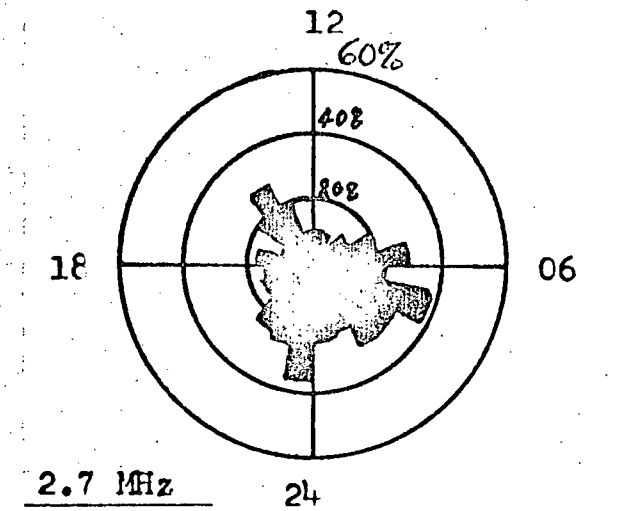
Fig. 3.5.3. Seasonal and diurnal variation 4.6 MHz Doppler events associated with magnetic micropulsations. Percentage of 'good' days when an event occurred in a given hour are shown.



ASSOCIATED EVENTS

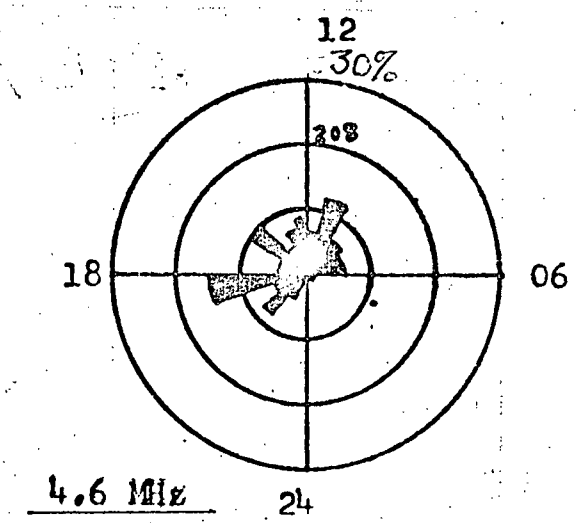


ASSOCIATED EVENTS



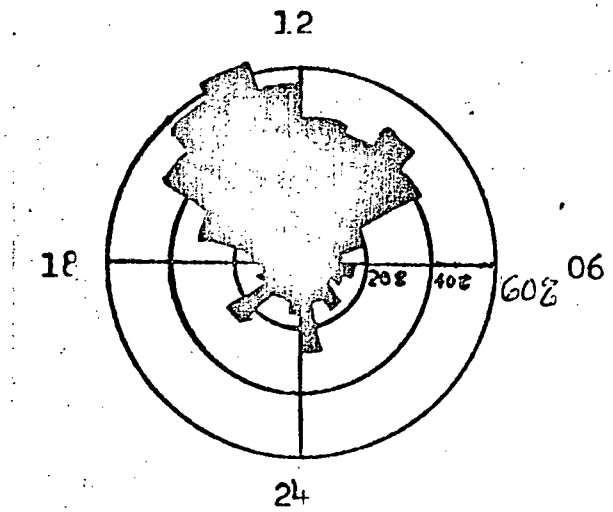
Δf GREATER THAN 0.25 Hz

TELLURIC (E-W) POTENTIAL

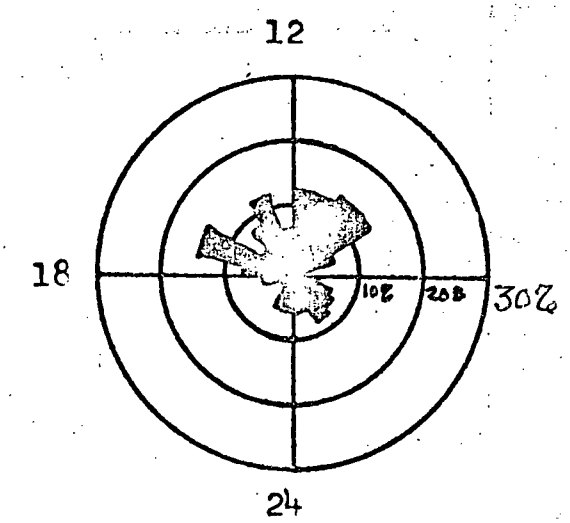


ASSOCIATED EVENTS

TELLURIC (E-W) POTENTIAL



ΔH GREATER THAN 0.05γ sec^{-1}



ΔH GREATER THAN 0.05γ sec^{-1}

Fig. 3.5.4 Diurnal variation of associated events, and of all events. Percentages of 'good' hours.

two months data (June 1965, March 1966). The diurnal variation of activity in the 0.005 - 0.1 Hz micropulsation band, and the diurnal variation in Doppler shift amplitudes are plotted together with the diurnal variation in associated events in Fig. 3.5.4. (Note that just before sunset virtually all micropulsation events were 'seen' by the Doppler sounder.)

While the diurnal distribution of events does reflect the magnetic activity distribution, proximity to ionospheric critical frequencies, i.e. sunrise or sunset, also seems important in determining the likelihood of an association.

Since the evening and morning (Pi and Pc) micropulsation regimes have distinct characteristics it seemed advisable to study their association with Doppler shifts separately. Further, since propagation characteristics are difficult to assess near sunrise and sunset, the periods near noon and near midnight were first examined.

C4) Midnight Events Synopsis

For the period April - Sept. 1965, hours with Doppler shifts on 2.7 MHz greater than 0.2 Hz and bandwidths greater than 0.2 Hz occurring between (0700 - 0859z) were tabulated together with the occurrence of telluric potential activity of amplitude greater than 0.02 gammas/second in the 0.005 to 0.1 Hz band. The results are given in tables 3.5.2* and 3.5.3*

RF / Magnetic	Doppler Shift ≥ 0.2 Hz B.W. ≤ 0.2 Hz	Doppler Shift < 0.2 Hz B.W. ≤ 0.2 Hz
Peak to Peak Telluric Pot. Amplitude ≥ 0.02 γ/sec.	28	11
Telluric Potential Amplitude < 0.028 γ/sec.	19	30

(88 hours total)

Table 3.5.2* Association Between Doppler Shifts at Midnight and Telluric Micropulsations. (Doppler Bandwidth Less Than 0.2 Hz)

It is apparent that there is a marked association between Doppler shifts and telluric potential; i.e. magnetic micropulsation activity (of types Pi-2 and Pi-1) gives rise to Doppler shifts about 75% of the time it occurs.

RF / Magnetic	Doppler Bandwidth > 0.2 Hz	Doppler Bandwidth ≤ 0.2 Hz No direct assoc'n.
PP amplitude ≥ 0.02 γ/sec.	36	24
< 0.02 γ/sec.	47	30

(137 hours total)

Table 3.5.3* Association of Doppler Bandwidth at Midnight, and Telluric Micropulsations.

[Doppler bandwidth in this case meant the envelope amplitude averaged over 20 seconds of unresolved excursions of the frequency meter output. If two or more independent signals of similar amplitude are present the frequency meter oscillates between the dominant frequency of one signal and that of the other. Consequently the bandwidth as defined above is roughly related to the actual bandwidth of the received signal due to multipath propagation.]

There does not appear to be a marked association between increased Doppler bandwidth and telluric activity. However, it is to be noted that it is difficult to distinguish between increased bandwidth and radio interference (QRM). Individual events, where Doppler bandwidth increases are seen to be related to magnetic disturbance, have been observed.

A tabulation was made of hours with direct association with Pi-2 pulsations in the presence and in the absence of Pi-1 pulsations and of magnetic bays. (> 15 γ lasting longer than 15 minutes in D or H) occurring between 11 p.m. and 1 a.m. (0700 - 0859 UT) between March 1965 and Sept. 1965. These results are given in table 3.5.4.*

Table 3.5.4* Association Between Pi-2 Micropulsations and Doppler Shifts (2.7 MHz)

a) in the presence or absence of Pi-1 riders:

RF / Magnetic	Direct Doppler Shift Association	No Direct Association
Pi-2 with Pi-1 riders	15	9
Pi-2 without riders	7	8

Table 3.5.4* partb)
in the presence or absence of H or D Bays
(> 15 γ, & > 15 minutes)

Magnetic \ RH	Direct Doppler Association with Pi-2	No Direct Assocn with Pi-2
Pi-2 with Bay	7	9
Pi-2 without Bay	12	11

Apparently the presence of Pi-1 greatly enhances the probability of seeing associated ionospheric motions while the presence of an H or D bay does not. This is borne out by the fact that the average local K_ℓ index at times when associated events occurred was 2.6 while the average K_ℓ index when no association was found was 2.5 (average of 113 periods 0900 - 1200 UT) (Local H, and D indices also had about the same average values at these times).

Association of Doppler shifts with magnetic bays is not as frequent as with Pi-2 pulsations. Considering the period March 15 to Sept. 17, 1965 (0700 - 0859 UT) direct associations with H or D bays of amplitude greater than 15 γ and duration greater than 15 minutes occurred on only 4 of the 63 'good'*1 nights while bays occurred on 23 of these nights.

*1'good' here (again) means periods when both the micropulsation equipment and at least one channel of the Doppler equipment were operating with satisfactory sensitivity and noise level. 'Good' periods occurred about half the time, down time occurred more frequently March, April and May, than in the other months, so that the results are more representative of the June to September period.

There are also magnetic variations with periods between 5 and 15 minutes which are fairly common. Between the hours of 10 p.m. and 4 a.m. (0600 - 1200 UT) during the months of June and October 1965 Doppler shifts associated with these long period variations occurred on about a quarter of the forty 'good' nights, these ten nights turned out to be 35% of the number of nights when K_ℓ was greater than 2.

The magnitude of the Doppler shift associated with a given amplitude magnetic disturbance, as a function of the period of the magnetic disturbance, is one of the most important statistics to be obtained.

For all good records taken between 0700 hours and 0859 hours U.T. between March 15, 1965, and April 30, 1966, the magnitude and sense of the ratio of Doppler shift to magnetic H component disturbance amplitude (peak to peak) as a function of period was tabulated. The magnitudes of this ratio are plotted in Fig. 3.5.5 These results have an uncertainty of about 15% since periods other than the dominant one may have contributed to the amplitudes measured. However, since the relationship between magnetic amplitudes at ground level and those in the ionosphere is rather uncertain more sophisticated analysis was not deemed worthwhile in general, (particular events will be dealt with later).

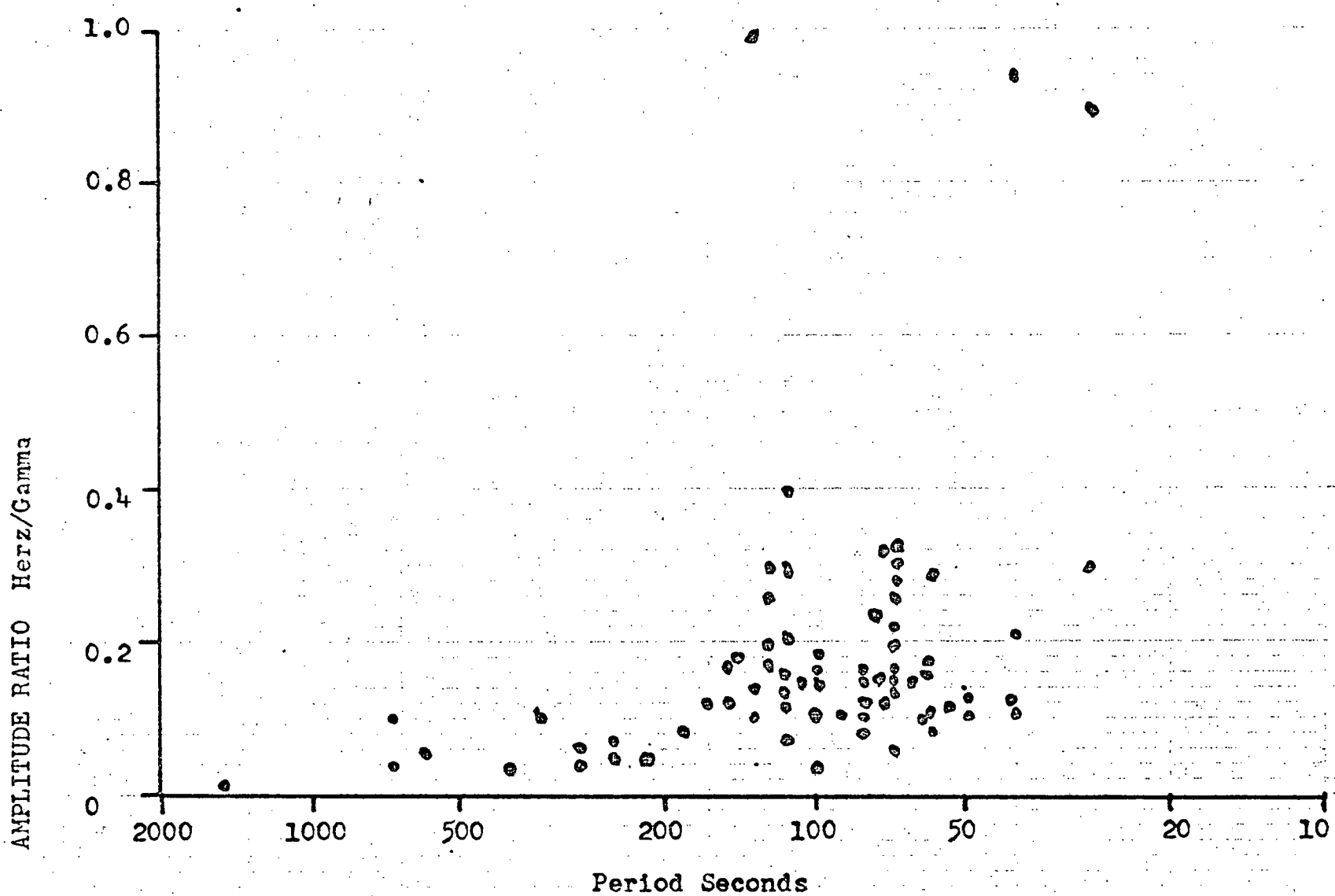


Fig. 3.5.5. Ratio of 2.7 MHz Doppler shift to magnetic H component variation as a function of dominant micropulsation period.
MIDNIGHT ± 2 h events March 1965 to April 1966

From Fig. 3.5.5 it is apparent that relatively greater Doppler shifts occur for shorter period fluctuations. For most of the events with periods longer than 90 seconds the Doppler shifts were either directly in phase or out of phase ($\pm$ 10 sec.) with the pulsations. For events with dominant periods of less than 90 seconds the phase frequently assumed intermediate values. A plot of the sense of the Doppler shift is given in Fig. 3.5.6 for those cases in which it could be specified. (If ΔH is considered + northwards and Δf is considered + for increasing frequency when both are + together, or both - together, one speaks of a positive sense.

The sense of Doppler shift at short periods, <300 seconds, appears to be random while for longer periods it gives some evidence of being negative. However, of the 60 events whose periods and phases were clearly distinguished, 30 had a positive sense and 30 had a negative sense.

It was found that the ratio $\Delta f/\Delta H$ did not depend in sense or magnitude on whether D or H bays were present, or upon the value of the local K_{ℓ} index.

The distribution of dominant spectral (period) peaks for the midnight associated events is given in Fig. 3.5.7. The gap between the peak at 70 - 80 seconds and the broad peak between 100 - 300 seconds is particularly noticeable.

Finally as part of the study of midnight events a tabulation was made of occasions (during the March 1965 - April 1966 period) when VLF skywave phase-shifts occurred in

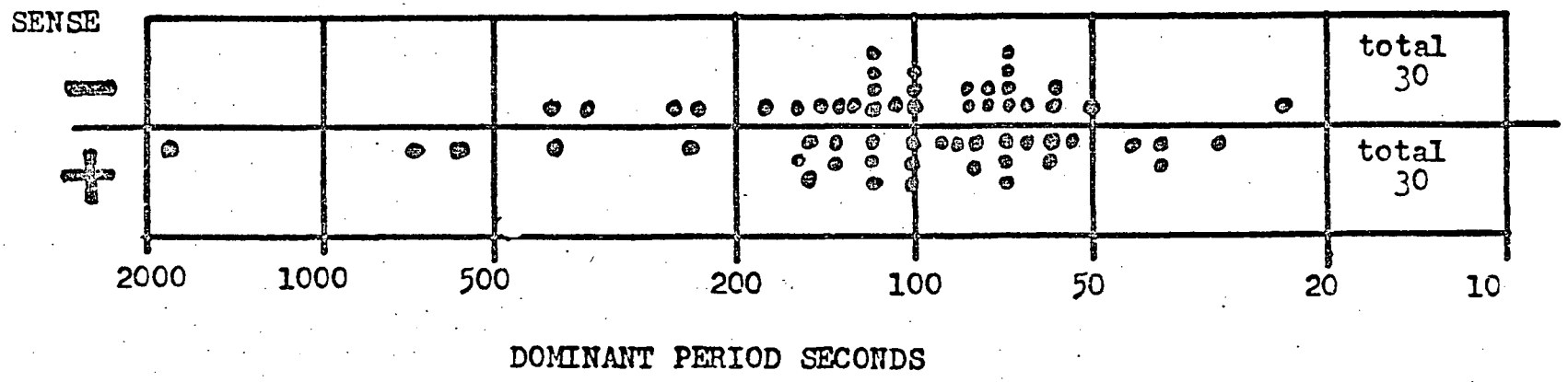


Fig. 3.5.6. Sense of the 2.7 MHz Doppler shift with respect to the sense of the magnetic H component deviation. If an H increase gives a frequency increase the sense is defined as positive.
MIDNIGHT EVENTS 1965 - 1966.

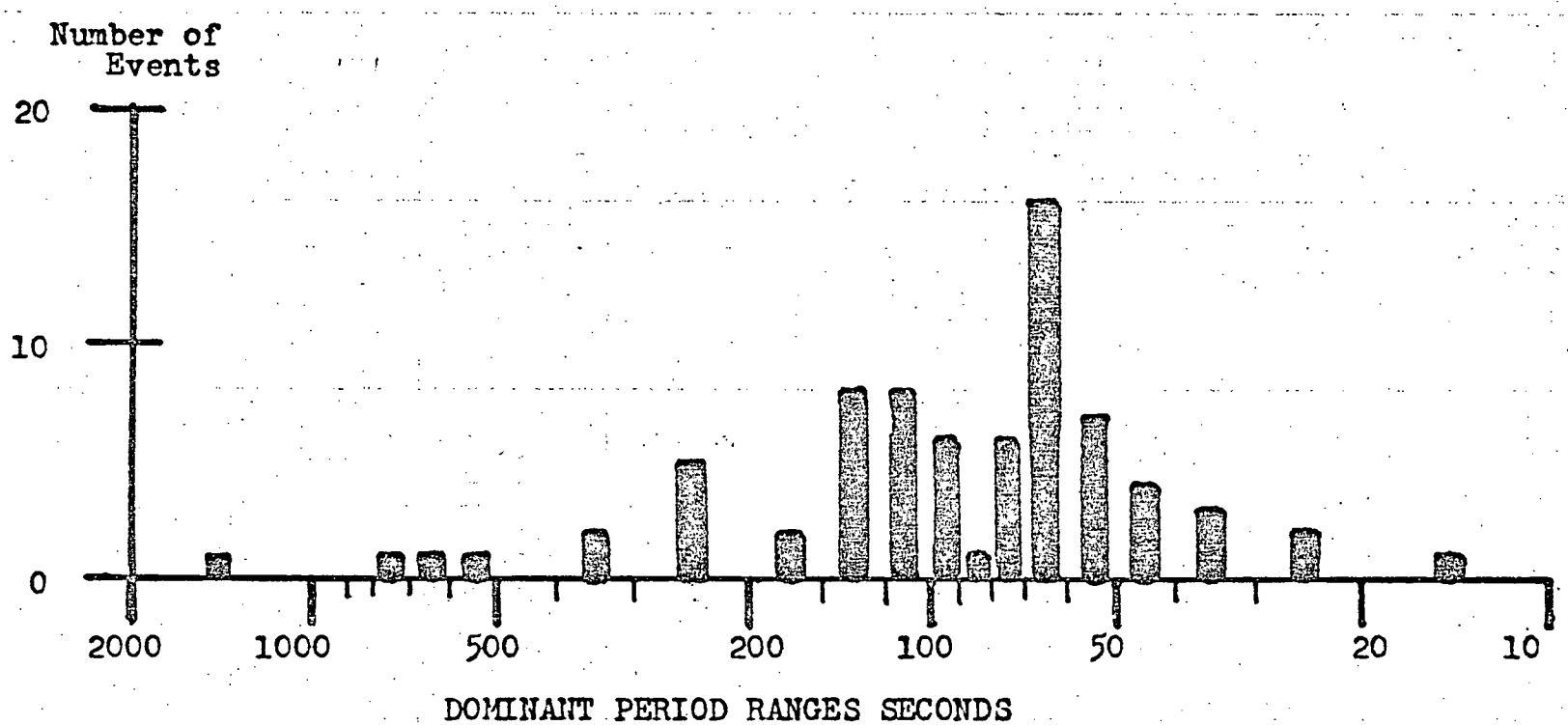


Fig. 3.5.7. Distribution of principal spectral peaks associated events 2.7 MHz Doppler and E-W telluric potential MIDNIGHT ± 2 h. 1965 - 1966.

direct association with Pi-2 micropulsations. There were 17 Pi-2 events with apparently associated VLF phase shifts. But there were 19 Pi-2 events which occurred when the VLF receiver was functioning properly but when its record exhibited no evidence of associated sinusoids. The events having VLF phase shifts also exhibited HF Doppler shifts if an HF channel was functioning. At night, the VLF phase channel is generally much more disturbed than the 2.7 MHz channel, hence association is much more difficult to evaluate.

C5) Noon Events Synopsis

Doppler shifts directly associated with micropulsations occurred between 11 a.m. (1900 z) and 3 p.m. (2259 z) on 35 of the 119 days between March 20, 1965 and April 30, 1966 when either or both Doppler channels were operating. That is to say that about 29% of the good observing periods yielded associated events. The majority of these events occurred on the 4.6 MHz channel. Of 25 events 'seen' on 4.6 MHz, 13 were not seen on 2.7 MHz; however there was only one event seen on 2.7 MHz which was not seen on 4.6 MHz (all channels in good order). Moreover, of the 12 events seen on both channels, 8 had larger Doppler shifts on 4.6 MHz than on 2.7 MHz; one had the same (± 5%) Doppler shift, while three exhibited larger Doppler shifts on 2.7 MHz. These results are plotted in Fig. 3.5.8.

The ratio of $\Delta f/\Delta H$ for the noon events as a function of the dominant micropulsation period is plotted in Fig. 3.5.9. The ratio increases with decreasing pulsation periodicity.

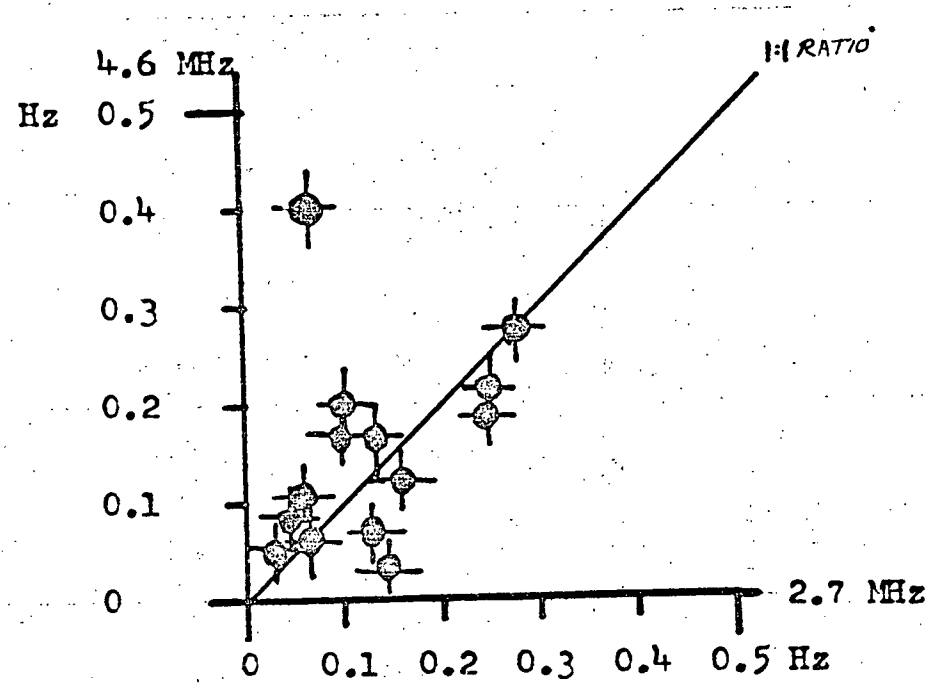


Fig. 3.5.8. Noon (± 2 h.) events (March 1965 - April 1966) Ratio of frequency deviation on 4.6 MHz to frequency deviation on 2.7 MHz.

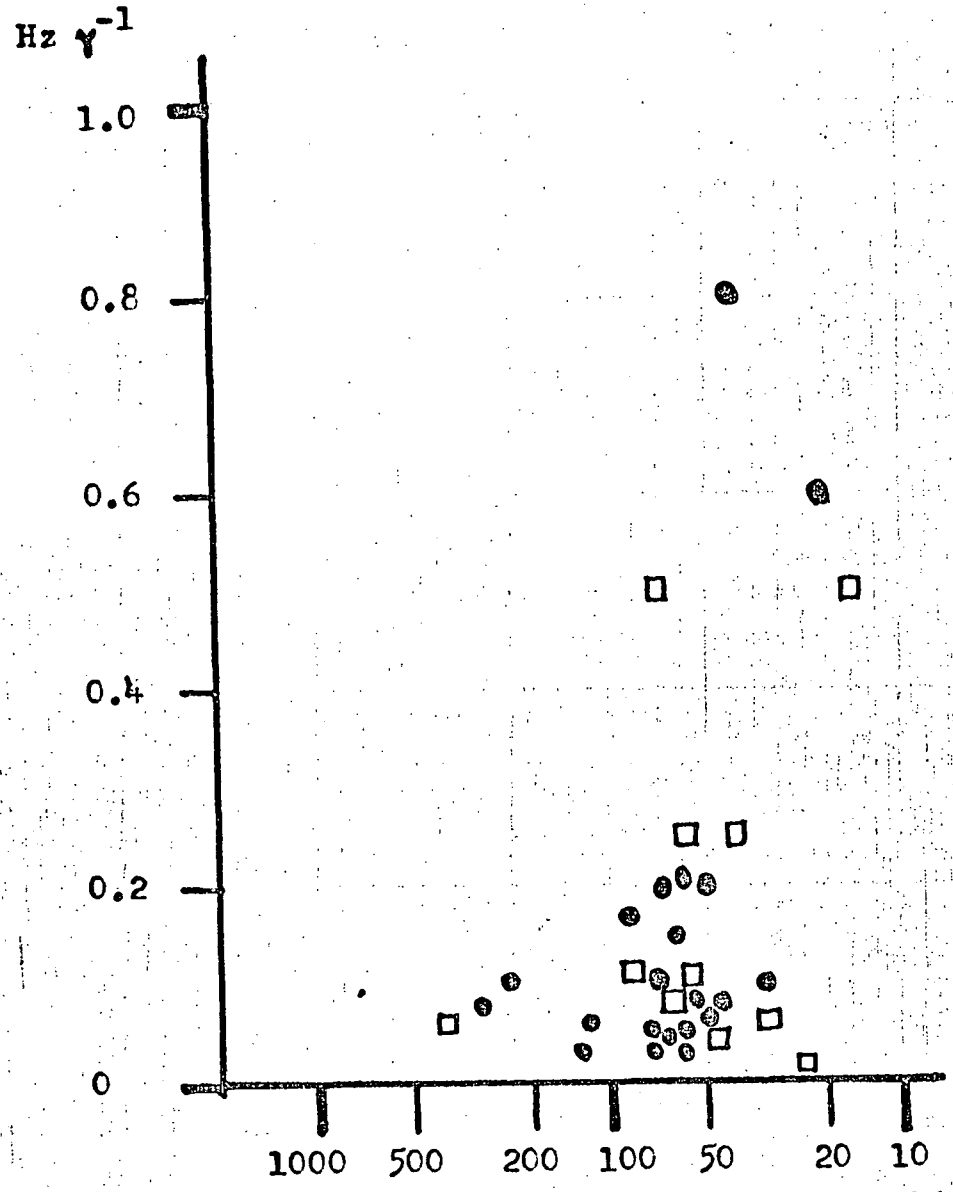


Fig. 3.5.9. Noon events ratio of Doppler shift to magnetic H component amplitude as a function of pulsation period (March 1965 - April 1966, 1900 - 2300 z) □ represent 2.7 MHz, • represent 4.6 MHz events.

The distribution of pulsation periods for associated events is plotted in Fig. 3.5.10. Nearly all the events at noon were of Pc-3 or Pc-4 type, and of shorter period than the majority of midnight events.

The phase relationship between the quasi-periodic 2.7 and 4.6 MHz Doppler shifts varied from time to time. Both in phase, and 180° out of phase, conditions occurred. A given phase relation tended to persist for five minutes or more. Both gradual and abrupt phase transitions occurred. Moreover the phase of the Doppler shifts changed with respect to that of the telluric potential pulsations, (or H or D component magnetic pulsations). It is perhaps more correct to think in terms of time displacement rather than phase shift.

At these shorter daytime micropulsation periods (Pc-3), even an 180° phase shift represents a time delay of only about 40 seconds. (The 20 cm/hr charts could be scaled to ± 10 seconds, the occasional, 100 cm/hr chart could be scaled to ± 3 seconds). The time displacements varied from less than three seconds to a maximum of about fifty seconds.

Assuming that the reflexion 'points' for 2.7 MHz and 4.6 MHz differed by at least 20 km, which is plausible in view of the ionograms, then the minimum group velocity (as points on irregular waveforms are matched this is probably group rather than phase velocity) between reflexion points would be about 400 m/sec while the average would be about 5 km/sec. The actual

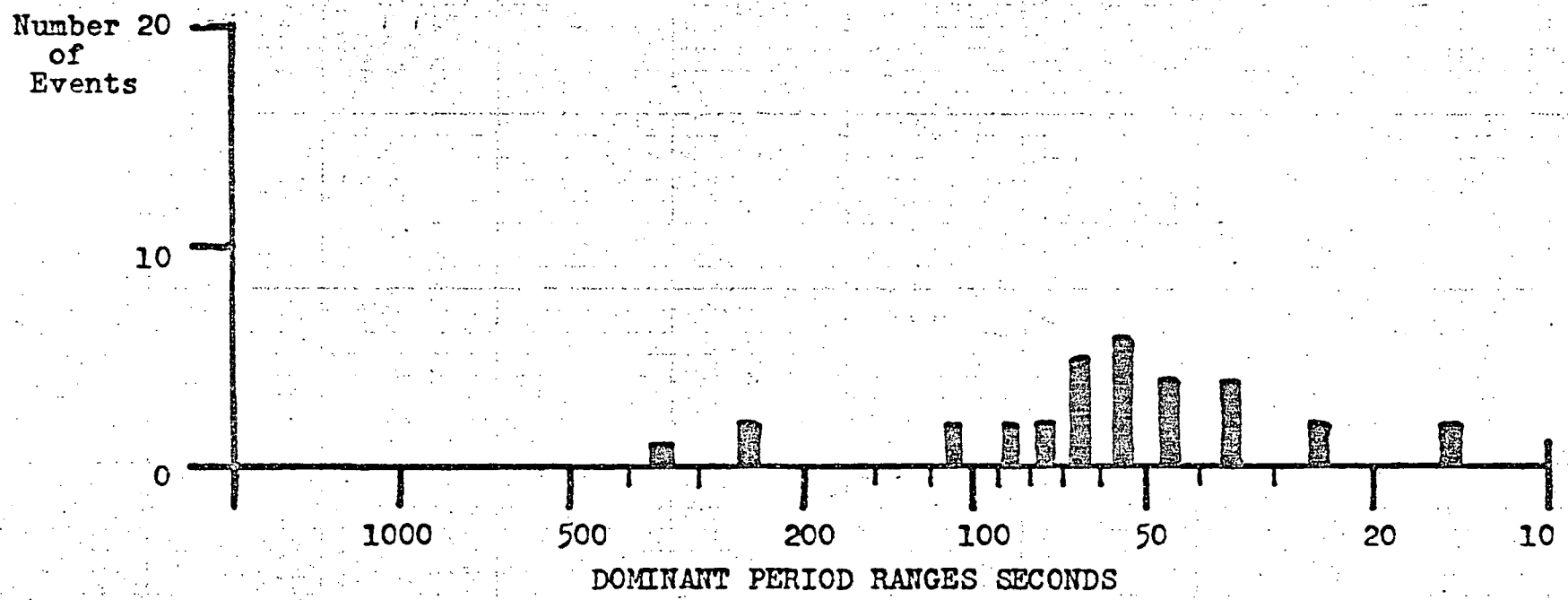


Fig.3.5.10. Distribution of principal spectral peaks associated events 4.6 and 2.7 MHz Doppler and E-W telluric potential Noon ± 2 h. 1965-1966.

Doppler shifts on 4.6 MHz ranged from 0.05 Hz to 0.5 Hz which for the simple moving mirror interpretation would represent vertical velocities of only about 1 to 6 m/sec. However, in the case of smooth sinusoidal waves there is an uncertainty in velocity of $\pm d/2\pi nt$, where d is the assumed separation and t is the period of the sinusoidal waveform, and n is an integer.

Associations with magnetic bays were not found at noon. This was not just due to the regular long period daytime Doppler variations (possibly internal gravity waves or Brunt resonance waves), because perfectly quiet Doppler traces sometimes occurred at the same times as D and H bays.

Note: ——— Flare-type events were not specifically tabulated.

C6) Sunrise and Post Sunrise Events

At 4.6 MHz ionospheric sunrise, or within the two succeeding hours, on seventeen days, events involving magnetic pulsations and Doppler shifts on both 2.7 and 4.6 MHz occurred. Most events were of the Pc type although there were some Pi and 'uncertain' type events.

The 4.6 MHz Doppler shift was invariably greater than the 2.7 MHz Doppler shift, and the Doppler shift appeared to be directly proportional to frequency, as may be seen in Fig. 3.5.11.

The ratio $\Delta f/\Delta H$ in Hz/gamma as a function of pulsation period is plotted in Fig. 3.5.12. Most of the values are in the neighbourhood of 0.05 to 0.1 Hz/gamma. No systematic dependence on period is apparent from the small number of events (17) available.

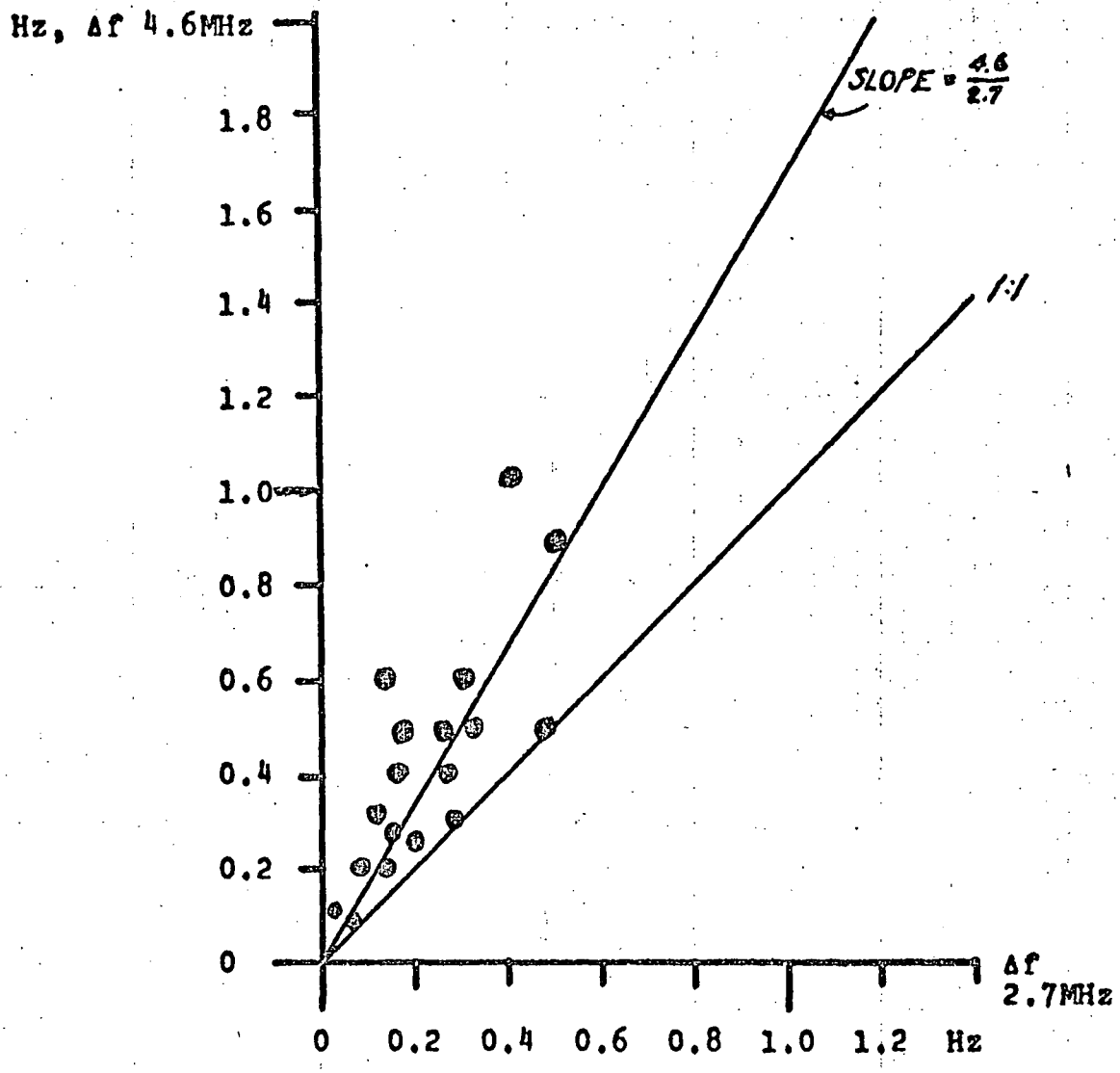


Fig. 3.5.11 Ratio of Doppler shift on 4.6MHz to shift 2.7MHz. Events occurring at 300km SUNRISE and during the following two hours. (1965-1966)

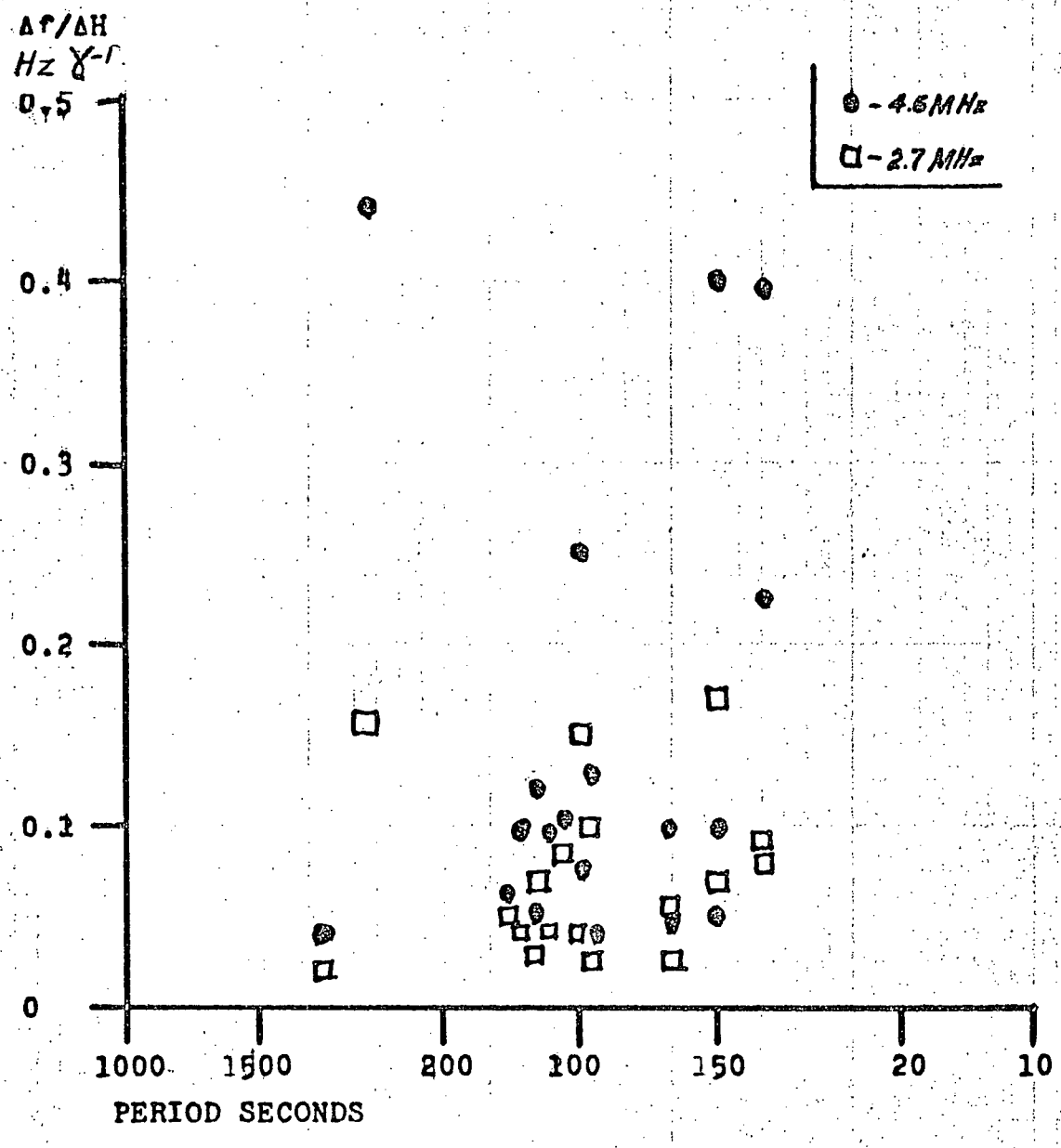


Fig. 3.5.12 Ratio of Doppler shift to magnetic H deviation as a function of dominant pulsation period for for SUNRISE events (1965-1966)

The time displacement between corresponding 4.6 and 2.7 Mhz Doppler shifts (related to pulsations) was measured for 34 pulsation groups. (The displacements between two or more pairs of peaks or troughs in the quasi-sinusoids were measured and averaged in each case.) The results are plotted in Fig. 3.5.13. It is seen that most events were simultaneous within ± ten seconds. (Even at sunrise when the reflexion 'points' of the two sounding waves should differ by many (20 - 50) km. The few exceptions, events involving large time delays (low group velocities), were long period events with periods of five minutes or more.

The shorter period events exhibited out of phase (180° ± 20°) Doppler waveforms between the 2.7MHz and 4.6 MHz records in 13 out of 29 cases. (The sense of the sunrise Doppler shift was checked to make sure that frequency shift inversion was not the result of improper heterodyning). On three days the 2.7 MHz waveforms went in and out of phase with the 4.6 MHz Doppler waveforms during single events.

Inconsistency of phase or 'sense' of the Doppler shift also occurs with respect to the magnetic H component, and the telluric E-W potential. Fourteen of twenty events studied exhibited Δf increases corresponding to ΔH decreases. The remaining six had Δf increasing as ΔH increased.

The distribution of dominant pulsation periods of Doppler associated events at sunrise and shortly thereafter is given in Fig. 3.5.14. There is a notable gap in associated

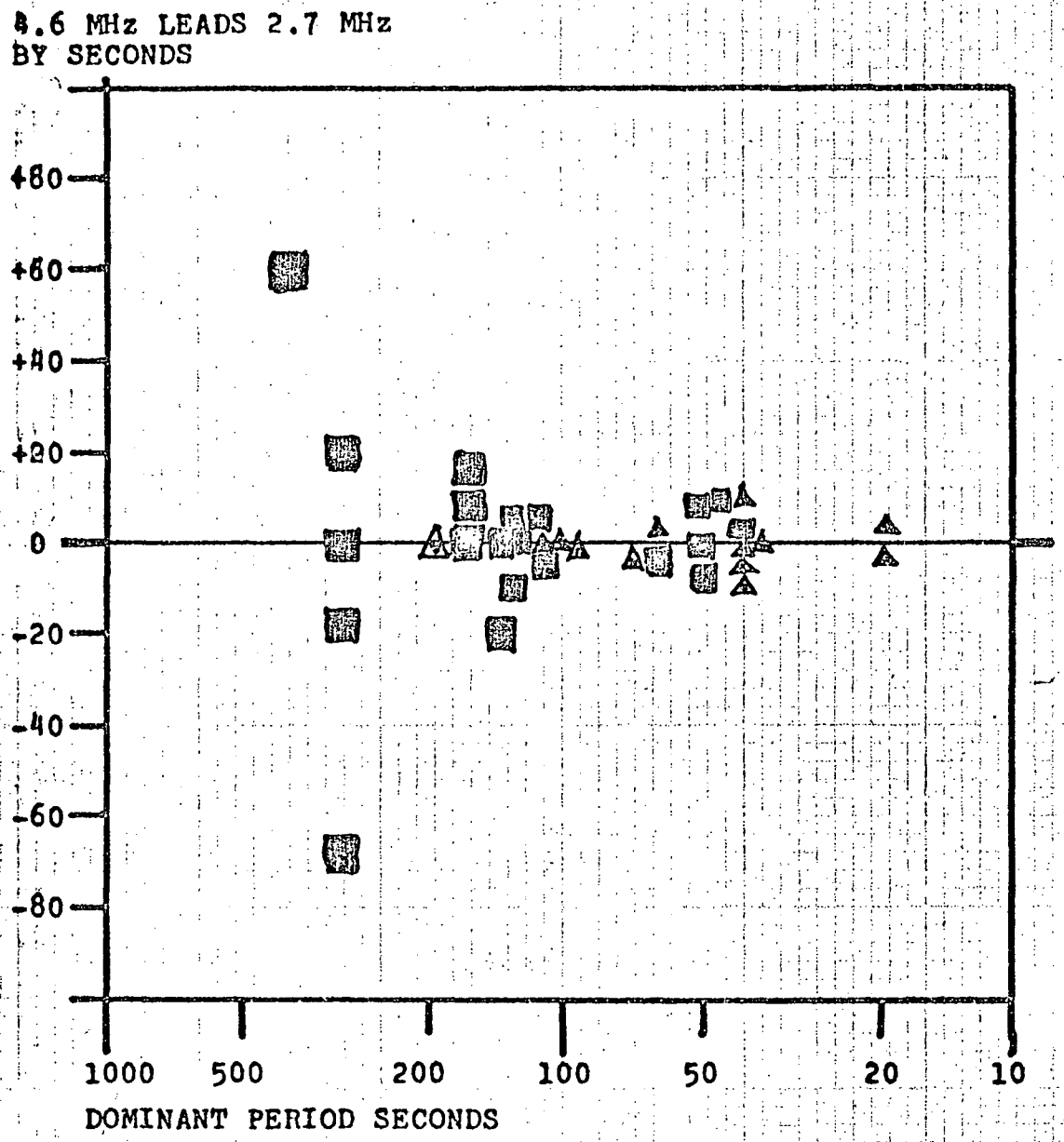


Fig. 3.5.13 Time displacements between Doppler waveforms on 4.6 MHz and 2.7 MHz as a function of pulsation period, for events occurring at (300km) SUNRISE and during the following 2 hours. (1965-1966)

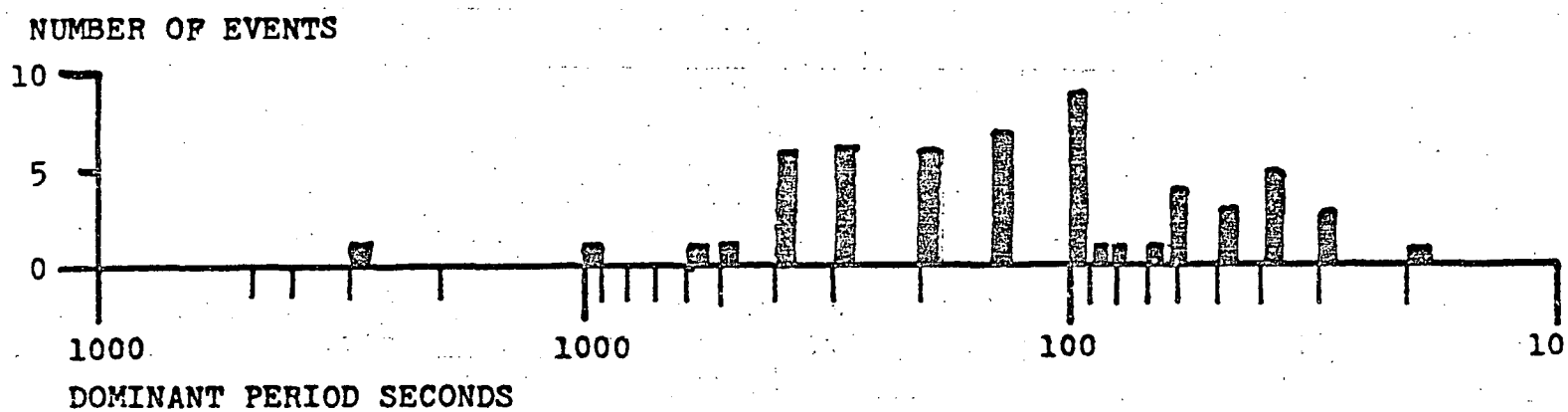


Fig. 3.5.14 Number of associated events with dominant periods in the ranges between scale divisions. Events occurring at 300km-SUNRISE, and within 2 hours thereafter.

event activity between 70 and 90 seconds periods, and an almost complete absence of associated events with periods greater than 500 seconds.

C7) Sunset and Pre-sunset Events

The two hour period preceding 4.6 MHz ionospheric sunset was examined on all records available. There were 34 evenings when Doppler shifts occurred on both 2.7 and 4.6 MHz channels in association with magnetic variations.

The magnitude of Doppler shift on 4.6 MHz compared to that on 2.7 MHz for these events is plotted in Fig. 3.5.15. The Doppler shift appears to be directly proportional to frequency (± 10%) for the majority of sunset events.

The ratio $\Delta f/\Delta H$ as a function of pulsation period is plotted in Fig. 3.5.16. Shorter period pulsations result in much larger Doppler shifts than do longer period ones.

The time displacements (differences between times of occurrence of similar waveform peaks and troughs) between 4.6 and 2.7 MHz Doppler shifts, associated with pulsations, are plotted in Fig. 3.5.17. Most delays are less than ± 10 seconds, except for those associated with pulsations with periods longer than 300 seconds, for which the pairs of records sometimes exhibited long delays in the order of 2 - 6 minutes.

Of 28 waveform groups analysed, 21 were in phase on the two Doppler channels, while seven were out of phase. On

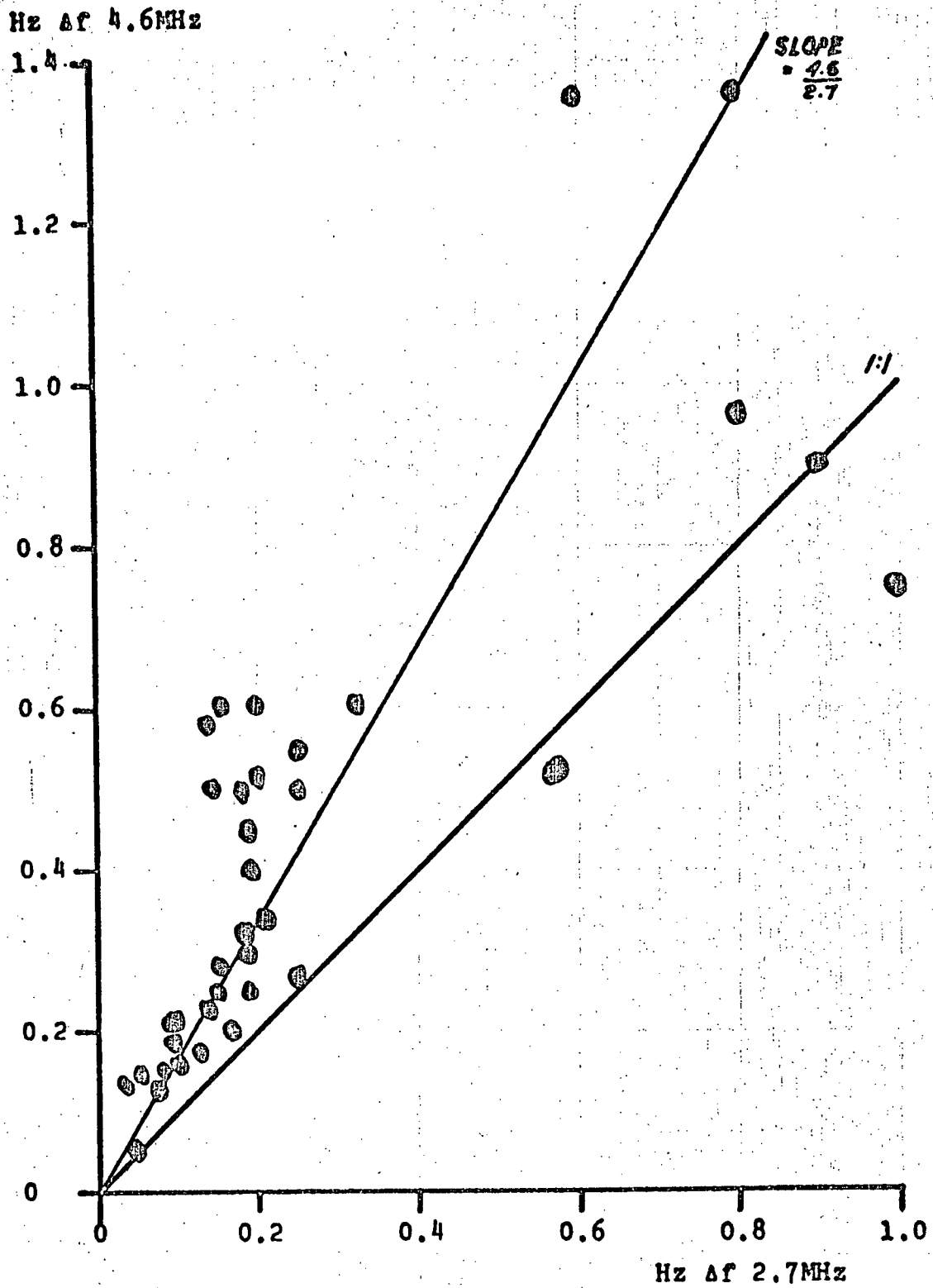


Fig. 3.5.15 Ratio of Doppler shift on 4.6MHz to Doppler shift on 2.7MHz. Events occurring at 300km SUNSET and 2 hours preceding. (1965-1966).

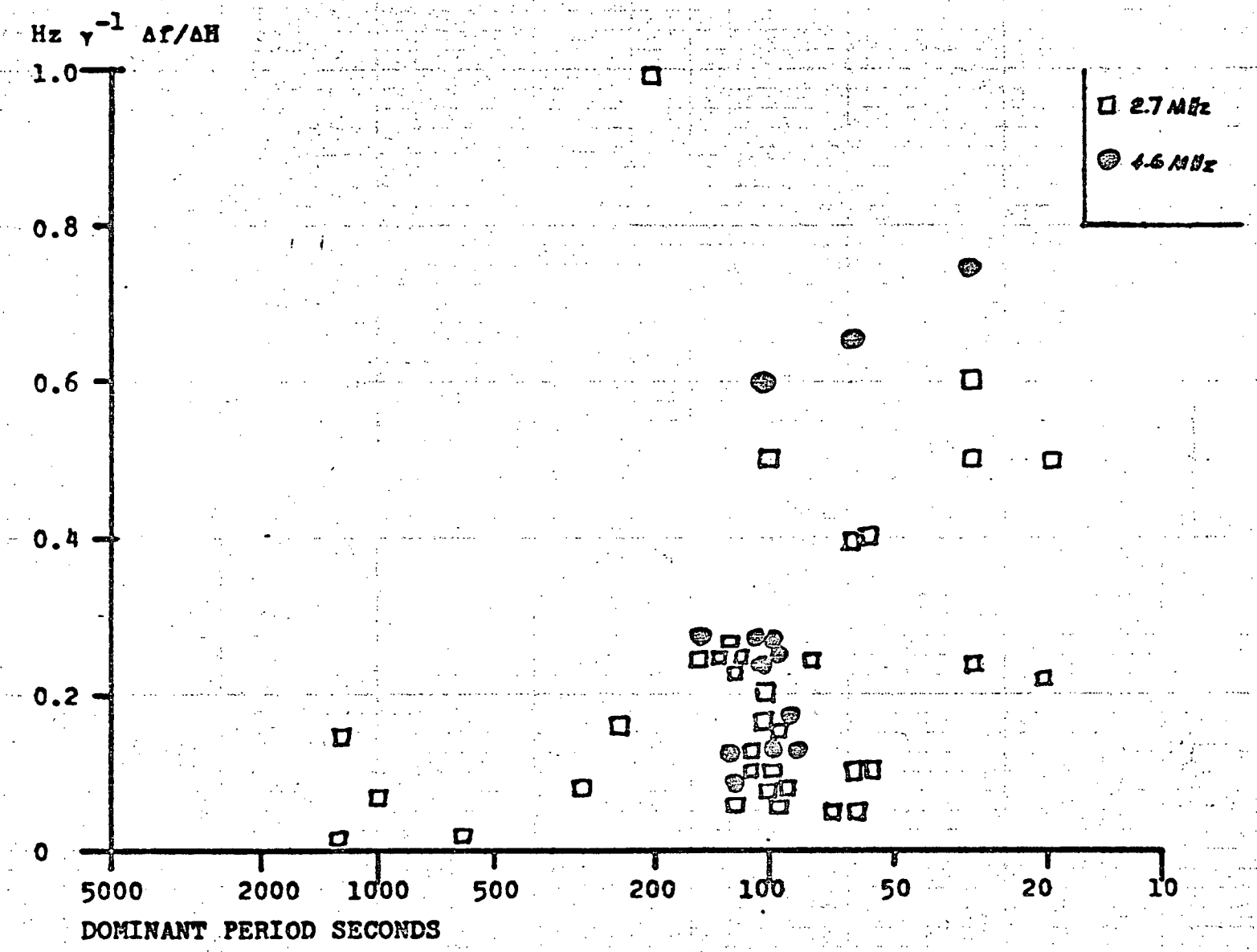


Fig. 3.5.16 Ratio of Doppler shift to magnetic (h) amplitude as a function of period, for events occurring at 300km SUNSET and 2 hours before.

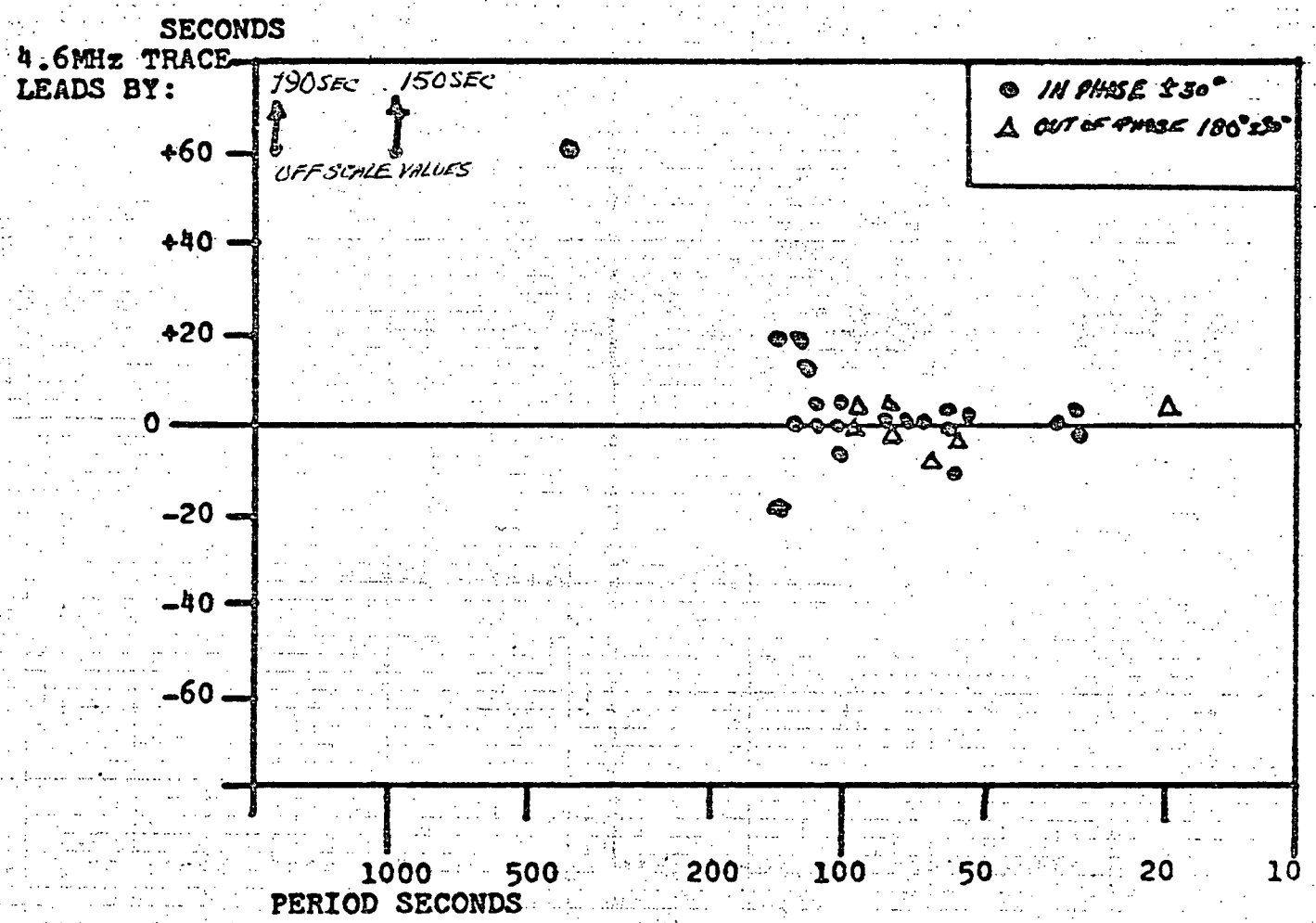


Fig. 3.5.17 Time displacements—between 4.6 MHz and 2.7 MHz Doppler trace waveforms for SUNSET and pre-sunset events (1965-1966).

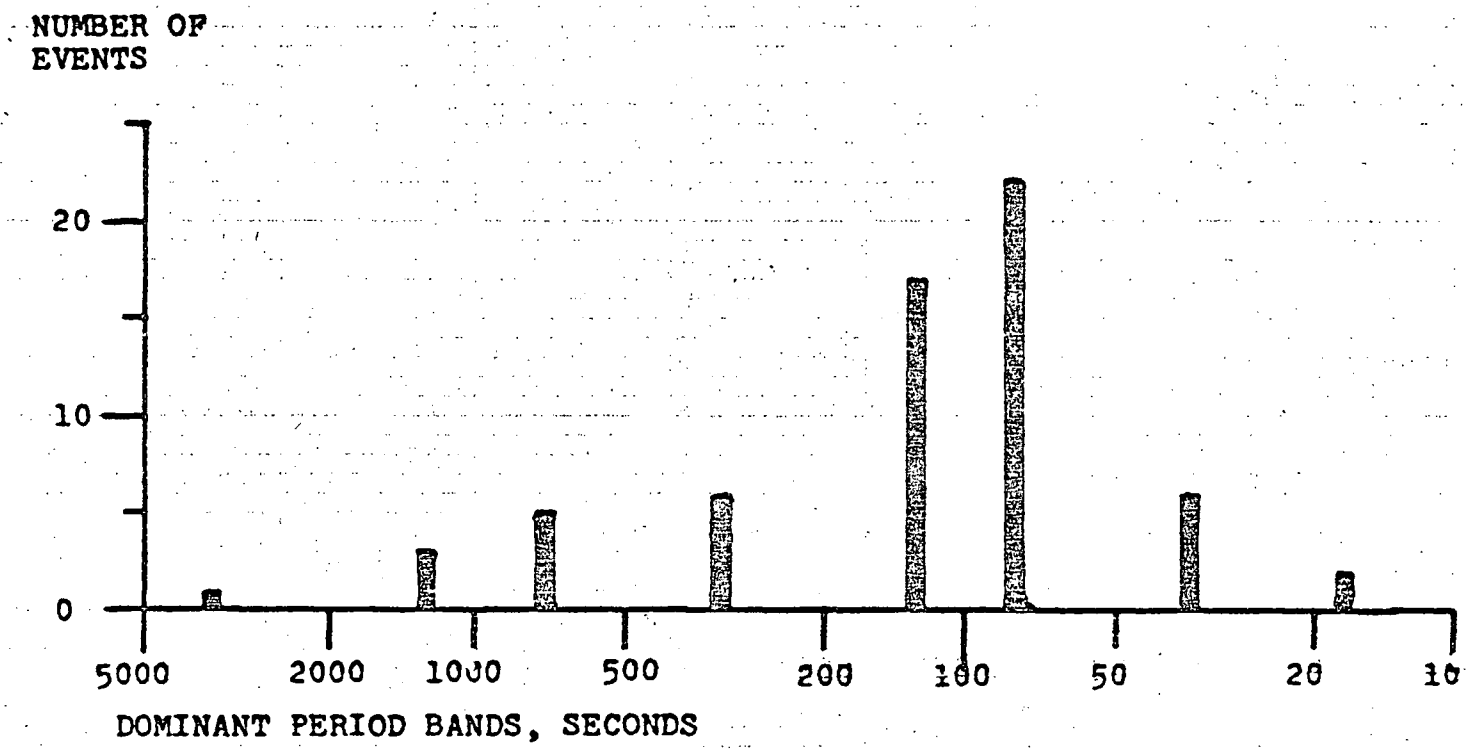


Fig. 3.5.18. Distribution of dominant periods of events occurring at F region SUNSET, and in the two hours preceding. (Ordinates represent number of events between frequencies marked on abcissa.)

several occasions phase was observed to reverse during the course of an hour.

The phase difference between the 2.7 MHz Doppler waveform and the telluric (E-W) potential record also reversed from time to time although it tended to remain stable during any given event. For 12 of nineteen events the Doppler waveform exhibited Δf increases associated with ΔH decreases, while the other seven events exhibited Δf increases associated with ΔH increases. There was no systematic dependence on period as far as the 'sense' of the shift was concerned.

The distribution of dominant pulsation periods is plotted in Fig. 3.5.18. Most events were in the 90 to 150 second period range, however a fair number with periods in excess of 300 seconds did occur.

3.6 Particular Doppler Events

Three groups of events are presented. Group A contains samples of each type of magnetic disturbance studied. Group B contains samples of various types of radio propagation conditions at the time of associated Doppler and magnetic perturbations. Group C contains examples of events studied in considerable detail in the light of the various interaction theories discussed in chapter two.

3.6A1) Pi-2/Pi-1 Event (March 20, 1966, 0630z) [Pt]

This event is shown in Fig. 3.6.1. There was no magnetic bay. (K_ℓ= 2). It is apparent that the Doppler shift induced by the (35 sec. period) Pi-1 pulsation component at 2226 LMT (0.40 Hz /γ) is relatively much greater than that associated with the Pi-2 (100 sec. period) component at 2235 LMT (0.13 Hz /γ).

The phase relationship between the micropulsations and the Doppler pulsations is constant ($\pm$ 5 seconds) and 180° out of phase; -- an increase in H corresponds to a frequency decrease. Similarly, Pi-2/Pi-1 events were the most numerous type observed; over 200 examples were recorded in the period May 1965 - April, 1966.

Ionograms taken earlier and later on the 20th of March showed no evidence of sporadic E . The echo therefore is a F region echo. [Both the 0626 and the 0645z events appear to be almost identical, on the College Alaska telluric current sonagrams. (High latitude geophysical data, University of Alaska, March (1966).) But the 0626z event was accompanied by riometer absorption while the 0645z event was not. (Also the 0645 event had an additional long period component on the telluric chart record.)]

3.6A2) Pc-3, 4 Event (February 19, 1966, 2030z)

This event is shown in Fig. 3.6.2. This was a magnetically disturbed period. (K_ℓ =4). However, the major portion

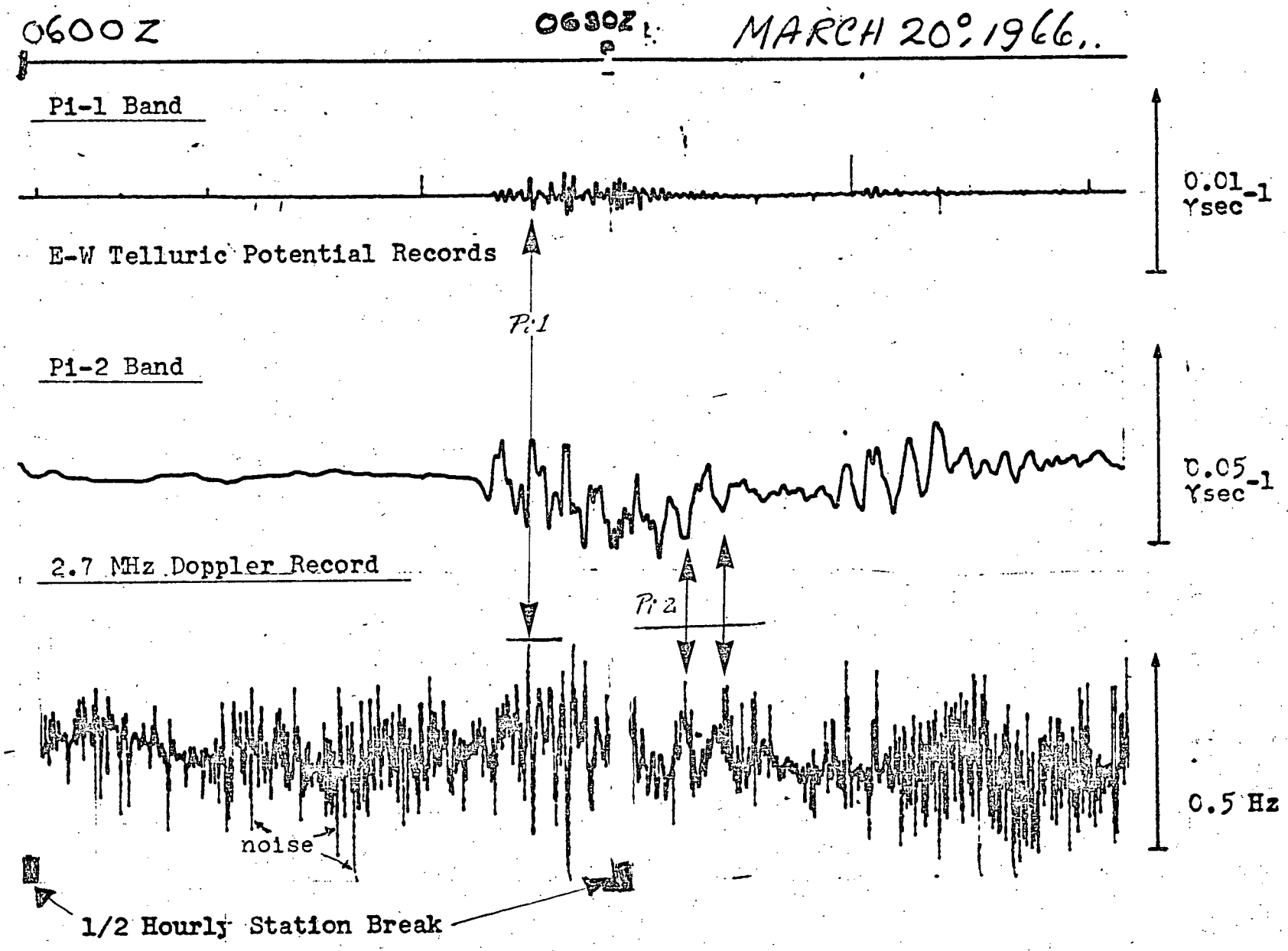


Fig. 3.6.1. Pi-2/Pi-1 Micropulsation Event and 2.7 MHz Doppler Pulsations

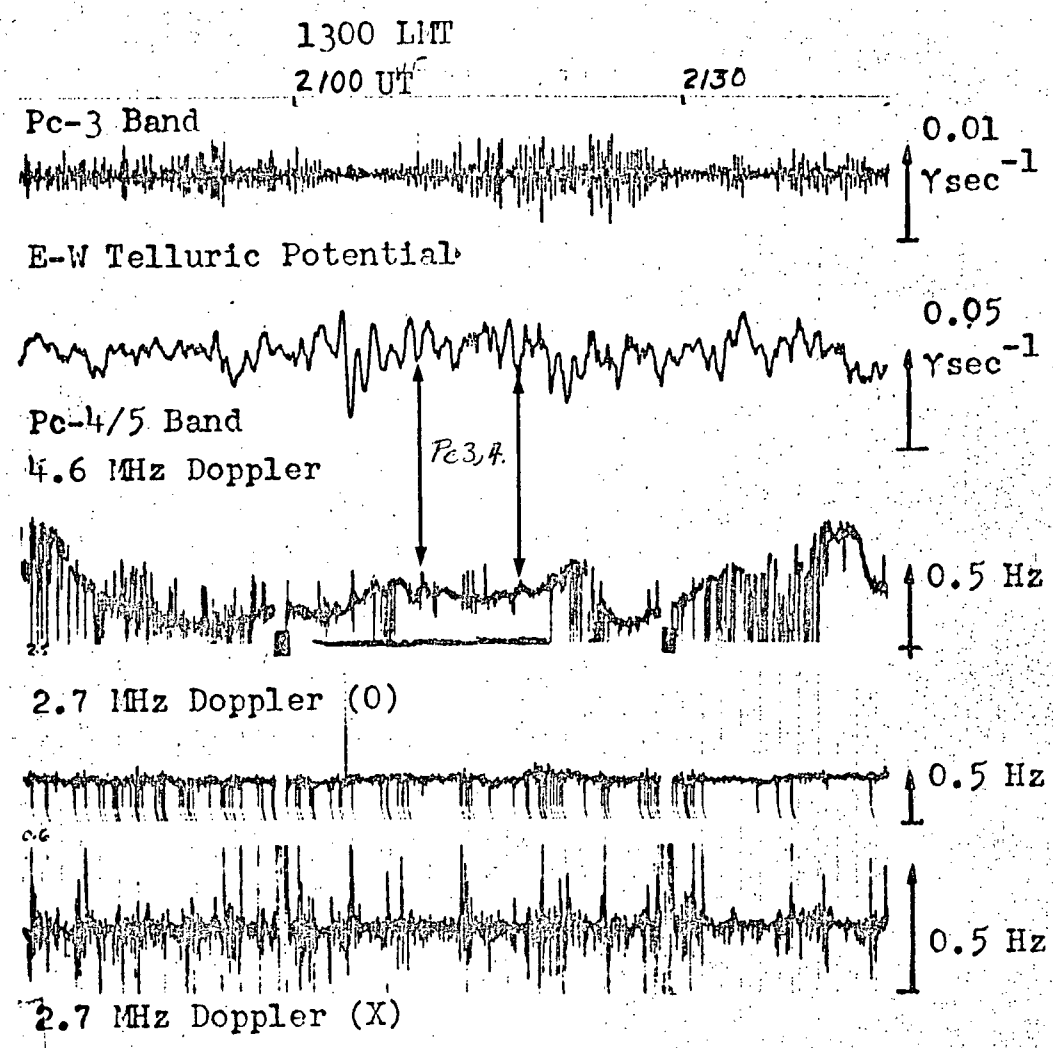


Fig. 3.6.2. Pc-3, Pc-4 Micropulsation Event and 4.6 MHz Doppler Pulsations. Note Absence of Pc-4 Pulsations on the 2.7 MHz Records.

of the storm ended at 2000z (noon), and only small bays (20 - 30 γ) occurred at the time of the pulsations. From about 2105z to 2125z (1305 - 1325 LMT) an 80 second period Pc-4 component was associated with large Doppler pulsations on 4.6 MHz ($\Delta f/\Delta H$ = 0.09 Hz /γ). Careful scrutiny of the 2.7 MHz traces did not reveal any corresponding Doppler shifts at all. At this time of day (noon) and year, 2.7 MHz is reflected from the E layer; 4.6 MHz from the F_2 layer. About 25 events similar to this occured.

3.6A3) Pc-4 Event (February 21, 1966 2330z)

See Fig. 3.6.3. This was a magnetically quiet period (K_ℓ = 2), and there were no magnetic bays persent. In contrast with the noon record (Fig. 3.6.2), this late afternoon record exhibits pulsations on 2.7 MHz as well as on 4.6 MHz in direct association with the micropulsations. (There was also a rather marked change in the smoothness of the 2.7 MHz record, which became much more active when the transition from E to F layer reflexion took place at about 2300z.) (Seattle ionograms exhibited 'S' (noisy) or 'C' (equipment failure) condition for both events, A2 and A3. However, on February 22, at 0100z (1700 LMT) the f_oF_2 was 6.5 MHz. The f_xE was 3 MHz and no E_s was present. About 20 events similar to this occured.

3.6A4) Sudden Impulse Event (April 4, 1966, 0905z)

See Fig. 3.6.4. This was a moderately disturbed afternoon. (K_ℓ =3). The magnetic impulse had a peak to peak amplitude of 1.6 gammas in the H component and 1.1 gammas intthe D component, and a quasi-period of about 100 seconds.

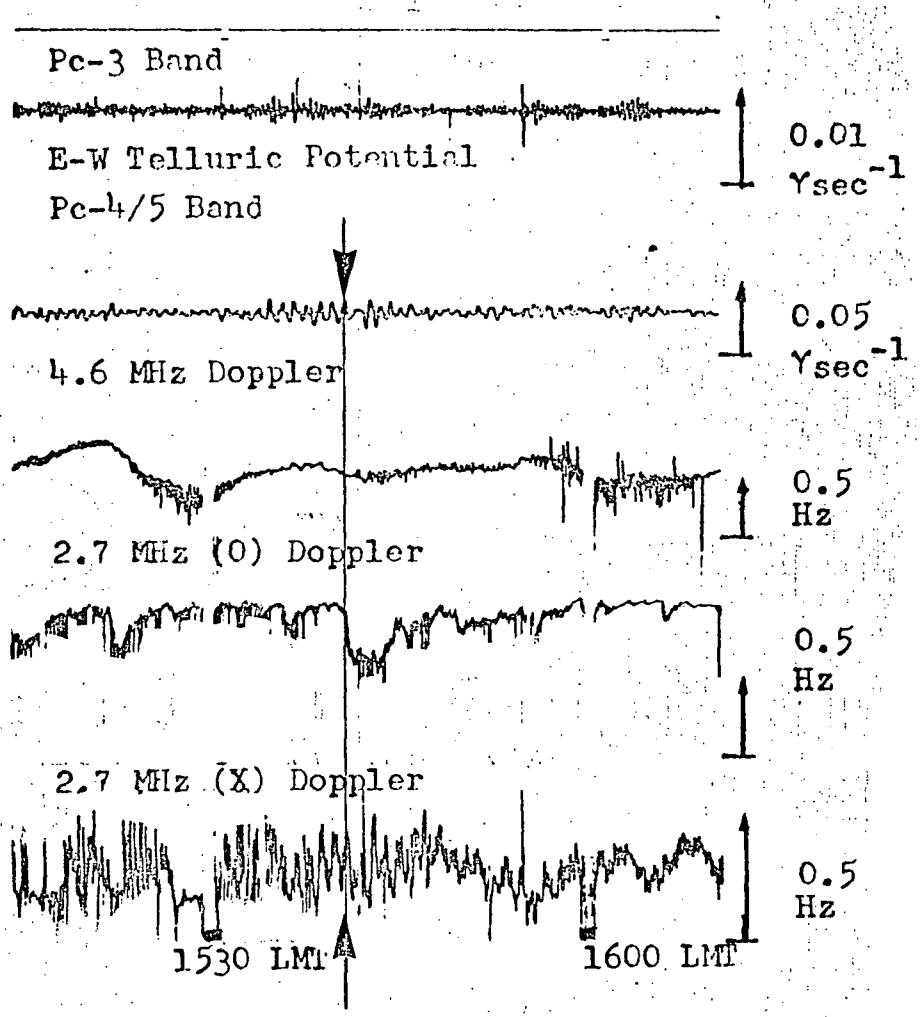


Fig. 3.6.3. Pc-4 Micropulsation Event and 2.7 and 4.6 MHz Doppler Pulsations.

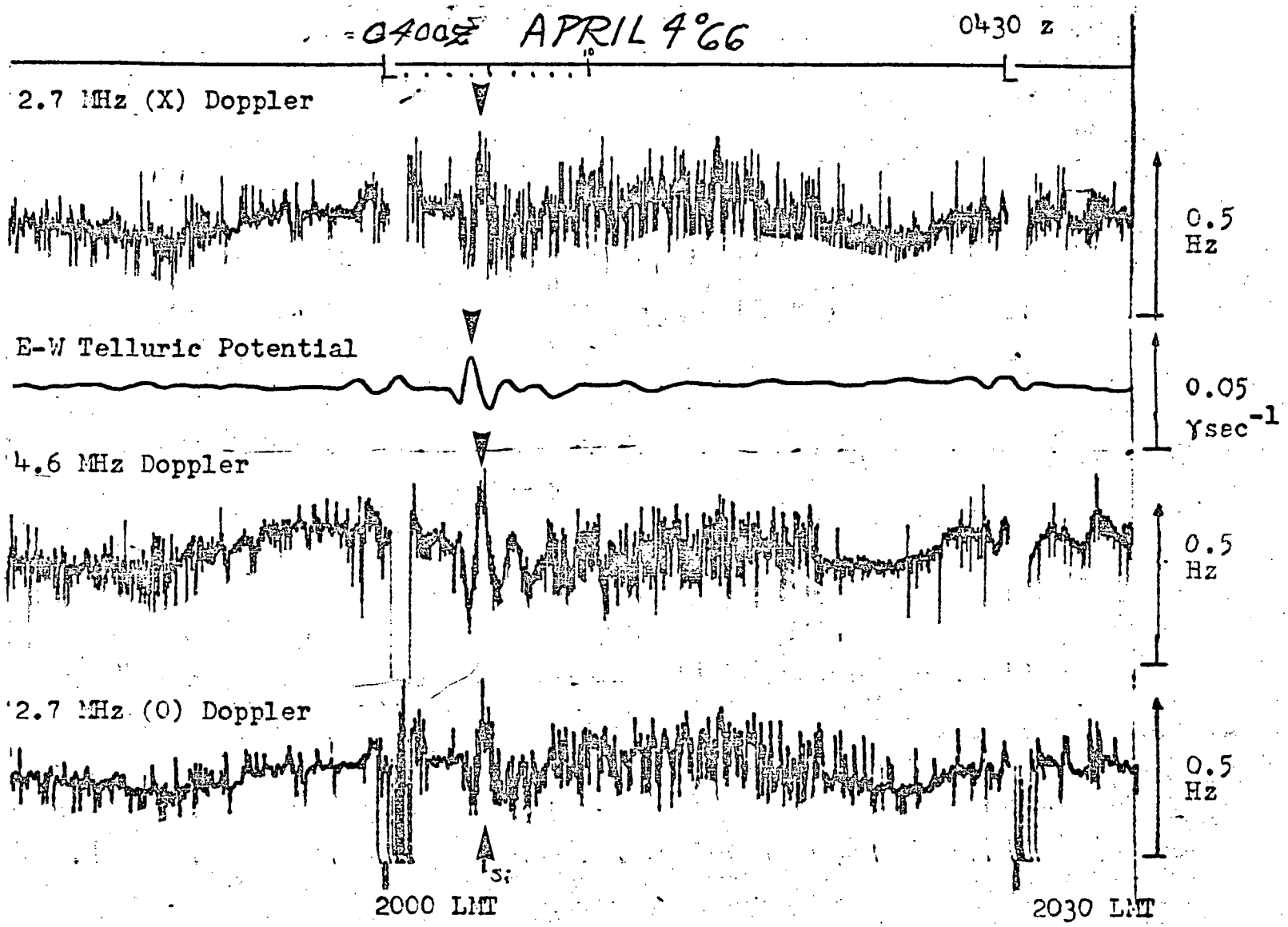


Fig. 3.6.4. Sudden impulse micropulsation event and Doppler pulsations on 2.7 and 4.6 MHz channels.

The associated 4.6 MHz Doppler shift is about 0.9 Hz p.p. ($\Delta f/\Delta H$ 0.6 Hz/γ). The 2.7 MHz ordinary mode shift is about 0.7 Hz (0.4 Hz/γ). The ratio of the 4.6 Δf to the 2.7 Δf is 1.5:1, while the ratio of frequencies is 1.7:1, so that Δf varies approximately as f.

The three (4.6 MHz and 2.7 MHz O and X) Doppler channels are perturbed, in phase with each other, and simultaneously (± 5 seconds). They all lag the E-W telluric potential channel by about 20 seconds. An H component decrease corresponds to a frequency increase. (The Westham X_B component fitted the 4.6 MHz pulseform best.) There were about 10 similar sudden impulse events recorded.

3.6A5 Sudden Commencement Event (July 6, 1965, 0951z)

See Fig. 3.6.5. This evening (0151 LMT) sudden commencement was followed by a large storm $K_\ell = 5$, $K_p = 5$.

The SC impulse was about 5γ p.p. in H and 6γ p.p. in D and of about 200 seconds quasi-period. The Doppler frequency shift on 2.7 MHz was out of phase with the H component change, (H increase → Δf decrease) but simultaneous within 5 seconds and of amplitude 0.6 Hz ($\Delta f / \Delta H$ = 0.12 Hz/γ). About 15 similar sudden commencement associations were recorded.

3.6A6 Isolated Bay Events (November 6, 1965, 1230z)
(October 23, 1965, 0730z)

See Fig. 3.6.6. The bay at 4:30 A.M. (1230z) has an amplitude of 6 gammas in the H component and an associated

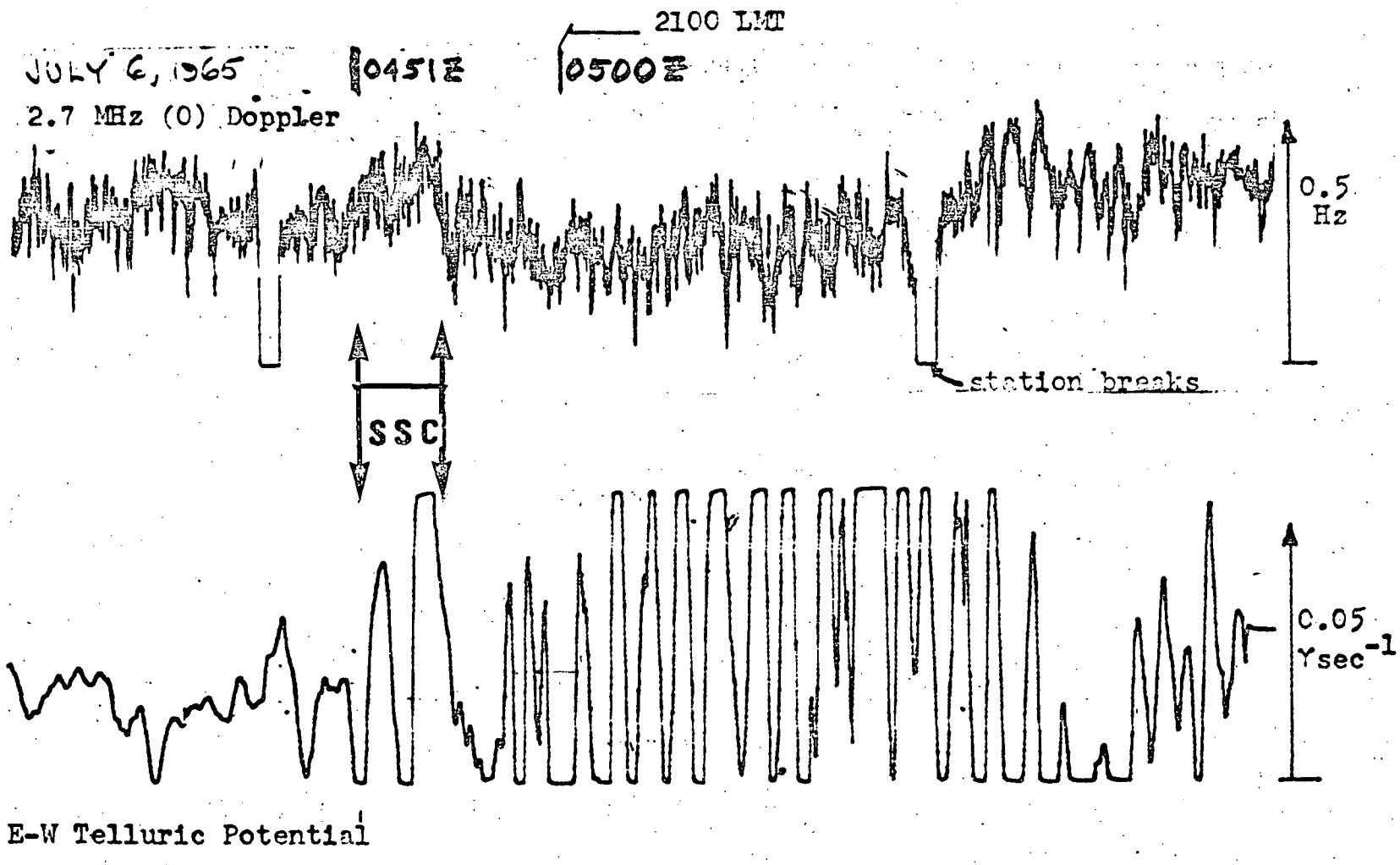


Fig. 3.6.5. Storm sudden commencement (followed by Pi-2 micropulsations) and accompanying 2.7 MHz Doppler shifts.

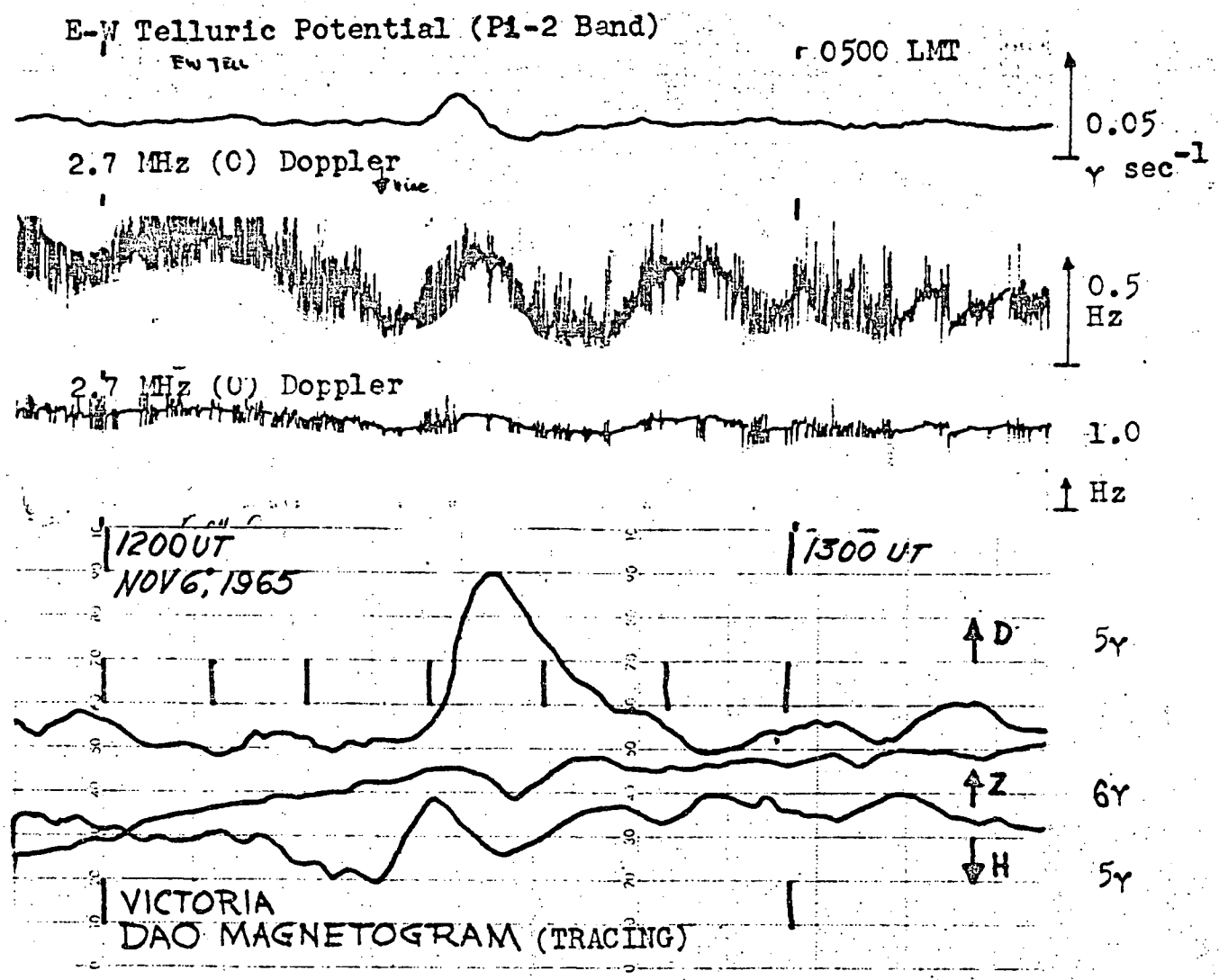


Fig. 3.6.6. Magnetic bay and telluric potential bay and 2.7 MHz Doppler bay. The closest association is between the H component and the Doppler record with the Doppler record leading by about three minutes and ΔH increasing corresponding to Δf increasing.

2.7 MHz Doppler shift of 0.25 Hz ($\Delta f/\Delta h$ = 0.09 Hz/γ). The bay's duration is about 12 minutes. H decreases correspond to Δf increase (K_ℓ = 2).

See Fig. 3.6.7. This bay just before midnight (K_ℓ = 3) involves a D component sense transition. Its amplitude increase in the H component is 13 gammas and its duration about ten minutes. The associated frequency decrease is 0.5 Hz. ($\Delta f/\Delta h$ = 0.09 Hz/γ). The Doppler bandwidth of this record is unusually great being about 0.3Hz, indicating multipath propagation with varying Doppler shifts, as well as possible rapid rates of change of Doppler shift. About ten events of this type were recorded.

3.6A7) Magnetic Storm (February 23, 1966 0800z)

See Fig. 3.6.8. The local K index was 5 during this event. Pi-1 and Pi-2 micropulsations accompany a series of bays.

The 2.7 MHz Doppler bandwidth increases from 0.1 Hz at 0730z to about 1.0Hz at 0900z. (Bandwidth increases up to as much as 10 Hz are observed to accompany magnetic storms). The 37 gamma H increase between 0759z and 0805z is associated with a Doppler frequency increase of about 1.9Hz. ($\Delta f/\Delta h$ = 0.05Hz/γ). The Doppler shift leads the E-W telluric potential variation by about 3 minutes.

The Pi-2 pulsations are associated with Doppler shifts, and the Pi-1 pulsations may be but the record is too disturbed to determine this.

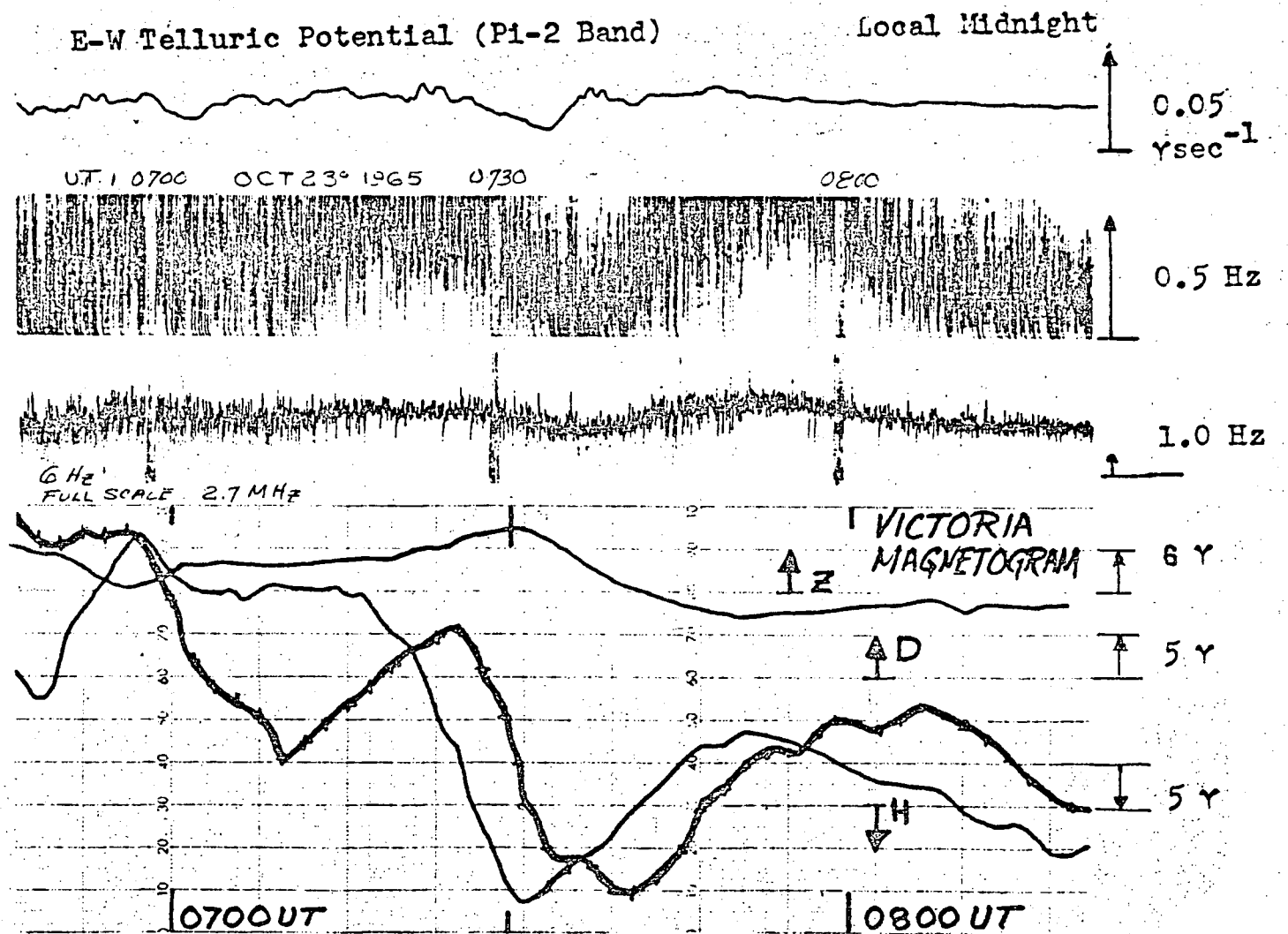


Fig. 3.6.7. Magnetic D Component 'transition' bay and 2.7 MHz Doppler shift. The H component association is best with the Doppler record leading by about 3 minutes and H increasing corresponding to f decrease.

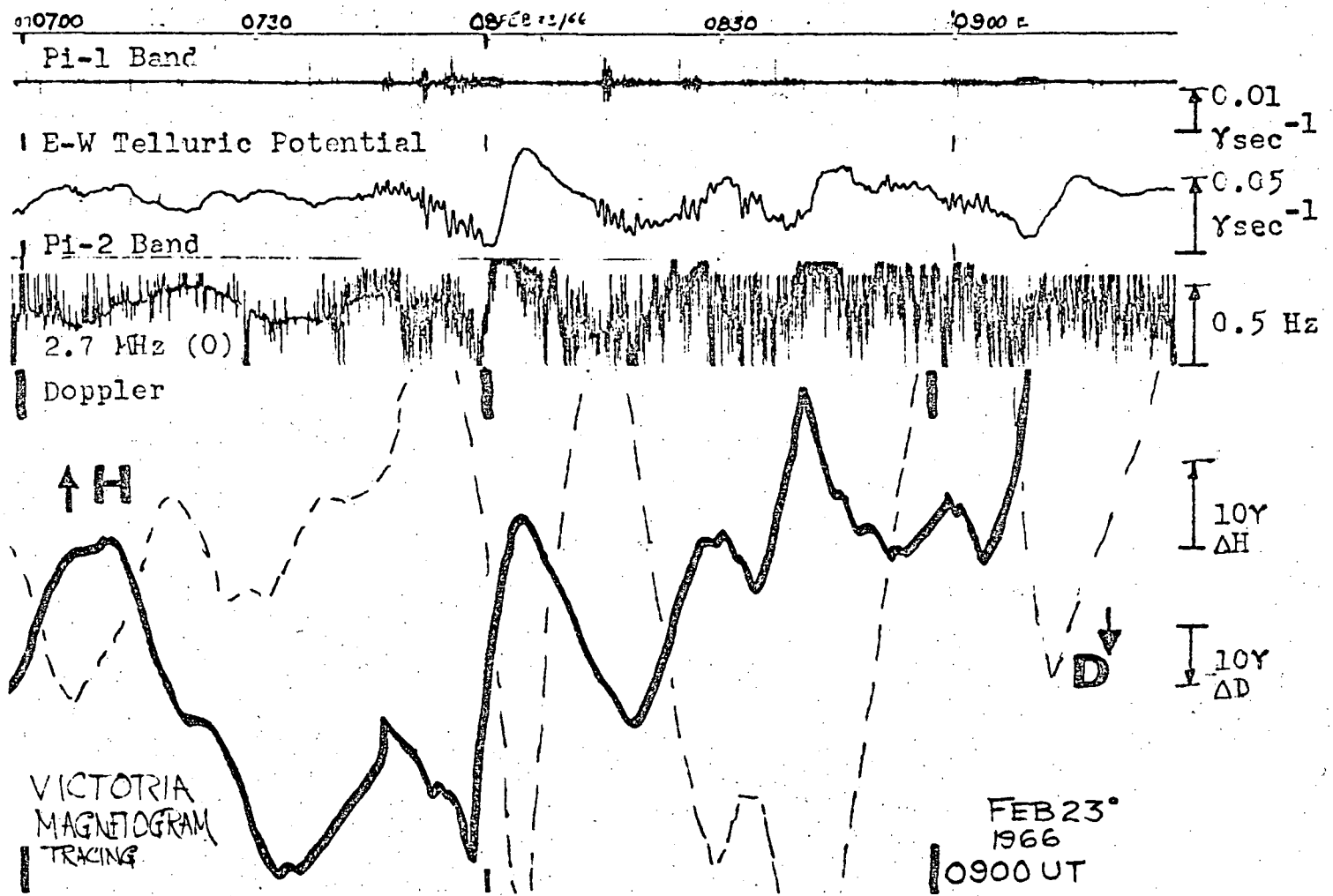


Fig.4.6.8. Magnetic storm and associated 2.7 MHz Doppler shifts and E-W telluric potential. (The z component has been omitted for clarity.) H increasing corresponds to f increasing. The Doppler record is virtually simultaneous with the H component record. (The telluric record lags by about 4 minutes.)

The Seattle ionogram at 0700z was noisy (S) but the f_xF_2 was estimated at about 5 MHz and E_s was not evident. About eleven events of this type were recorded.

3.6A8) 'Non-Magnetic' Event (March 24, 1966, 0010z)

See Fig. 3.6.9. This event occurred at a magnetically quiet period. (K_ℓ = 0) and there was no detectable activity on the micropulsation records or on the magnetograms. K at College Alaska was 1, and no telluric or cosmic noise absorption occurred.

The 2.7 and 4.6 MHz channels exhibit striking sinusoidal pulsations of 90 - 120 second period. Both E and F region motions are in phase, however their relative amplitudes vary considerably. A time displacement of about 10 seconds between the perturbations on the two frequencies corresponds to an apparent vertical velocity of about 15 km./sec.

At 1615 LMT (0015z) the ratio between the 4.6 and 2.7 MHz frequency shifts is 1.3:1 which is rather less than the frequency ratio 1.7:1, indicating the relatively greater importance of ionisation motion in the E region. The Doppler velocities are in the neighbourhood of 10 - 12 m/sec.

Another good example (Fig. 3.6.10) was recorded on January 6, 1966, at 1900 - 2300z. (Two or three other somewhat noisier and shorter-lived events of similar character were also recorded.) Again the dominant period is 90 - 120 seconds. The telluric potential record shows no associated

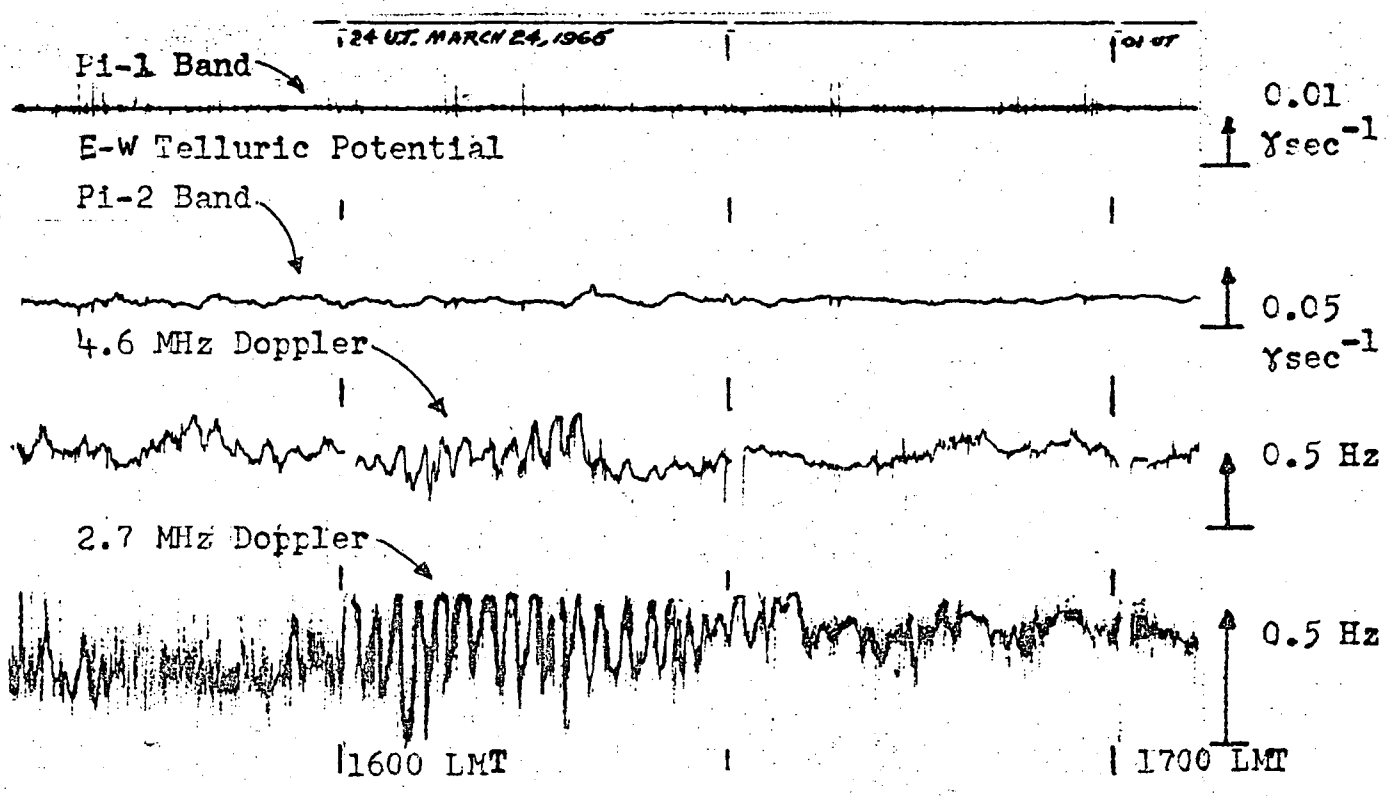


Fig. 3.6.9. 2.7 and 4.6 MHz Doppler pulsations of about 90 sec. period unaccompanied by telluric potential or magnetic pulsations.

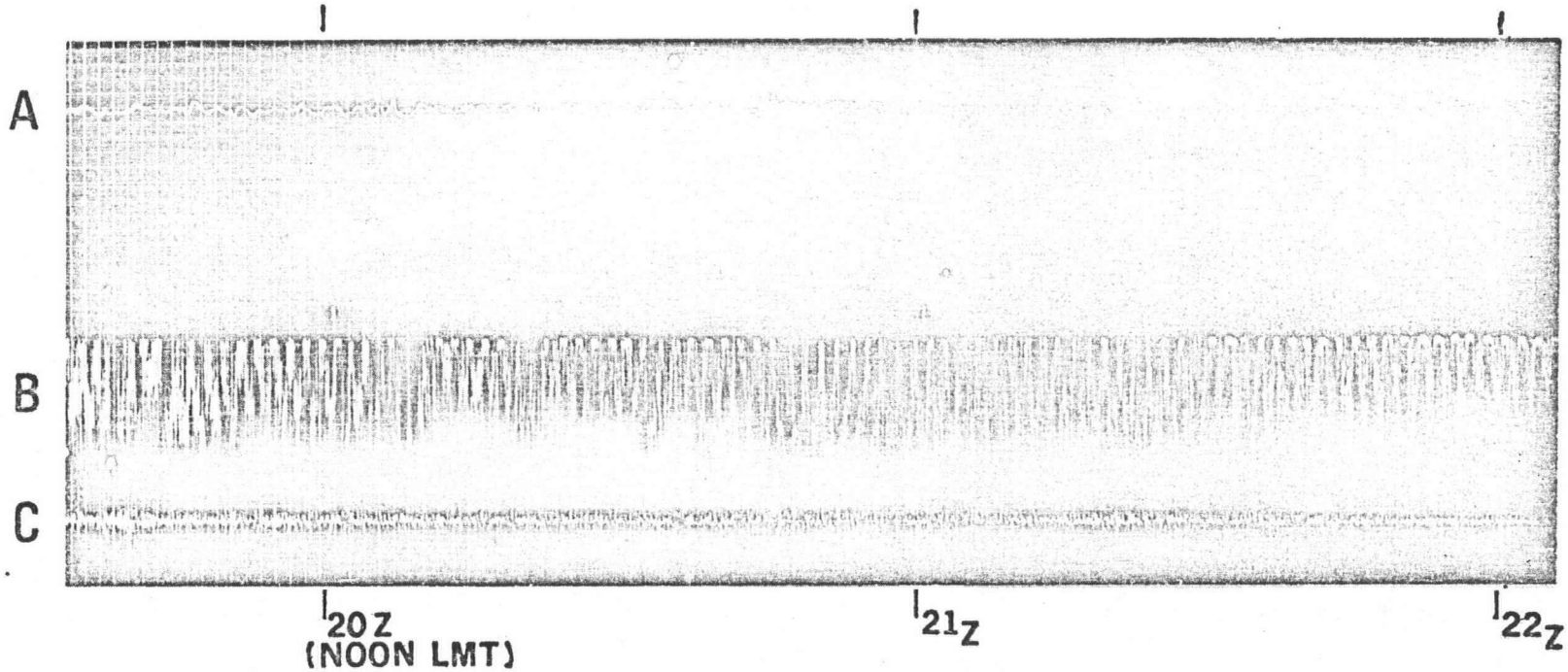


Fig. 3.6.10. Ionospheric pulsation event January 6, 1966. 'A' is the low band telluric potential channel, 0.07 γ sec^{-1} full scale. 'B' is the 2.7 MHz Doppler channel 0.6 Hz full scale exhibiting large 90 second period pulsations. 'C' is the high band telluric channel 0.005 γ sec^{-1} full scale. The telluric records show their normal background noise. The Victoria magnetograms were quiet at this time.

activity. The regular magnetograms show no bays, or other disturbance ($K_\ell = 0$). The College Alaska K_ℓ index was also 0 and again no telluric or riometer pulsations were observed there.

3.6A9) Low-Frequency Wave Event (March 10, 1966, 0300z)

See Fig. 3.6.11. This was also a magnetically quiet period ($K_\ell = 2$). Some Pi-2 pulsations occurred at about 0345z and show up on the Doppler records but there were no magnetic variations or bays in the 10 - 20 minute period range.

The period of the possible 'waves' is about 6 - 12 minutes. At 0306z the VLF (18.6 KHz) phase dip corresponds to a D region motion upward with a speed of about 60 m/sec. The 2.7 MHz Doppler shift corresponds to an E region upward velocity of about 20 m/sec. and the 4.6 MHz Doppler shift corresponds to an F region velocity of about 40 m/sec. upward. At this time the entire ionosphere appears to be moving in phase. (Again at 0332 the corresponding velocities were : D region 45 m/sec. up; E region 30 m/sec. up; F region 50 m/sec. up.) About five exactly similar events were recorded. But, waves of about this period were commonplace on the daytime 4.6 MHz (F region) records.

3.6 B1) Proximity to Critical Frequencies

Ionospheric Sunrise Event (February 23, 1966, 1500z)

See Fig. 3.6.12. This event illustrates the effect

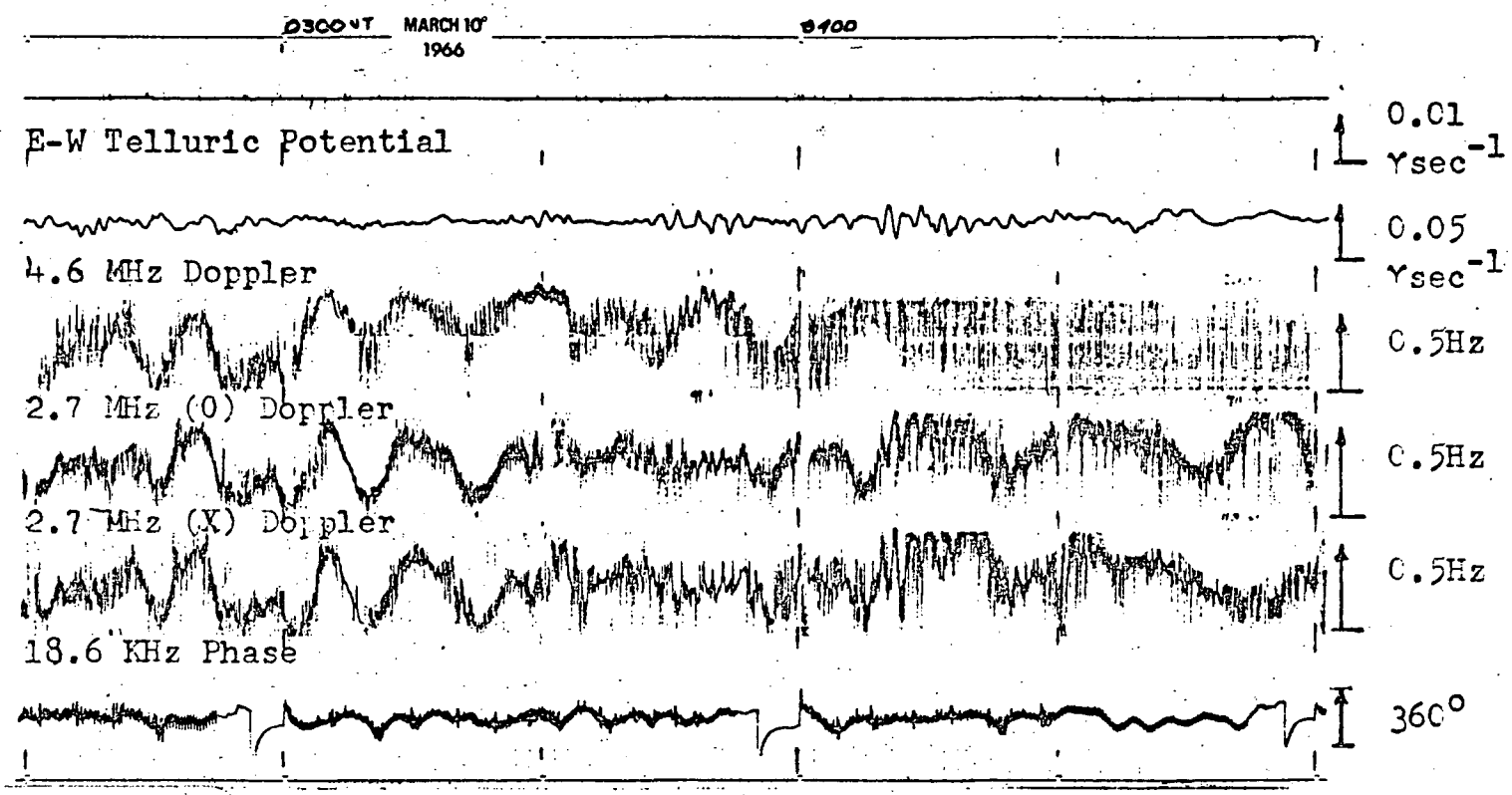


Fig. 3.6.11 Long period (10 min.) ionospheric motions observed on 18.6 KHz 2.7 MHz and 4.6MHz Doppler channels (0310z) but not on the telluric potential or magnetic records. (There are also some Pi-2 pulsations at 0345 and 0410 which appear on both the HF Doppler and the telluric records. Ionospheric sunset occurs for the 4.6 MHz record at 0410.)

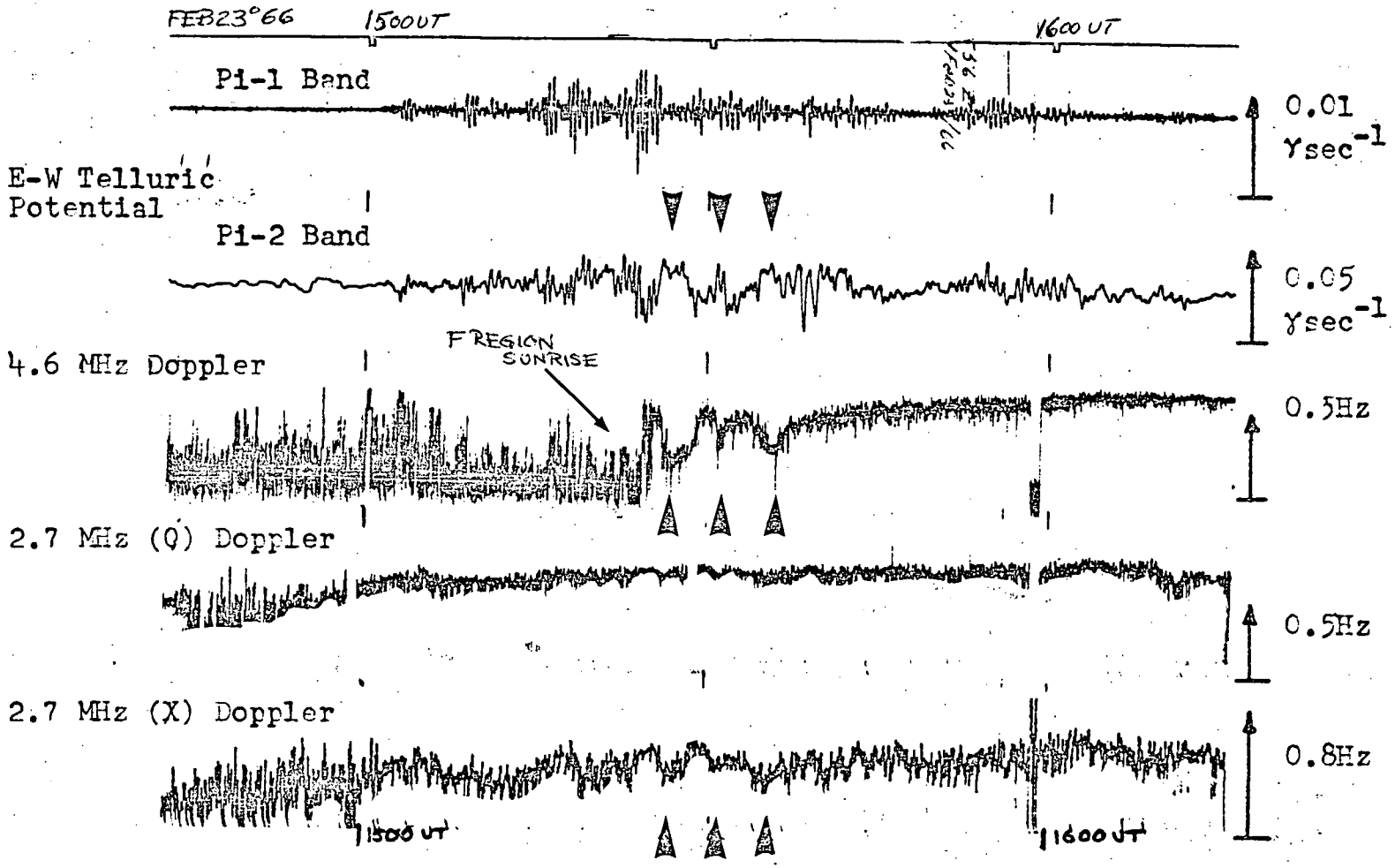


Fig. 3.6.12. Ionospheric sunrise accompanied by Pi-2/Pi-1 micropulsations and associated 2.7 and 4.6MHz Doppler shifts.

of the proximity of Doppler sounding frequencies to ionospheric critical frequencies. (1500z = 0700 LMT.)

The 2.7 MHz O polarisation wave was only intermittently received during the night although a good signal occurred on the X channel. It is probable that the f_oF_2 but not the f_xF_2 dropped below 2.7 MHz, and the resumption of signal at 1450z indicates the f_oF_2 has exceeded 2.7 MHz. Then, at 1523z, the f_xF_2 exceeded 4.6 MHz and the 4.6 MHz channel came in.

Fortunately there occurred a Pi-1 with Pi-2 micropulsation event just at this time. The Pi-2 pulsations of about 4 minutes period are clearly seen to be associated with Doppler shifts on all three HF channels. Despite the great amplitude of the Pi-1 pulsations they do not seem to be accompanied by comparable Doppler shifts. At 1526z, a ΔH increase of 5γ corresponds to a 4.6 MHz Δf decrease of 1.2 Hz, ($\Delta f/\Delta H$ = 0.2 Hz/γ). The O polarisation 2.7 MHz frequency decrease was roughly about 0.6 Hz. ($\Delta f/\Delta H$) = 0.12 Hz/γ).

The $\Delta f/\Delta H$ ratios for the modes nearest critical frequencies are larger than average. Also the ratio between Δf 4.6 MHz and Δf 2.7 MHz X components is 4:1, which is appreciably larger than the ratios found when the critical frequencies are not near the sounding frequencies -- (the average then being about 1.8:1). (However, the ratio between the 4.6 MHz Δf and the 2.7 MHz (O) Δf is about 2:1, which

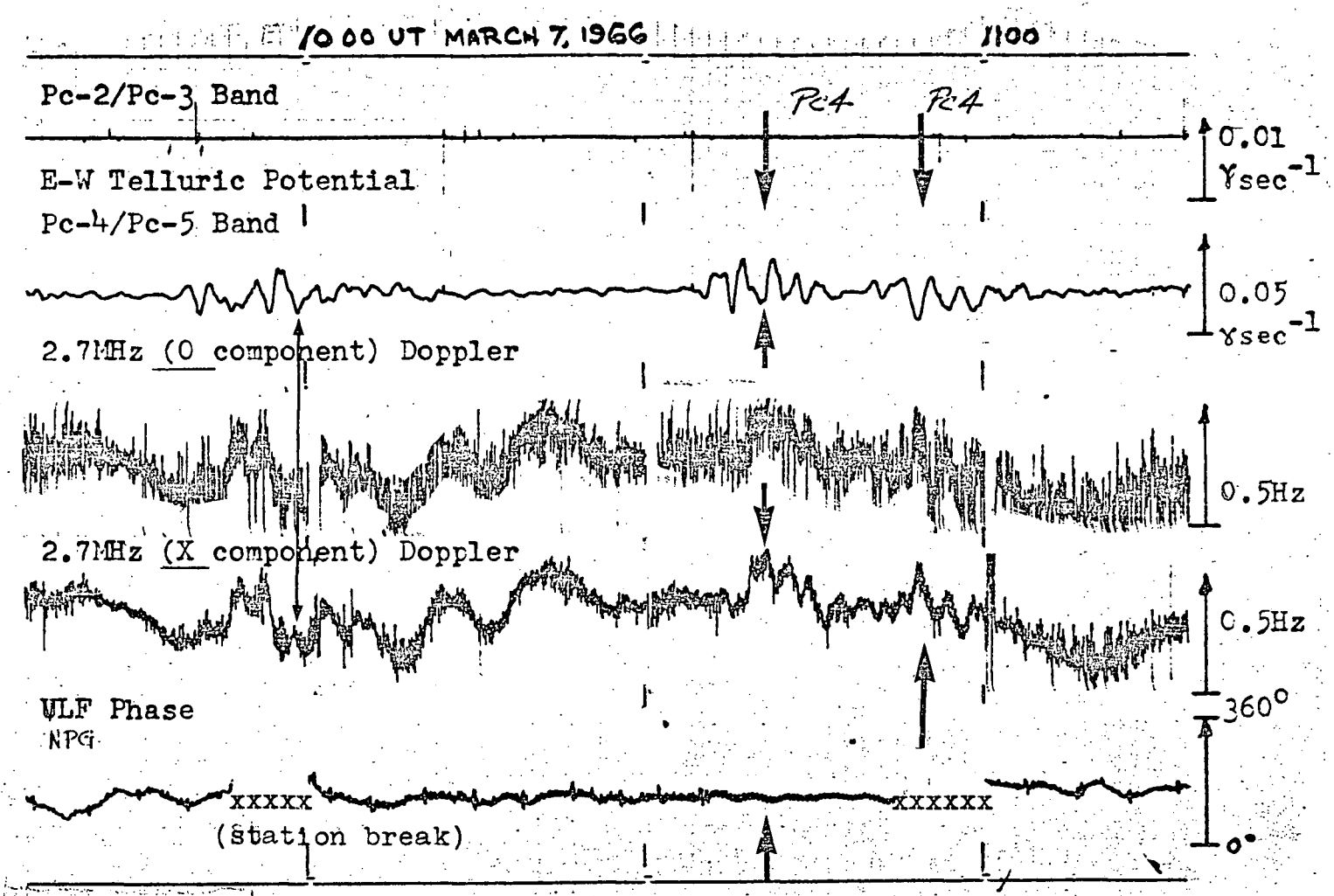


Fig.3.6.13. Comparison of Doppler shifts for O and X components associated with Pc-4 micropulsations.

is closer to the average. Interpretation is rendered difficult by the probable formation of F_1 and E layers with critical frequencies approaching 2.7 MHz.)

At night in the winter and early spring the Doppler shift on the O component on the 2.7 MHz tends to be slightly greater than on the X component as would be expected since the f_oF_2 is at a lower frequency than the f_xF_2. This effect is illustrated in Fig. 3.6. 13. (March 7, 1966, 1000z). The record was taken at 2 - 3 A.M.

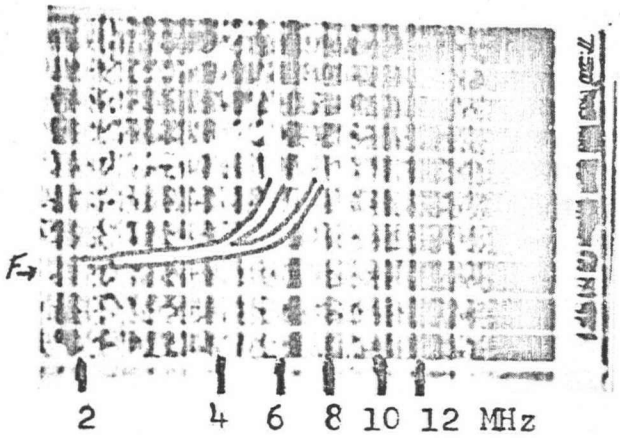
At 1050z an H decrease of 3γ occurred, accompanied by a 2.7 MHz O component frequency increase of 0.29 ($\pm$ 0.05) Hz and an X component frequency increase of 0.16 ($\pm$ 0.05) Hz.

The ratio between the O and X component shifts was 1.8:1 ; at 0954z the ratio was about 1.3:1. (Unfortunately, no ionograms were available for this date.)

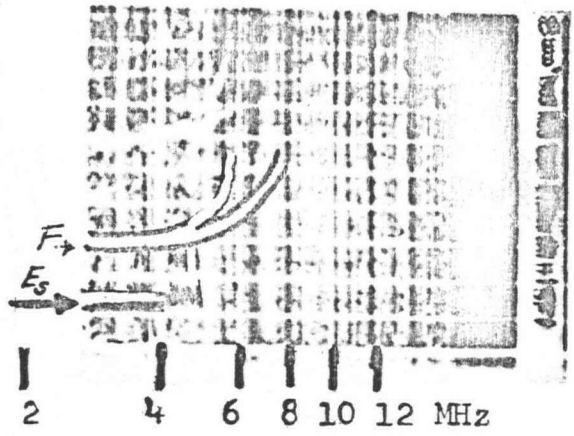
This (March 7, 1966) record also is an example of association with a Pc-4 event (no Pi-1 riders are present) (K_p = 2). The $\Delta f/\Delta H$ ratio for the X channel at 0957z is 0.07Hz/γ ($\pm$ 10 %). The Pi-2 dominant period is about 150 seconds. (The large excursions on the VLF record are due to hourly transmitter phase offset.)

3.6B2) Sporadic E Event (August 12, 1965, 0600z)

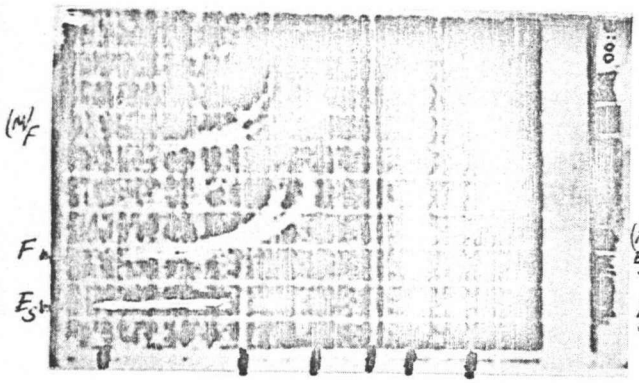
In Fig. .6.14 (a, b, c, d) four ionograms are reproduced. These were taken at Seattle at 0330z, 0400z,



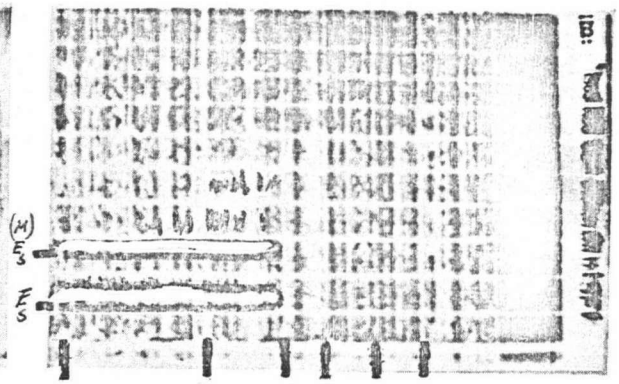
0330z No E_s



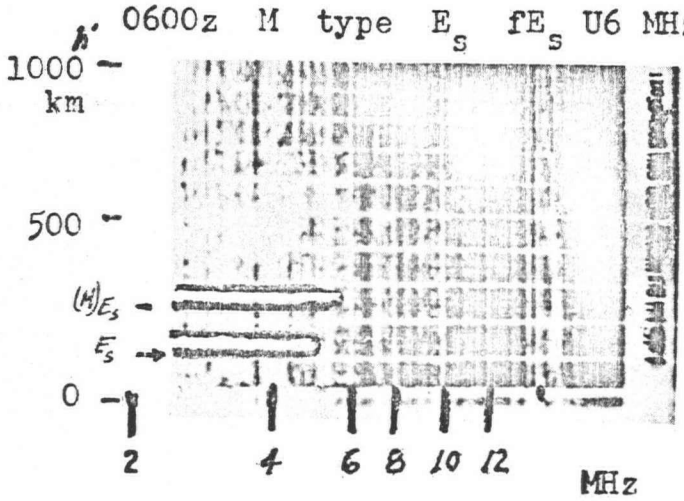
0400z fE_s 4 MHz



0500z fE_s 3.5 MHz



0600z M type E_s fE_s U6 MHz



0630z M type E_s persists

Fig. 3.6.14. Seattle ionograms showing sporadic E event, August 12, 1965.

(M) = MULTIPLE ECHOES

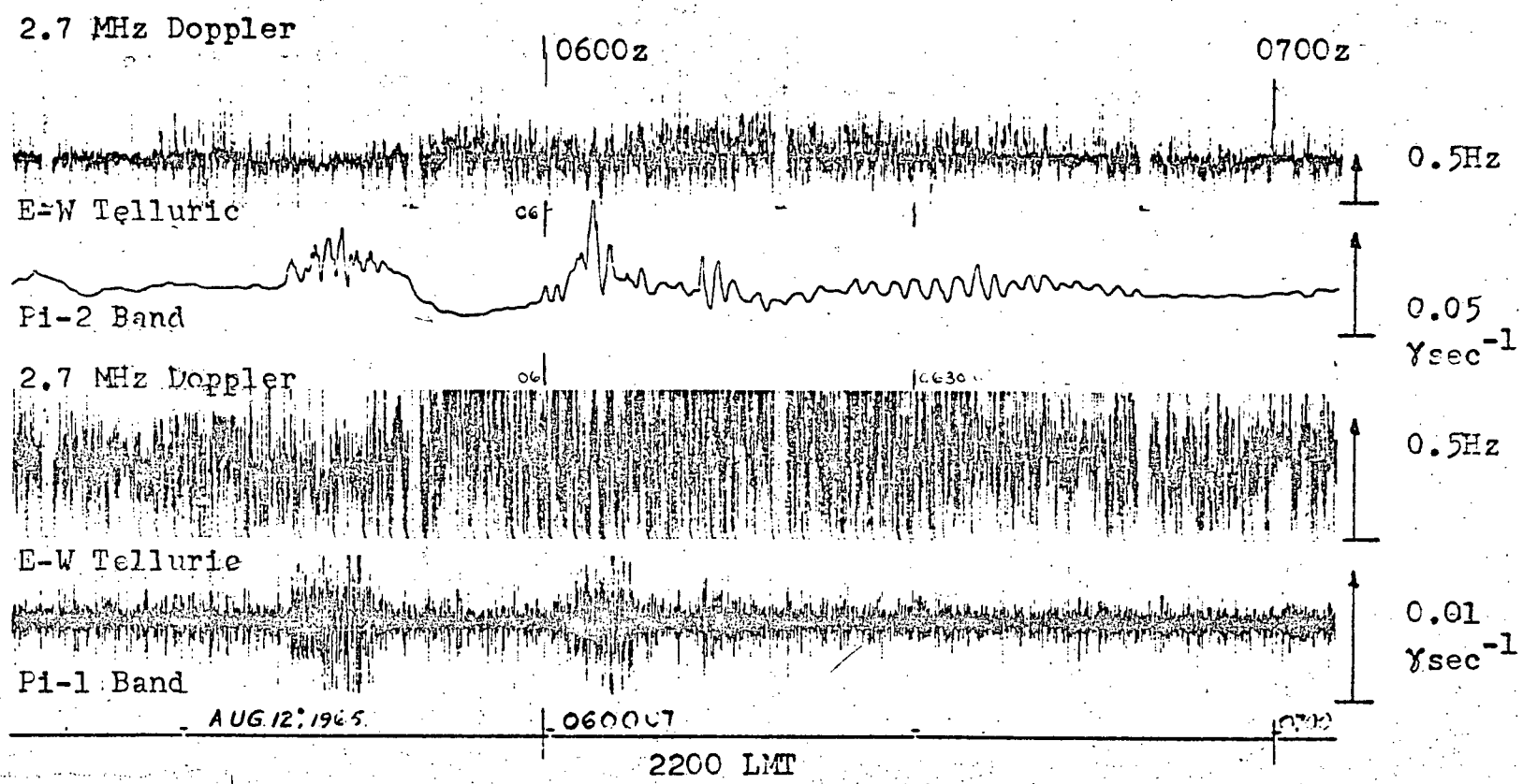


Fig. 3.6.15 Telluric potential Pi-2/Pi-1 micropulsations and 2.7 MHz Doppler pulsations when reflexion occurred at a sporadic E layer.

0600z and 0630z. They show the development of a sporadic E layer.

a) At 0330z, the F region echoes are clearly seen. The f_xF_2 is about 6 MHz and there is no Es echo.

b) At 0400z, an Es echo has begun to appear, but it does not blanket, or cut-off, the F region echoes which are still stronger than the Es echo.

c) At 0600 the Es layer is now well established, and blanketing the F region. There are multiple (M type) Es echoes, and the fEs is about 6 MHz.

d) At 0630z, the Es is still blanketing but the fEs has dropped to about 4.5 MHz.

Figure 3.6.15, illustrates the Doppler and telluric pulsation records obtained at the same time as the ionograms. During the period preceding the Es and later during the period when blanketing Es occurred, Pi-2 micropulsations also occurred. At 0540z, a ΔH impulse of 3γ p.p. and about 90 seconds period is associated with a 2.7 MHz frequency shift of about 0.6 Hz. ($\Delta f/\Delta H$ = 0.2Hz/γ). The bandwidth of the Doppler channel at this time is 0.1 Hz. Later at 0604z, when blanketing Es had developed, a Pi-2 of 3.5γ p.p. (ΔH) and about 80 seconds period occurred. This was associated with a Doppler shift of 0.8 Hz; ($\Delta f/\Delta H$ = 0.2Hz/γ). That is, of the same order as for the F region echo. However, now the Doppler bandwidth has increased to about 0.5 Hz and remains broad until the sporadic E disappears. Several other pairs of no-Es, Es events were investigated, all occurring at night,

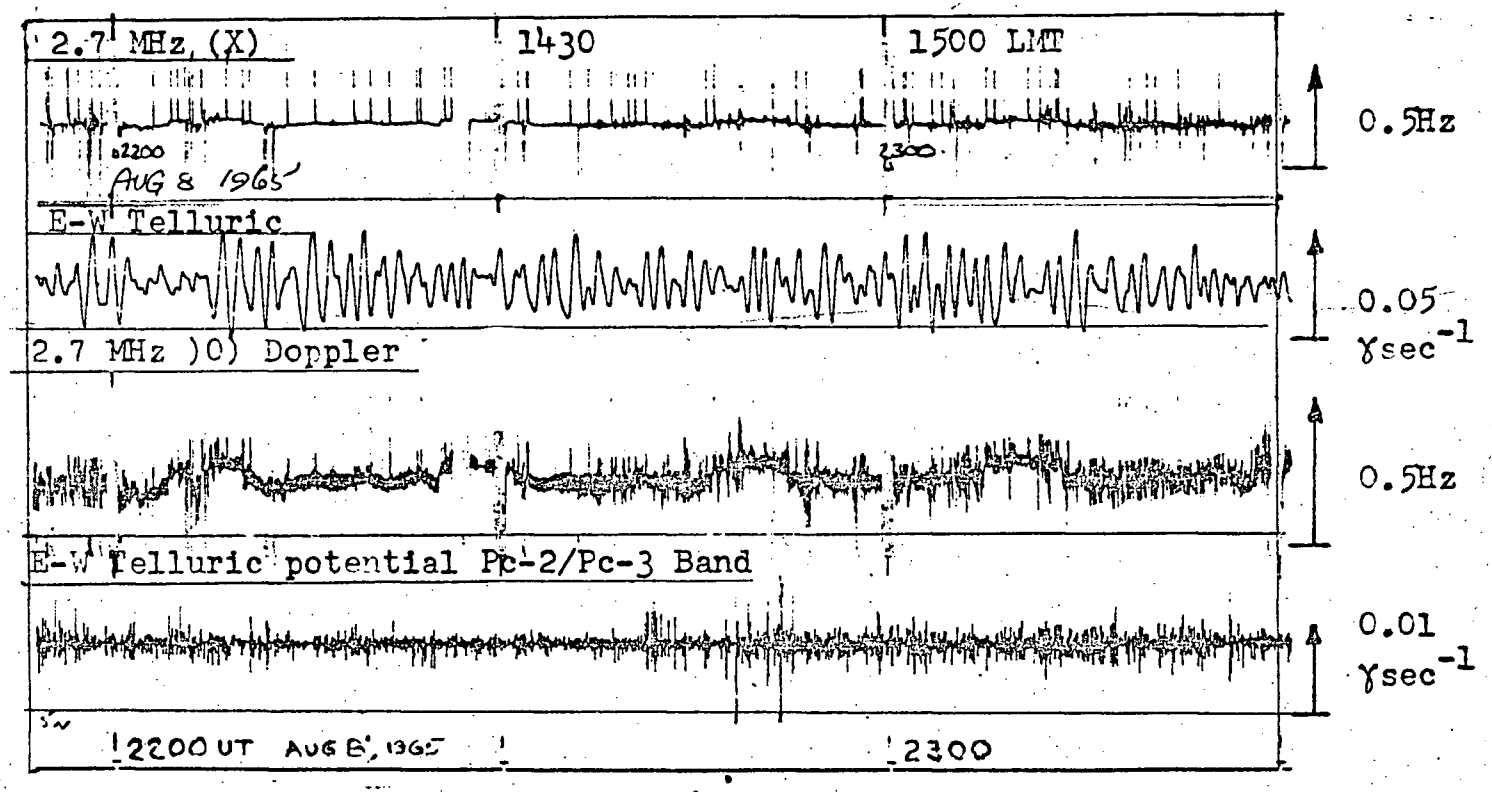


Fig. 3.6.16. Early afternoon Pc-4 micropulsation event unaccompanied by any detectable sinusoidal Doppler shifts on the 2.7 MHz channel.

and the same general result was obtained. That is : for a given periodicity of pulsation the $\Delta f/\Delta H$ ratio for F_2 layer and for E layer reflexions is about the same, but the Doppler bandwidth is considerably increased whenever E_s occurs.

The phase shift between the telluric pulsations and the Doppler shifts is not constant but no systematic change associated with F_2 vs. E_s reflexion was found.

3.6 B 3) Noon Events (August 8, 1965, 2200z)
(February 20, 1966, 2130z)

The most striking difference between daytime and night-time results is that the 2.7 MHz channel does not show pulsations associated with micropulsations near midday while the 4.6 MHz channel does. Fig. 3.6.16 illustrates an early afternoon Pc event, with peak-to-peak amplitudes of about 4 gammas, which is not associated with any 2.7 MHz Doppler shifts visible above the noise level, (which was 0.05 Hz).

Fig. 3.6.17 illustrates a Pi-1/Pi-2 event (of about 5 gammas p.p.) at 1325 LMT which was accompanied by 4.6 MHz Doppler shifts (of about 0.3 Hz). Although the 2.7 MHz record is somewhat noisy it is apparent that no comparable Doppler shifts occurred.

3.6 B4) Oblique Propagation (February 17, 1966, 0630z)

Fig. 3.6.18 illustrates a late evening (2215 LMT)

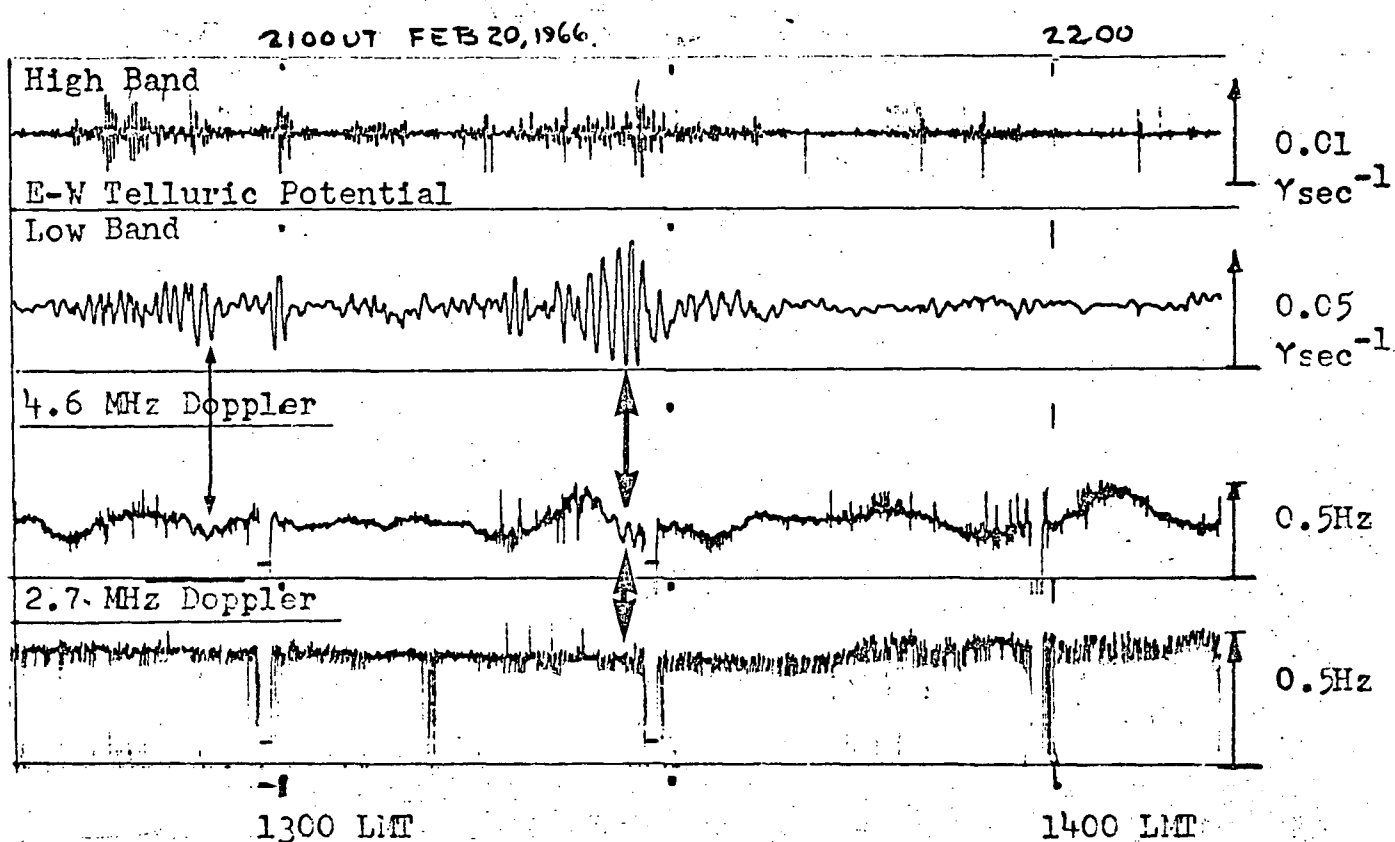


Fig. 3.6.17. Noon micropulsation event and corresponding 4.6 MHz Doppler pulsations, without Doppler pulsations on 2.7 MHz.

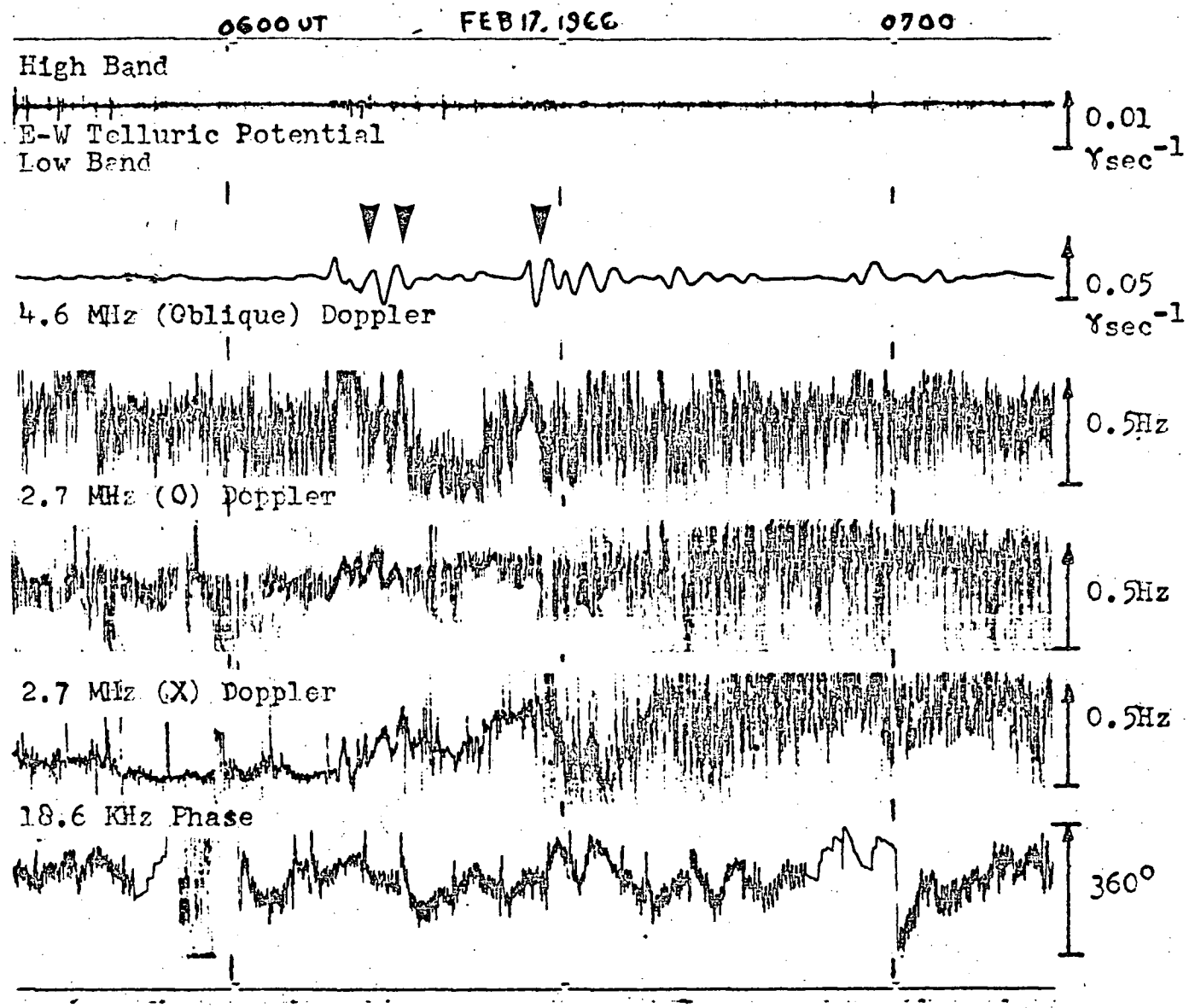


Fig. 3.6.18. Pi-2 micropulsations and Doppler pulsations on 4.6 MHz (Oblique propagation) and on the 2.7 MHz channels, and possible on the 18.6 KHz channel.

impulsive event for which a 4.6 MHz record was obtained. The received signal was not due to VE9CF as the half-hourly station breaks were not recorded, and also long period drifts typical of thermostated crystal oscilators were recorded.

Apparently a distant 4.6 MHz signal was received. A ΔH negative impulse of 2 gammas was associated with a Doppler shift of 0.15 Hz (0.07Hz/γ) on the 2.7 MHz (X) channel and with a 4.6 MHz (oblique) Doppler shift of 1.3 Hz (0.6Hz/γ) which is very large. This tends to indicate that larger Doppler effects are observed for oblique propagation. (However, the proximity of 4.6 MHz to the MUF for the path from the unknown transmitter is unknown.)

The 2.7 MHz (O) channel is rather disturbed and the pulsations only bear a rough resemblance to those on the other HF channels.

3.6C1 Phase Change or Time Displacement 2.7 vs. 4.6 MHz (February 21, 1966, 1733z)

Fig. 3.6.19 is an enlarged tracing of a morning Doppler/Pc-3 record.

From 1731 to 1733z the 4.6 and 2.7 MHz frequency shifts are in phase while from 1733 to 1737z they are 180° out of phase. This sudden phase shift corresponds to a time displacement of 20 ± 2 seconds.

With longer period pulsations occasional apparent phase reversals also occur but is difficult to decide whether or not the occasional noise burst is responsible for the

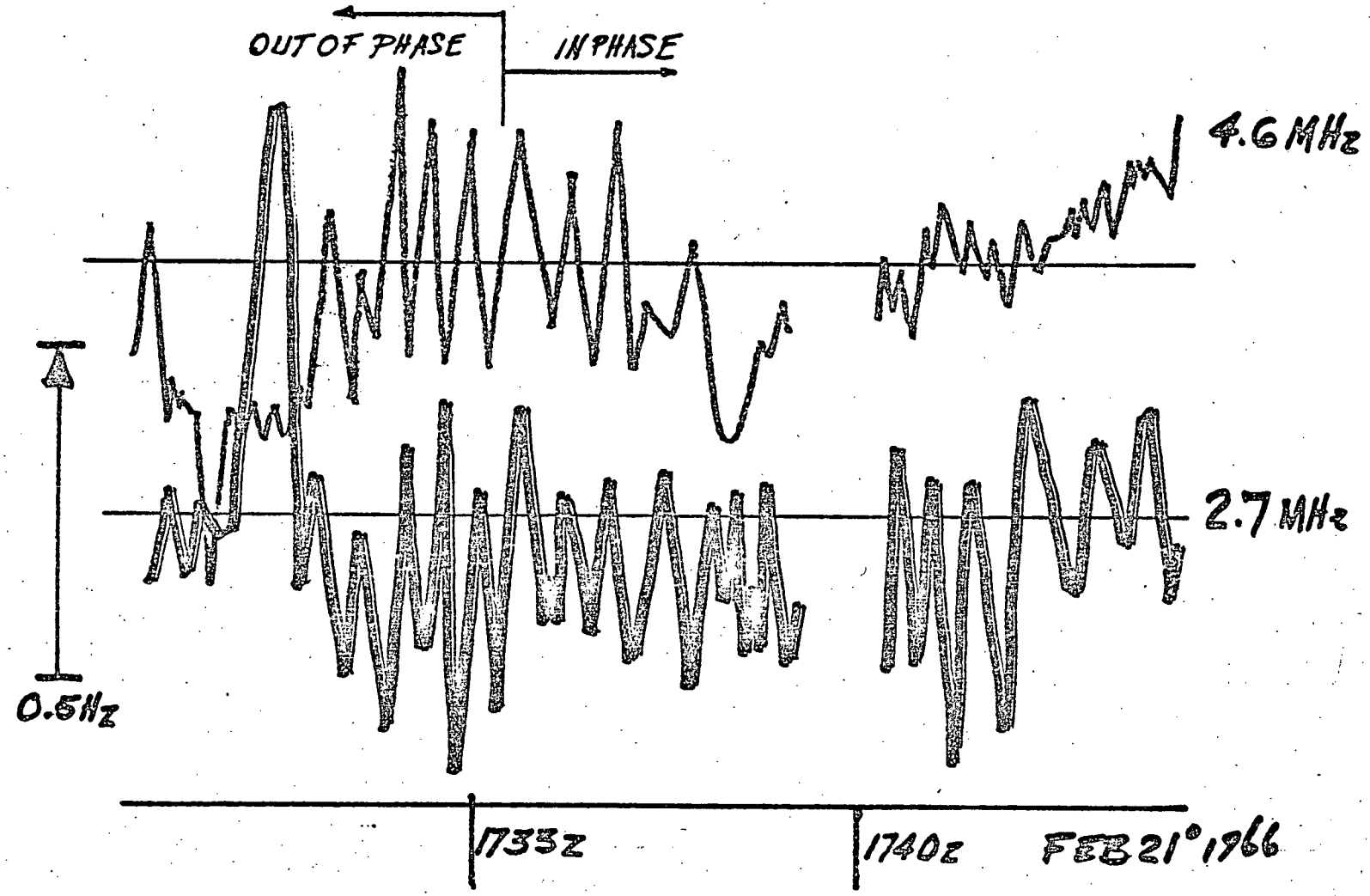


Fig. 3.6.19 Pc3 event (traced) showing transition from in-phase to out-of-phase Doppler waveforms.

temporary out of phase frequency offset, rather than electrodynamic processes or propagation delays.

3.6C2 Time Displacement or Phase Change 2.7 MHz and 18.6 KHz (September 7, 1965, 0530z)

See Fig. 3.6.20 and 3.6.21. A Pi-1/Pi-2 event occurred at 0530 - 0603z (2130 - 2200 LMT) accompanied by 2.7 MHz and 18.6 KHz phase path changes. (The 18.6 KHz signal was reflected from the E layer and phase changes of the sky wave are recorded. The Doppler velocities are equal to the time derivatives of this record consequently a one-to-one correspondence with the 2.7 MHz record would not be expected; there would be a 90° phase change even if both were reflected from a single moving mirror.)

The 2.7 MHz record is in-phase with the telluric potential record, but lags it by 15 ± 5 seconds, throughout the event. An H component increase corresponds to a frequency decrease (upward motion) throughout.

The VLF record exhibits varying phase with respect to the telluric and 2.7 MHz Doppler records; sometimes in phase, sometimes 180° out of phase, sometimes in between.

It is also of interest to note that the regular 90 second period pulsations commenced on the VLF record at about 0430z an hour before they appeared on the 2.7 MHz record and on the telluric potential record. The VLF pulsations did, however, die-out at the same time as the HF pulsations at 0603z.

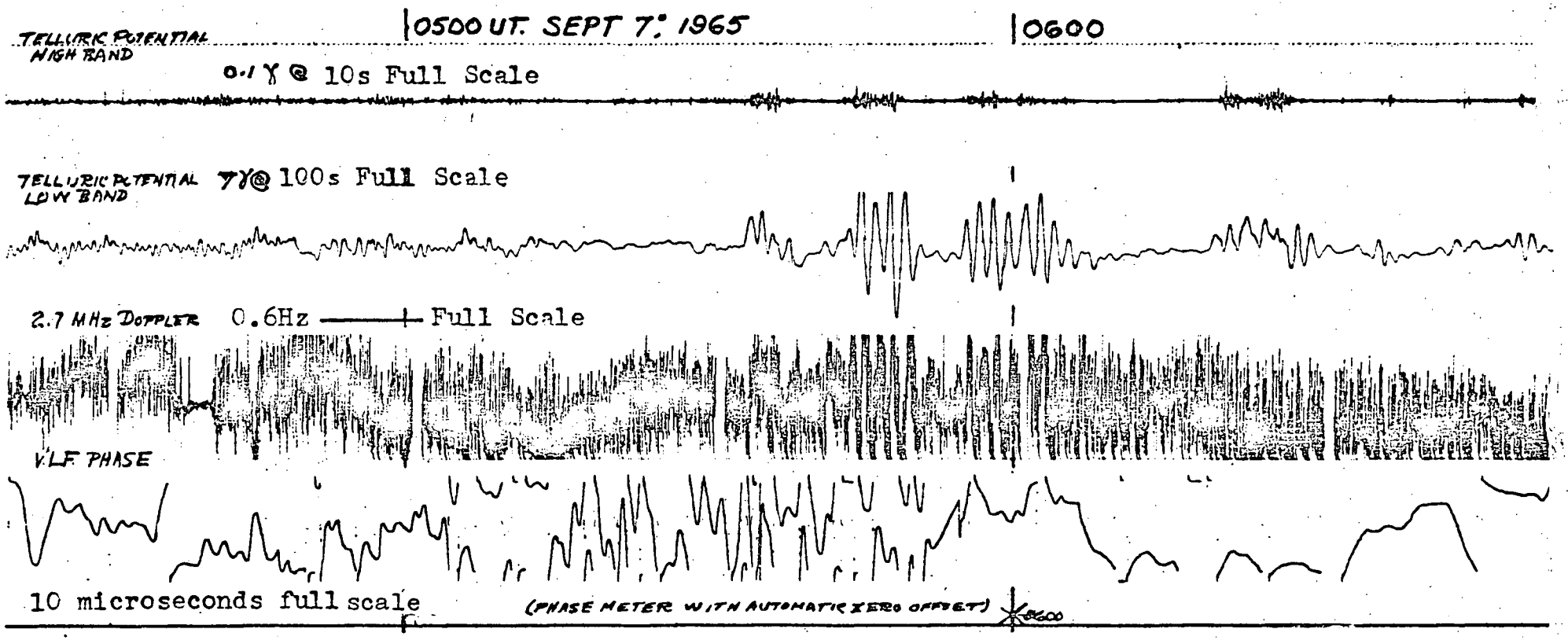


Fig. 3.6.20. 90 second period pulsations occurring on the 18.6 KHz skywave phase records and later, occurring on both the 2.7 MHz Doppler and E-W Telluric potential records.

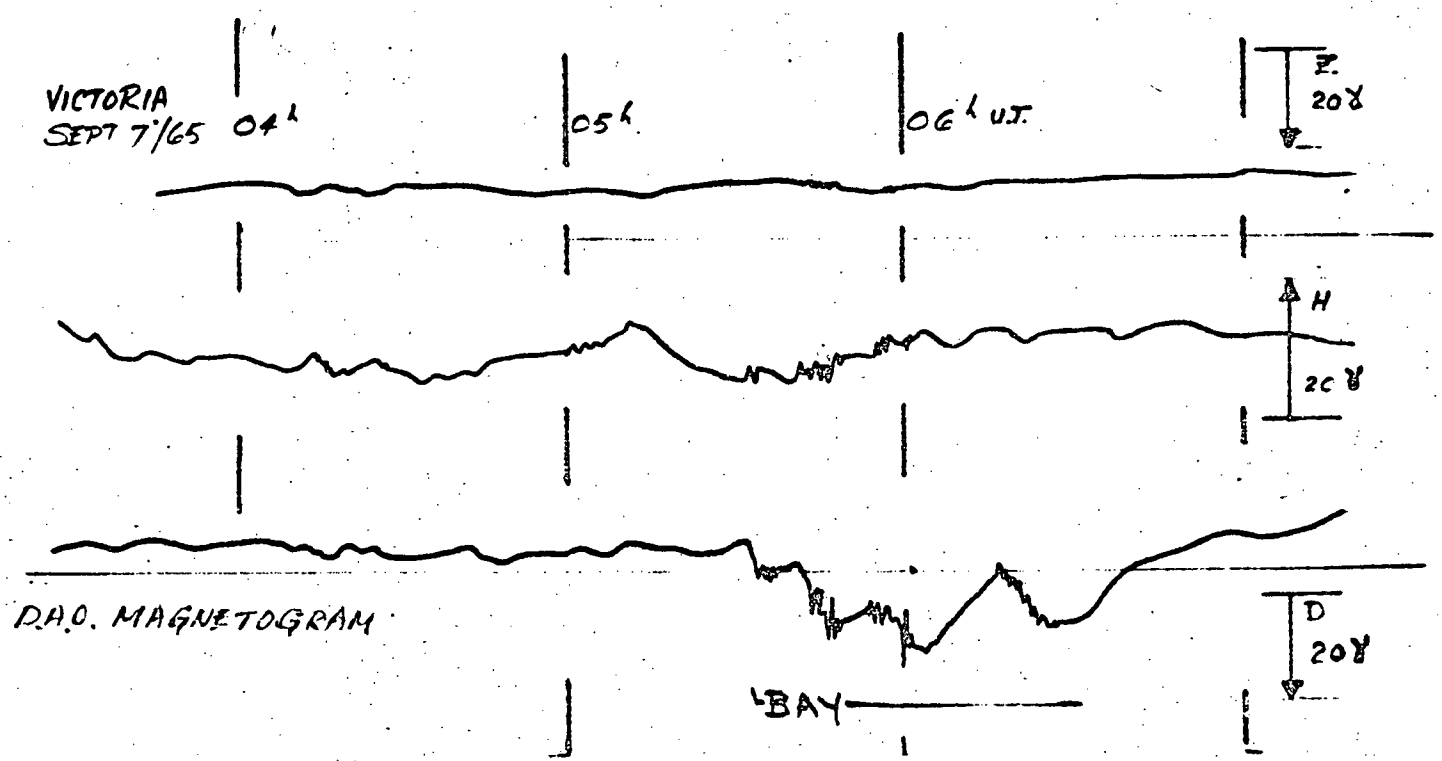


Fig. 3.6.21. Tracing of regular magnetogram for the period of the event of Fig. 4.6.20 showing micropulsations occurring in conjunction with the D component bay at 0530z and subsequently.

The occurrence of the telluric and HF pulsations was simultaneous with the onset of a positive D bay of about 15γ amplitude as may be seen in Fig. 3.6.21 (K_ℓ = 3).

The pulsations had a peak-to-peak amplitude of about 3γ in the H component. The 2.7 MHz Δf was about 0.7 Hz p.p. (Δf/ΔH = 0.2Hz/γ). This is equivalent to a vertical velocity of about 10 m/sec.

The VLF pulsations were of about 8 microseconds Δφ peak-to-peak (at 90 sec. period) which corresponds to a vertical velocity of 24 m/sec. (on the basis of simple reflexion from a moving mirror).

The phase shifts between the 18.6 KHz and the 2.7 MHz records could be interpreted as time lags, in the order of 10 - 50 seconds which might represent vertical velocities of about 2 - 10 km/sec, assuming a 100 km. separation in E and F' layer reflexion heights. (No ionograms were available for this event.)

One curious aspect of this record is that the Pt (Pi-1/Pi-2) event at 0620z is not associated with any VLF pulsations although it is associated with 2.7 MHz pulsations.

3.6.C3) Micropulsations Without Doppler Shifts

Fig. 3.6.22 illustrates a Pt micropulsation event which occurred at 1110z, March 7, 1966, and was not accompanied by any apparent associated pulsations of either the 2.7 MHz or the VLF radio channels.

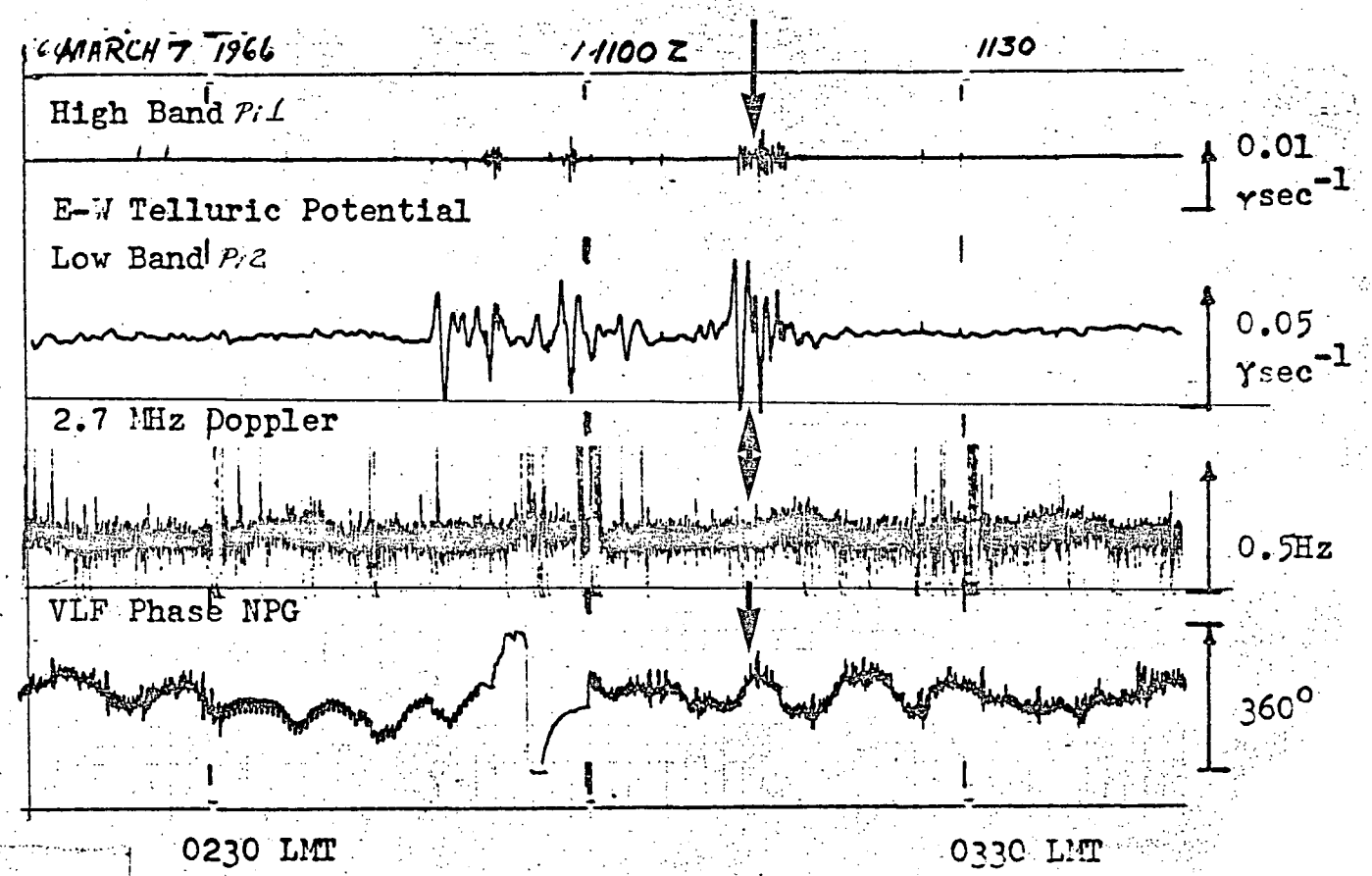


Fig. 3.6.22. Pi-2, Pi-1 Micropulsation event not accompanied by any associated Doppler pulsations, or by any apparently associated VLF phase changes.

3.7 Records Analysed by Machine Computation

Tape recorded Doppler and telluric pulsation records were filtered and digitised, and chart records were digitised using a converted plotter. The digitised records were then replotted by machine or printed out to check for errors. Then the means were removed and the records were analysed using the Pacific Naval Laboratory computer with computer programme 61-11, which follows the method of Munk et alia (1959).

The programme computes : the autocovariance for each input channel. The spectra and log spectra for each channel. The inphase, quadrature correlation coefficients, the absolute value of the correlation, coherence, and the phase angle. See appendix section 6.6, for definitions of these quantities.

Figure 3.7.1 shows a machine plot of digitised data. Two magnetic components, the D and the H were digitised together with the 2.7 MHz Doppler record. The sampling interval was 15 seconds. The total record length was 29 minutes - (0700 - 0800z, June 4, 1965). Fig. 3.7.2 is a plot of the coherence vs. pulsation period for the June 4 record. The D trace is the coherence between Doppler shift and the D component. This coherence is very low for periods longer than two hundred seconds, because the large D bay is not reflected in the Doppler record. The maxima at 130 seconds and 90 and 70 seconds periods are probably sign ificant. The H trace is the coherence between the

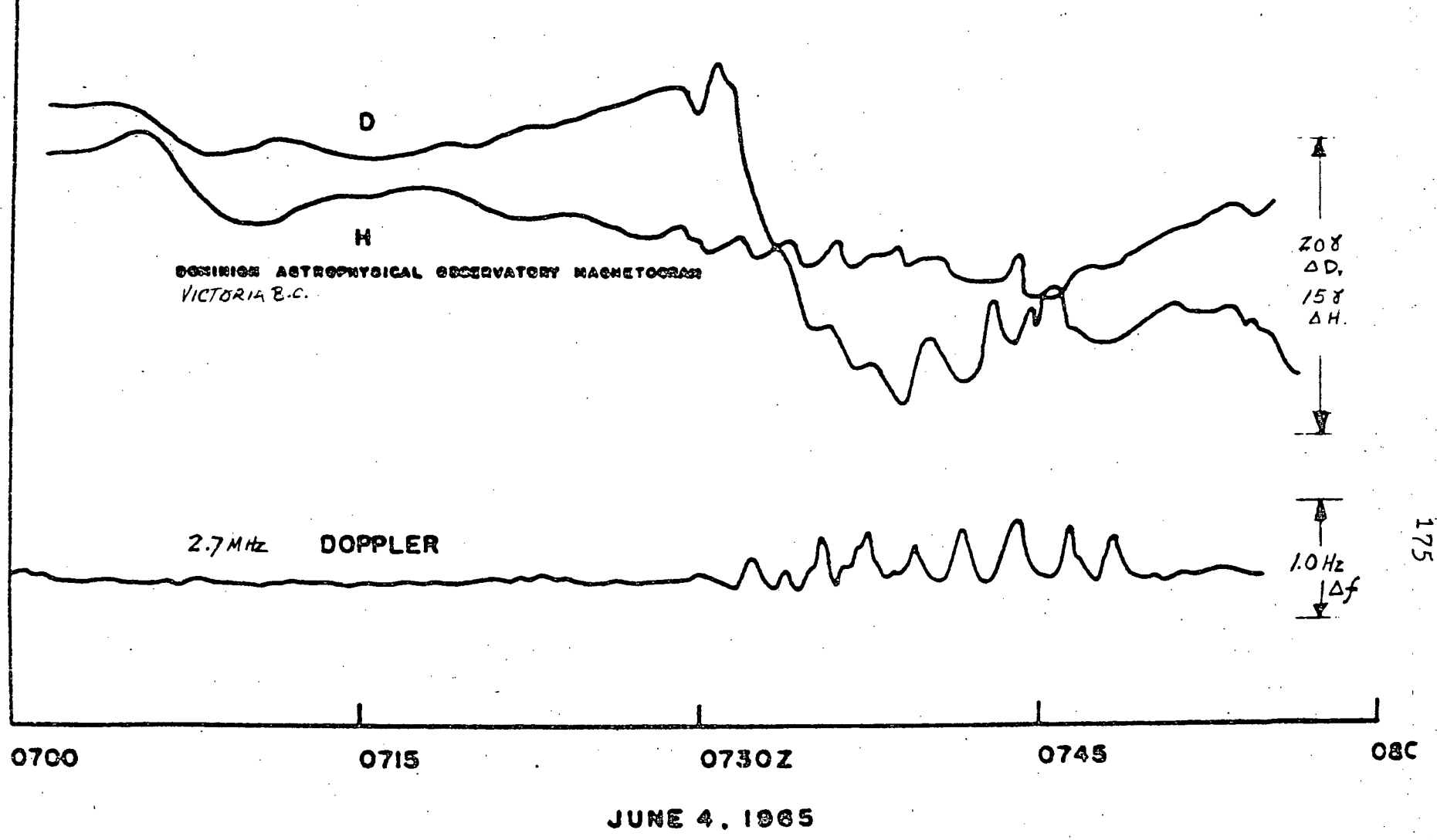


Fig. 3.7.1 Machine plot of previously digitised records.

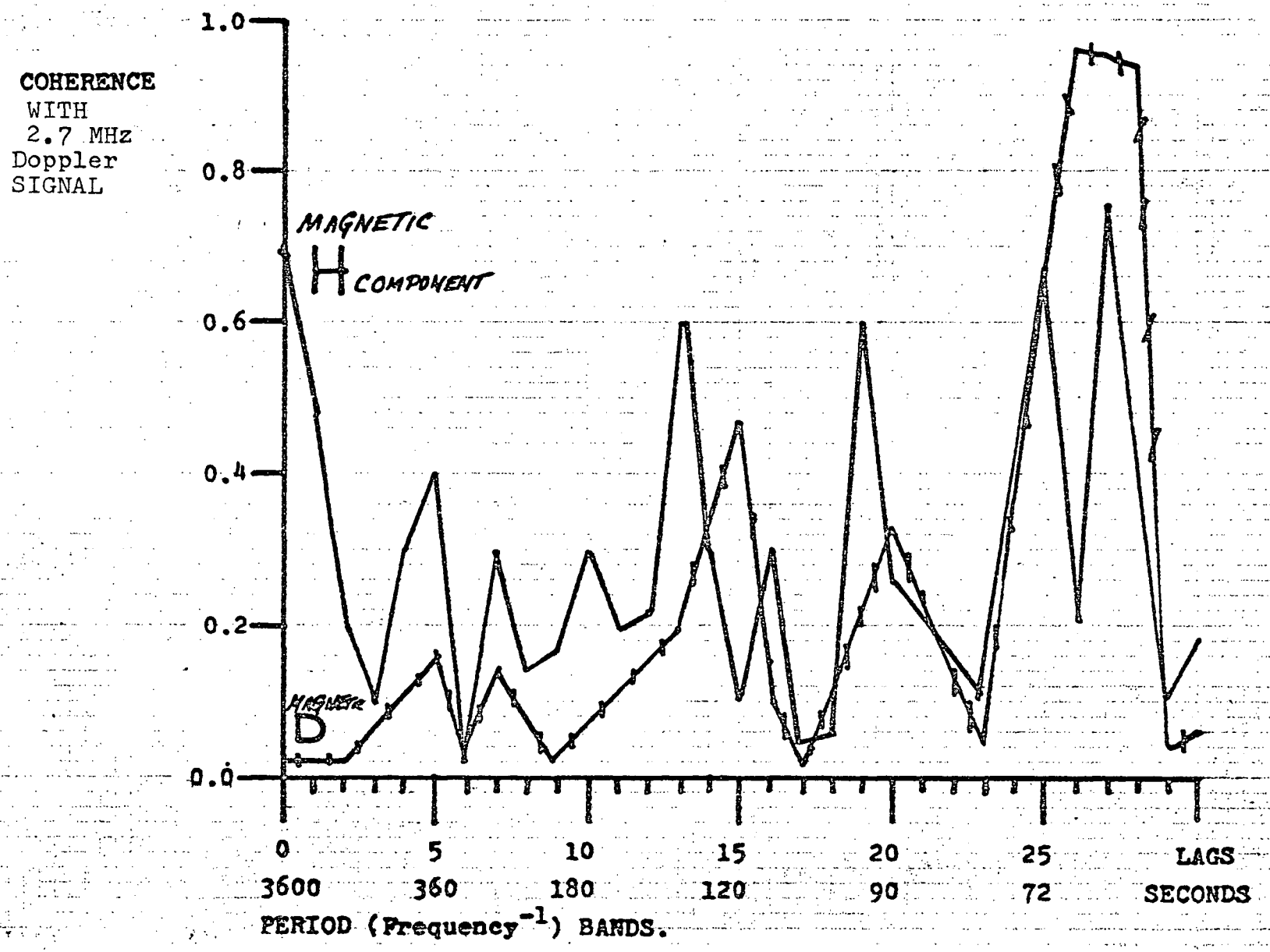


Fig. 3.7.2 Coherence versus pulsation period for the June 4, 1965, 0700 - 0800Z event.

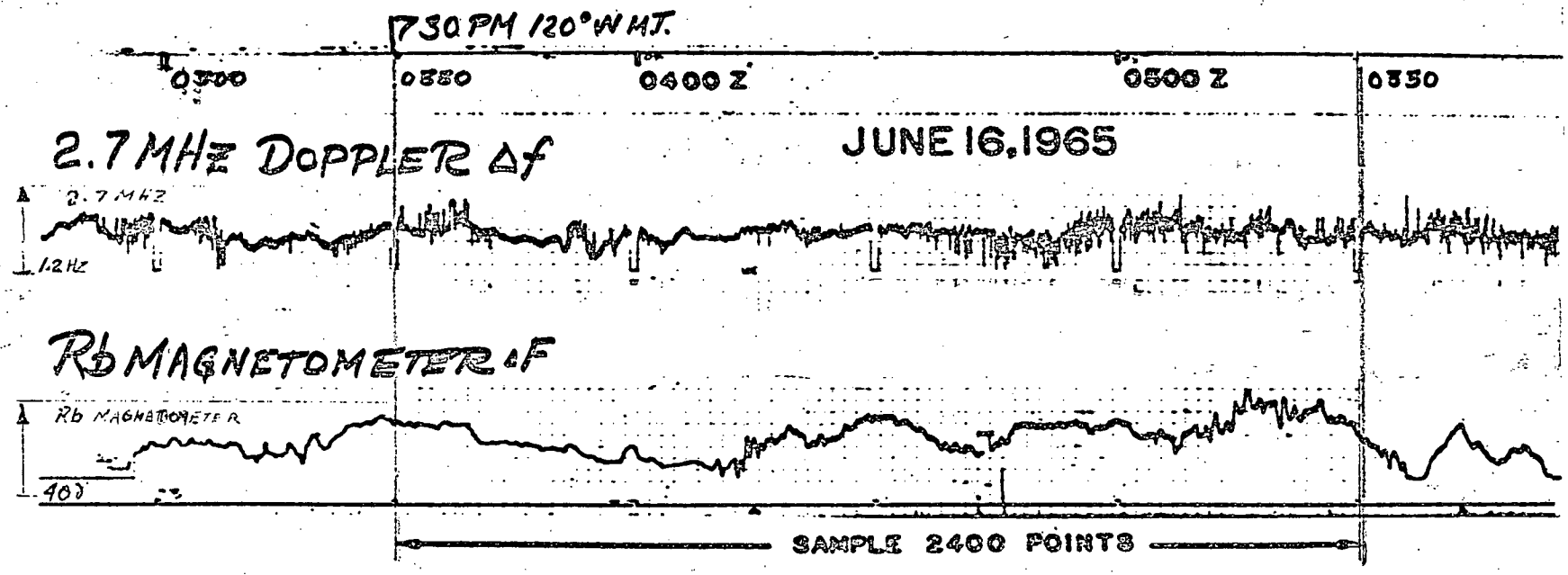


Fig. 3.7.3. Records digitized for spectral analysis. The station breaks in the Doppler record were interpolated across, and both records were filtered to avoid aliasing effects.

Doppler frequency and the magnetic H component. It is high for very long periods since both traces are rather flat. It is generally higher than the D component coherence in the 80 to several hundred seconds period range, but somewhat lower for shorter pulsation periods (however, these are less certain because they are approaching the sampling rate. Sixty lags were used in computing the coherence.)

Figure 3.7.3 shows a digitized event with two records: total magnetic intensity (ΔF) and 2.7 MHz Doppler beat-frequency shifts. (Δf) Both records were filtered and sampled (3.5 second intervals) and their coherence computed. Peaks in coherence were found at : 500 - 2000 seconds (coh. = 0.32), 70 - 85 seconds (coh. = 0.03), 40 - 50 seconds (coh. = 0.07) and at 28 - 32 seconds period (coh. = 0.20). (The Fourier transform of the in-phase correlation co-efficient R for the lowest frequency band was 0.58).

The variation of $\Delta f/\Delta H$ as a function of pulsation period was investigated for a number of events. Log power spectra were plotted against log period. Then various functions of the period were added to the log spectra. For example : in Fig. 3.7.4, T' represents a log Doppler shift spectrum to which an ω^{I} dependence has been added. T^{o} is the original Δf spectrum. $T^{1/2}$ corresponds to an $\omega^{1/2}$ dependence.

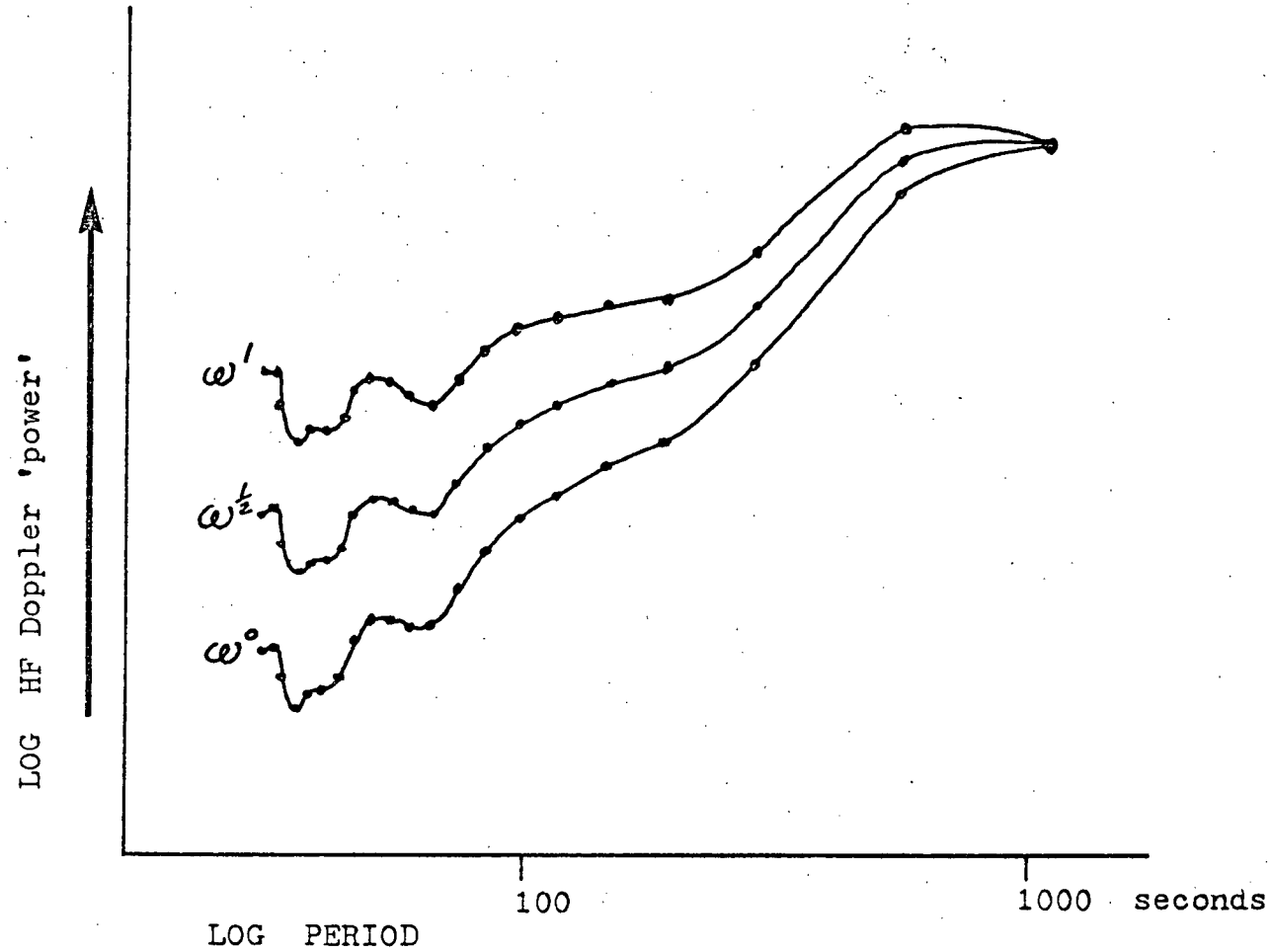


Fig. 3.7.4. Log power spectrum vs. log period weighted with three different dependencies on period. (Period $\tau = 2\pi/\omega$)

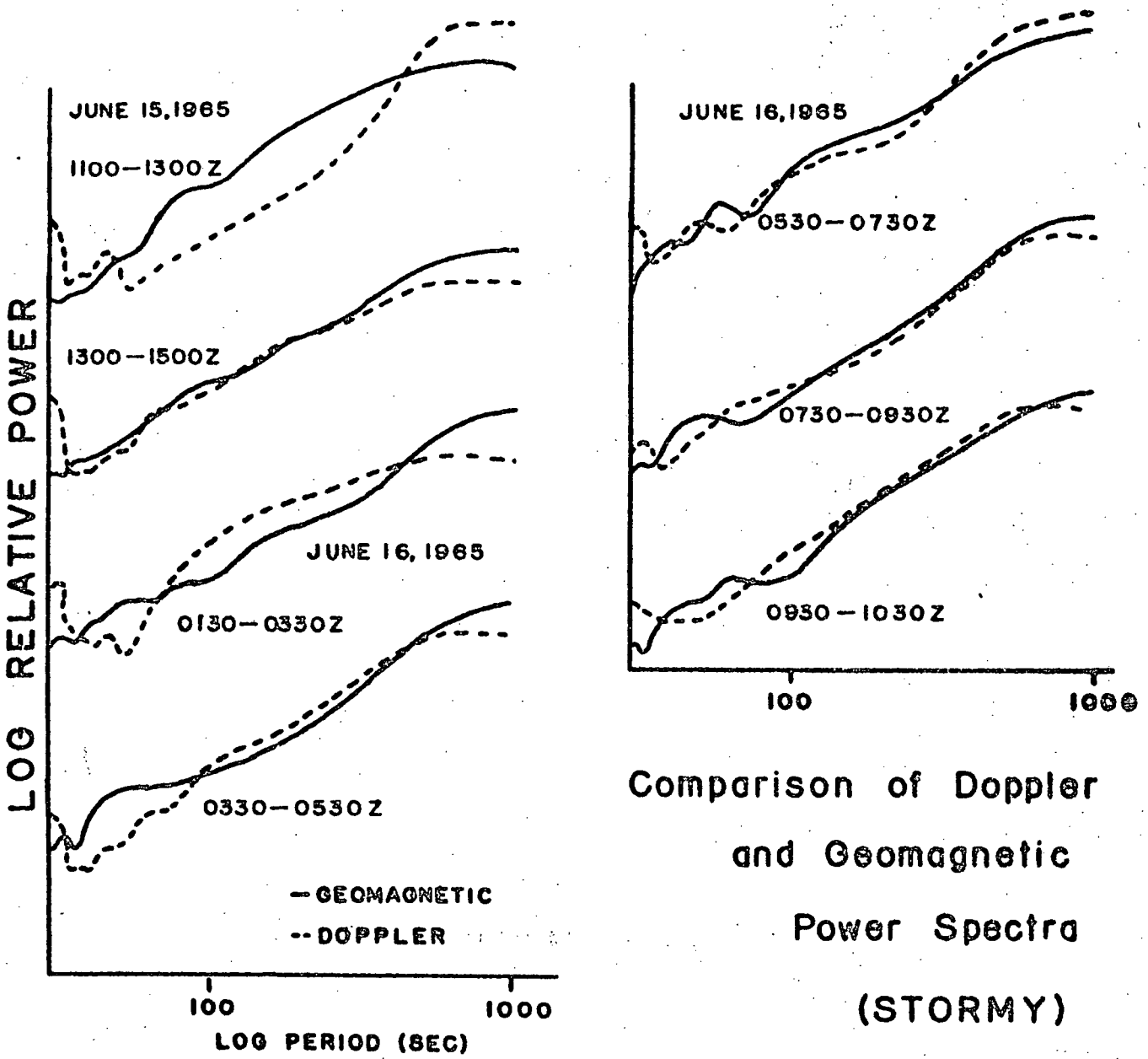


Fig. 3.7.5 Geomagnetic disturbance spectra compared to 2.7 MHz Doppler spectra weighted by an $\omega^{+1/2}$ dependence factor.

Figure 3.7.5 shows a group of simultaneous power spectra for which the Doppler shifts have been adjusted according to an $\omega^{1/2}$, dependance of $\Delta f/\Delta H$ on ω (C). The general agreement between the curves is quite good. In each case the area between the curves is less than if other powers of ω were used. This criterion of area was chosen because the computation produces a high density of data points at short periods (as may be seen from Figure 3.7.4), whereas the energy density is greatest and the system noise is least at long periods. The linear correlation between the curves is about 0.9 regardless of which power of ω is used, and does not serve to distinguish between them.

Examination of Figure 3.7.4 will show that the points representing the position of the longest period will have a great effect upon the area between the two curves, and hence upon our conclusion. There are several difficulties associated with the computation of this final point. First, any error due to a d.c. bias will introduce extra power at the last point. Second, the bandwidth of the arithmetic filter is less for the last point than for other points of the curve. Corrections have been made for these effects. Third, the arithmetic filter has side bands which will introduce power from different parts of the spectrum. This has not been compensated for; the side bands are not large, and in the absence of any very large peaks elsewhere in the spectrum, their small effect on the last points should be comparable for the pairs of spectra shown in Figure 3.7.5. Disregarding

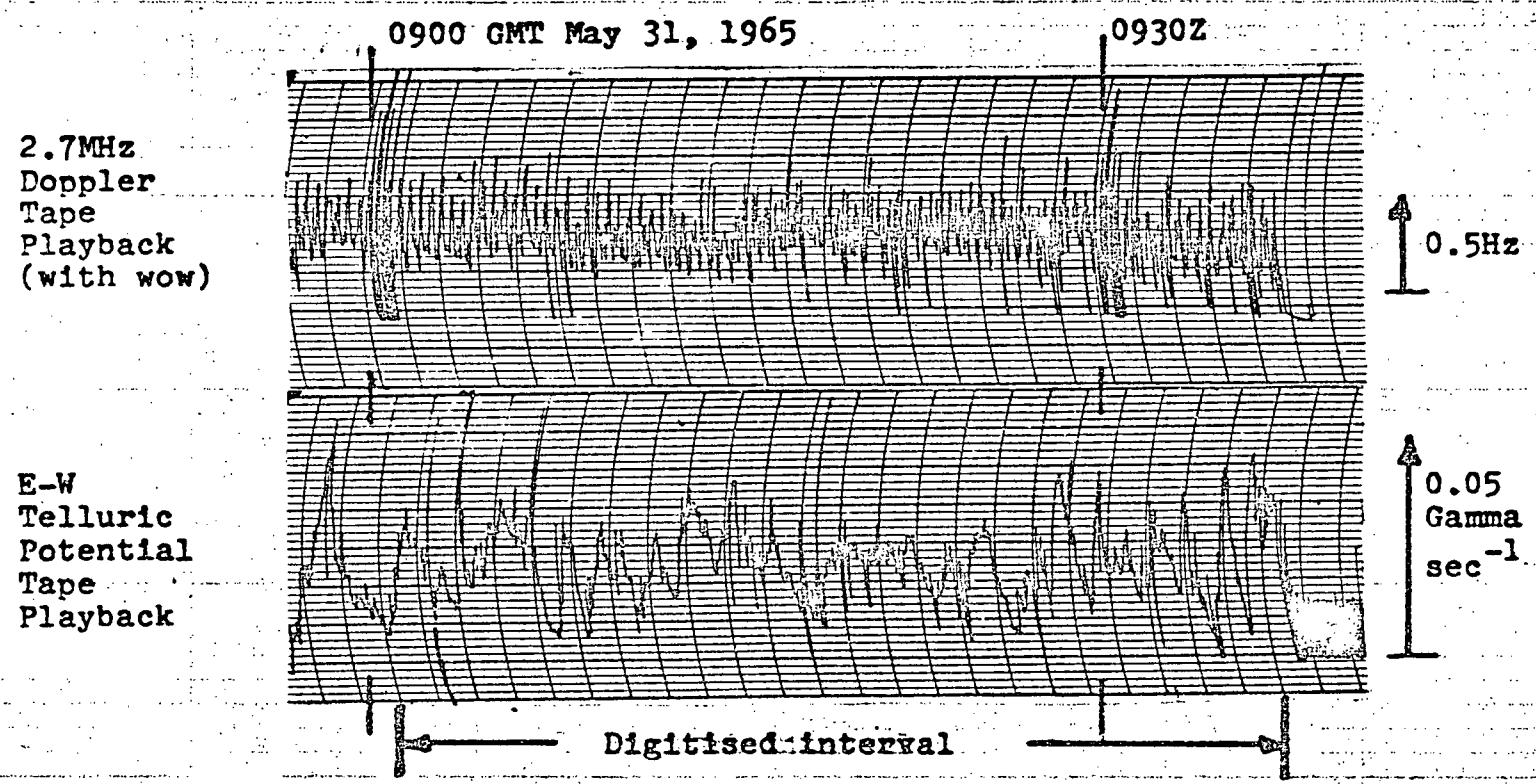


Fig. 3.7.6 Daytime records used for spectra and coherence calculations. (subsequently filtered prior to digitisation)

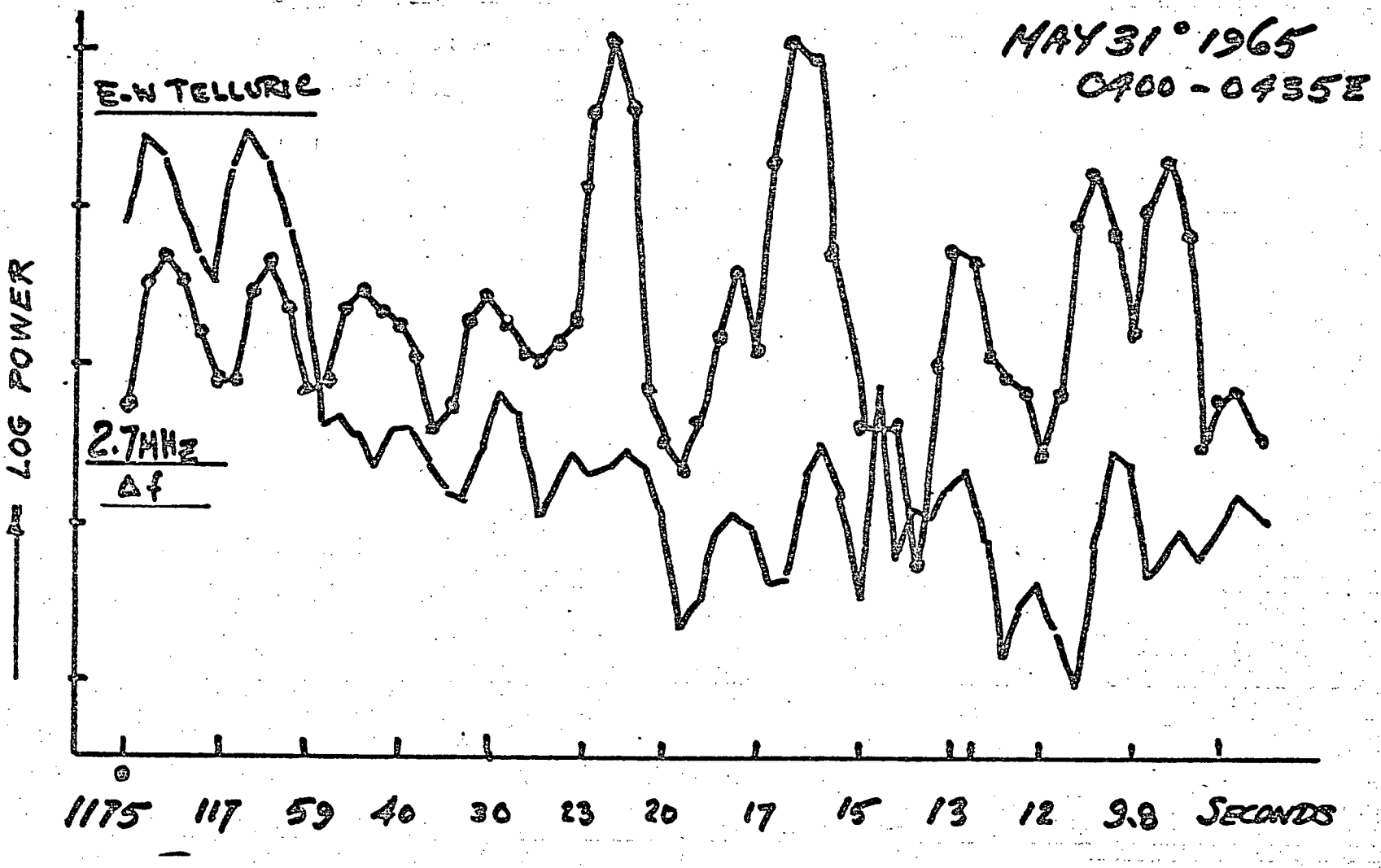


Fig. 3.7.7 The spectra of the telluric potential and Doppler records for the period 0400 - 0430Z, May 31, 1965.

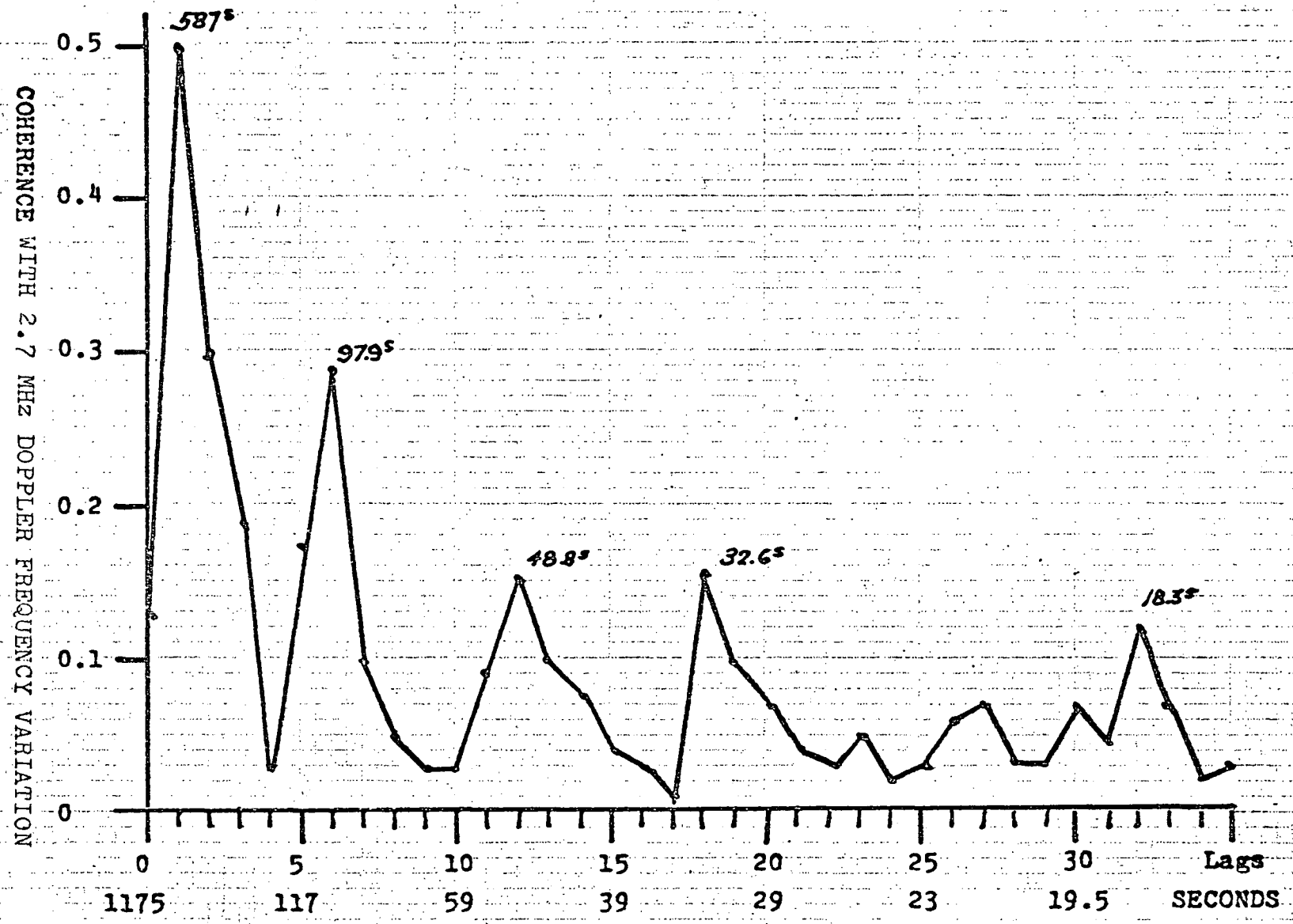


Fig. 3.7.8. Coherence between 2.7MHz Doppler waveforms and E-W tellaric potential for the event 0400 - 0430 May 31, 1965.

the lowest frequency end of the spectra, the association shown in Fig. 3.7.5 is still quite good.

Sporadic E Event

On May 31, 1965 at 0400z (2000 LMT) 2.7 MHz echoes were received from a dense sporadic E layer, (seen on Seattle ionograms) and a micropulsation event occurred.

Figure 3.7.6 shows the Brush chart record for this event. Doppler and telluric records for the period 0400 - 0440z were filtered and digitized (a 2.29 second sampling interval was used). Spectra and coherencies were computed.

Fig. 3.7.7 shows the spectra of the two signals. Fig. 3.7.8 shows the (absolute) value of the coherence as a function of pulsation period.

Marked associations occurred for pulsation periods (spectral peaks) of : 587 seconds, 98 seconds, 49 seconds, and 33 seconds. (The peaks at 18.3 seconds represent the wow-frequency of the slow speed FM tape-recorder,

3.8 Summary of Results

a) The initial radiometer experiment results (section 3.2) established that increases, and fluctuations in 20 MHz noise level are associated with night-time Pi-2 activity. It was not clear, however, whether these changes in signal strength were due to scintillation, or forward scattering of HF transmissions, or to absorption fluctuations.

b) The high sensitivity riometer experiment results section (3.3) showed that 30 MHz scintillation of about 0.5 db amplitude was definitely associated with night-time Pi-2 activity of about 0.05γ/sec. amplitude. While on the other hand, at this sub-auroral latitude and during periods of only moderate disturbance, no pulsating absorption events were found in association with the micropulsation activity.

c) The association between radio wave perturbations and micropulsations was only demonstrated on a statistical basis in the case of the early radiometer, and of the riometer results. The broad-band riometer results (section 3.4) showed clearly that the character of HF perturbations was related to the spectral and temporal character of the micropulsation events, and that the radiometer-observed association was not just a matter of both kinds of disturbance being independently related to magnetic storms, etc. (In particular, the correlation between telluric-potential-pulsations and HF fading is higher than the correlation between either and the magnetic K index.

d) The CW Doppler experiment results (section 3.5, 3.6, 3.7) lead to a much more detailed characterisation of the phenomena.

Possibly the best way to summarise the results is to examine what appears to occur in firstly the lower F region and secondly the E region of the ionosphere and then to make some comments on the peculiarities of the Doppler

sounding technique as evidenced in the results.

e) If one considers only the lower F region from 140 to 300 km. altitude, a few generalisations may be made :

1) Regions occasionally as small as 10 km., but usually somewhat larger than 10 km. in horizontal scale move vertically in synchronism with virtually all rapid magnetic field variations observed at ground level.

2) The vertical incidence Doppler shift for a given magnitude of magnetic change is roughly proportional to the square root of the frequency of the magnetic pulsation, or to the inverse of the square root of the characteristic time in the case of single impulses.

The corresponding electron gas speed is given approximately ((equation 2.4.4) by $v \approx 3 \times 10^{-2} \omega^{\frac{1}{2}} \Delta H$ (3.8.1) where : v is in m/sec. and H is in γ and ω is the angular frequency of the pulsations.

The vertical speed seems almost constant with height between 140 and 300 km. However, time shifts (or phase shifts) in the order of 20 seconds frequently exist between the (complex) F_1 and F_2 layer echo waveforms. This may indicate vertical group velocities in the order of 5 km/sec., or may just be due to the tilted wavefront of a horizontally propagating disturbance.

3) Associated F region vertical motions occur both in the daytime and at night. However, an association if any with very long period (>20 minutes) events was not detected in the daytime and the magnitude of the

vertical speed associated with events with periods longer than 300 seconds (and allowing for ΔH amplitude) was rather less by day than by night.

f) If one considers the E region (90 - 170 km.) then the picture is somewhat different.

1) By day there appear to be few detectable E region vertical motions associated with magnetic rapid variations. By night, however, the regular E region (as observed by VLF) exhibits (100 second period) pulsations from time to time which are sometimes directly associated with geomagnetic micropulsations. Sporadic E layers exhibit the same 100 second period pulsations, but also exhibit vertical speed variations associated with bays (sudden commencements), and other classes of micropulsations, notably Pi-2. (Sporadic E layers, however, frequently result in multiple echoes which produce a noisy Doppler record making the investigation of short period pulsations difficult.)

2) The vertical speed for a given magnitude of magnetic disturbance of a given period is about the same for the night-time E region as for the (night-time) F region, except in the case of the predominant 90 second period waves which result in $\Delta f/\Delta H$ ratios as large as 1 Hz/γ on occasion. This would correspond to a vertical speed of ionospheric motion of about 20 - 60 m/sec. for a typical event (moving mirror approximation).

g) No information was obtained on the night-time D region. No examples of VLF skywave phase pulsation associated events were found for the daytime D region.

h) In the case of both E and F region echoes the phase relationship between the horizontal H component and the vertical drift tended to be fairly stable for intervals of five minutes or longer; and usually for an entire event (if the pulsations in the event were of period greater than 70 seconds). In more than half of the cases an upward vertical velocity corresponded to an H decrease, while the reverse was true for most of the remaining cases.

i) The percentage of Doppler perturbations not associated with any magnetic disturbance (no wave-form similarity or no magnetic disturbance present greater than 0.01 γ sec^{-1}) was investigated for the 2.7 MHz channel for June 1965. The overall percentage of Doppler perturbations greater than 0.25 Hz lasting for longer than three min. associated with magnetic perturbations was 56 %. The percentage varied from a low of about 10 % around noon to a high of about 90 % in the late evening.

3.9 Current Results

At present there still exists considerable Doppler/telluric potential data recorded on magnetic tape, some of which is currently being analysed. However, it does not appear that further analysis of this data will materially alter the results or conclusions presented in this thesis.

IONOSPHERIC LAYER \ CLASSES OF MAGNETIC EVENTS		MICROPULSATIONS Pc 3	4	5	Pi 1	2	Si & SSC &c	BAYS	NON-MAGNETIC 'WAVES' period ranges 1-2'	3-10'	10'-2h
F	other's records		✓3	✓1,4		✓2,3	✓1,2,3.	✓2,5,3.		✓2	✓2
	this project	✓	✓	✓	✓	✓	✓	✓	O	✓	✓
E_s	other's						✓8				
	this		O	O	✓	✓	✓	✓	✓		
E	other's		O_4	O_4						✓9	✓11
	this	✓	✓	O	✓	O	✓	O	✓	✓	✓
D	other's	← ✓7,10 →			12✓,7		✓10	✓6			
	this	O	O	O	O	O	O	O	O	✓	✓

TABLE 4.1.1* TYPES OF EVENT OBSERVED IN THIS PROJECT AND BY OTHER WORKERS

KEY-- BLANK- not looked for. 'O' looked for but not observed. ✓ observed.

1) Chan & Villard, 1962.
2) Davies & Baker, 1966.
3) Lewis, 1967.
4) Watt, 1964.
5) Becker, 1965, &others.
6) Oguti, 1963.
7) Campbell, Parasarathy, 1962.*
8) Thomas, 1962.
9) Georges, 1967.
10) Sato, 1965.*
11) Bowman, 1965.
12) Sechrist&Felperin1962.

Note------starred* workers report auroral zone observations, all others mentioned refer to mid-latitude observations.

CHAPTER IV

CONCLUSIONS

This chapter consists of four sections : Section 4.1 presents conclusions with regard to the various classes of magnetic events and the observed associated ionospheric perturbations. Section 4.2 presents conclusions with regard to the characteristics of the experimental techniques. Section 4.3 presents recommendations regarding further theoretical work, and Section 4.4 presents recommendations regarding further experimental work in the area of magnetic variations with associated ionospheric perturbations.

4.1 Conclusions Concerning the Various Types of Events

These are treated in separate sections as follows :

4.1.1 Pc-1, Pc-2

4.1.2 Pc-3

4.1.3 Pc-4, Pc-5

4.1.4 Pi-1

4.1.5 Pi-2

4.1.6 Si, ssc

4.1.7 Bays and Storms

4.1.8 (90 - 120 sec.) waves

4.1.9 (5 - 15 min.) Daytime waves.

4.1.1 Pc-1, Pc-2 Micropulsations ($\tau < 10$ sec.)

The radio frequency experiments were not capable of resolving perturbations in this highest frequency range.

Consequently no results were obtained. Moreover, it is unlikely that either the riometer or the 'Dopplometer' can be adapted to study such rapid small variations.

4.1.2 Pc-3 Micropulsations

These are continuous trains of pulsations occuring mainly in the morning and having periods in the 10 - 45 sec. range.

a) Pc-3 events are seen on the (4.6 MHz) Doppler records implying that ionospheric perturbations at mid-latitudes are associated with them. Pc-3 are seen on about 3 percent of 'good' hours of morning Doppler records in the summer and on about 10 percent of hours of 'good' time on winter mornings. About twenty percent of the Pc-3 seen on the telluric potential records show up on F region Doppler records.

b) Pc-3 associated disturbances occur in the F region since they frequently appear only on the F region reflected (4.6 MHz) channel.

It is probable that the absence of daytime E layer echoes having Doppler shifts associated with Pc3 is due to the absence of appreciable electric fields, or to neutral wind induced transport rather than being due to recombination, since the recombination time constant is about 100 sec. (vid. appendix IIA)

c) The magnitude of the Doppler shifts as a function of period for Pc-3 is uncertain because of the small number of (good) records actually studied (17) and the limited period range involved. The largest ratios were as large as any observed (1 Hz/γ), while most examples lay in the 0.1 - 0.4 Hz/γ range (e.g. Fig. 3.5.10).

d) 2.7 and 4.6 MHz records exhibited micropulsation wave-forms (180°) out of phase with each other on at least two occasions (e.g. Fig. 3.6.C1) indicating a variation of ionospheric perturbation with height. The ionospheric perturbation, moreover, must have an effective vertical speed of the order of a few km./sec. to account for the results. This is to be contrasted with the Doppler velocities which (equation 2.4.4) on the basis of the moving mirror approximation are of the order of 10 m/sec. While the Doppler velocity depends on the amplitude and kind -- (N_e, VN_e, $\mathcal{D}_e$) of perturbation, the apparent vertical speed depends on the direction and speed of propagation of the disturbance. The high apparent vertical speeds can be accounted for by horizontal propagation of near-vertical wave-fronts.

e) Interaction Mechanisms

It is not possible that modulation of steady currents (5.3-2) is responsible for Pc-3 since they are observed in association with overhead ionospheric perturbations when no magnetic bays are recorded locally. Energetic particle precipitation is not likely to be involved at these latitudes, as no riometer

absorption was observed in association with (morning) Pc-3 events. This is in agreement with Wilhelm (1967) who found only 'poor interrelation' between daytime Pc events and auroral zone X-ray bursts and riometer data.

The magnitudes of the Doppler shift observed are just compatible with a Hall drift mechanism where the electric field is the result of induction. Consider a 1γ change occurring in 15 sec. (t = 30 sec.). Then if the scale of the induction region is 200 km. [vid. Patel (1966)], the E field will be about $0.07 \times 10^{-9} \times 2 \times 10^{5}$ Vm^{-1} using equation (5.3.10). Putting this field into the Hall drift equation (5.3.8) and taking cos I = 0.3 to obtain v_z, and then using equation (2.4.4) to estimate the Doppler shift, yields $\Delta f/\Delta H = 0.002$ Hz/γ which is much less than the average value observed on 4.6 MHz (Fig. 3.5.10).

However, as a reversal of the sense of Δf with respect to that of ΔH was observed during the course of each of a number of events either complex E region currents intervened or Hall drift which would have a constant sense was not responsible for these observations.

The variation of perturbation with height within the F region evidenced by the differences in 4.6. and 2.7 æHz echoes might be accounted for by horizontal current lamina stacked above one another and flowing in different directions.

f) Source Phenomena

The results are compatable with EM/hydromagnetic wave theory [Watanabe (1959)] and somewhat less so with the theory that ionospheric currents (in the E region) are responsible for

the observation of Pc-3 at mid-latitudes [Saito (1966)]. A horizontally propagating (F region) disturbance is favoured by the results. Consequently it is concluded that at least 20 percent of the Pc-3 observed at mid-latitudes are not due to the 'propagation' of EM waves in the spherical waveguide between the earth and the ionosphere, as such propagation would be unlikely to result in measureable ionospheric perturbations in the F region and none in the E region.

4.1.3 Pc-4, Pc-5

These regular pulsations in the 45 - 150 sec. and 150 - 600 sec. period ranges occur mainly between 4 a.m. and 3 p.m. local time. Associated Doppler sinusoids and Pc-4, 5 pulsations were observed on from 10 to 30 percent of the 'good' hours, during the daytime span 4 a.m. - 3 p.m. About one Pc-4 event in four seen on the telluric potential records showed up on the Doppler records. Comparatively few Pc-5 events were recorded, most events lying in the 90 - 150 sec. period range. (See sections 3.5.C5, 3.5.C6). Sometimes Pc-4's observed on the Doppler records were also accompanied by Pc-3 (e.g. 3.6.A2). At noon (vid. section 3.5.C5) both 4.6. and 2.7.MHz channels exhibited Pc-4; however, the Doppler shifts on 4.6 MHz were generally larger. As the f_oF_2 was usually well above 4.6.MHz at noon, the larger Doppler shifts probably indicate larger perturbations in the F_2 layer, than in the F_1 layer where 2.7 MHz was often reflected. The absence of any perturbations

on some 2.7 MHz noon records may have been due to E layer reflexion. Since the period of these Pc-4, Pc-4 pulsations are comparable to the recombination time constant in the E layer (appendix II A) it is probable that disturbances in the E region are attenuated by recombination. It is also possible that winds may smear out the perturbed ionisation in the E region (vid. 3.6.A2).

At sunrise (vid. section 3.5.C6) the 4.6 MHz Pc-4 Doppler shifts exhibited a greater $\Delta f/\Delta H$ ratio (up to 0.4 Hz/γ) than at noon (up to 0.2 Hz/γ) while the 2.7 MHz channel showed an opposite effect ($\Delta f/\Delta H$ max dawn = 0.17 Hz/γ, $\Delta f/\Delta H$ max noon = 0.5 Hz/γ). This effect is probably due to the proximity to critical frequencies. The 4.6 MHz channel being at f_xF_2 at dawn and well below f_oF_2 at noon while the 2.7 MHz channel is below f_oF_2 at dawn but in the vicinity of f_oF_1 or sometimes f_xE at noon, and this confirms the expectation that larger Doppler shifts should occur near critical frequencies.

It is concluded that Pc-4 frequently result in F region ionospheric perturbations at mid-latitudes, while E region perturbations are probably 'damped-out' by recombination.

The Pc-4, 5 period distribution histogram, section 3.5.C5, indicates a gap in the spectrum in the 70 - 90 sec. period range similar to that observed by Wescott et al. (1964) for the same L value. This is not the case for the night-time regime however (see section 4.1.8).

a) Pc-4, Pc-5 Interaction Mechanisms

Doppler shifts are observed for Pc-4, 5 when no 'bays' are present and hence modulation of ionospheric electrojets is ruled out as a general mechanism. The theory of (high latitude) torsional oscillations which is generally accepted [Saito (1967)] does not imply : charge injection, parallel electric field drifts, and dynamo effects. At sub-auroral latitudes either the electric field of return currents related to currents induced in the auroral zone or less likely the electric field induced overhead by mid-latitude 'field-lines' oscillating might be expected to produce Hall drift in the F region. This is compatable with most of the observations.

Consider a Pc-4 of amplitude 1γ. If this is produced by an infinite current sheet 20 km. thick in the E region, then by equation (2.1) the current density is 3.2×10^{-8} amps m^{-2}. [vid. Paulson et al (1965) and Harang (1939)]. Then using Ohms law and taking the conductivity to be 10^{-4} mho m^{-1}[Obayashi (1963)] $E = 3 \times 10^{-4}$ v m^{-1}. Putting this into the Hall drift equation (5.3.8) and taking cos I = 0.3, we have $v_z = 6$ m $sec.^{-1}$. This would give a $\Delta f/\Delta H$ ratio of 0.1 Hz/γ on the basis of the moving mirror approximation and f = 2.7 MHz. However, the calculations are so crude that even order of magnitude agreement is of interest.

However, occasional examples of the sense of ΔH reversing with respect to that of Δf suggest that for some Pc-4 events that either Hall drift is not involved, or the electric fields leading to the drift are not uniform with height. No absorption was observed in association with Pc-4, 5 events here, so that local energetic precipitation is unlikely to be involved at mid-latitudes. In the auroral zones, precipitation may be involved with some Pc-4, 5 pulsations [Sato (1963), Wilhelm (1967)].

4.1.4 Pi-1 Micropulsations

Micropulsations of frequency higher than 0.1 Hz (10 sec. τ) were not usually recorded. Pi-1 events in the 30 - 40 sec. period range were occasionally observed to be accompanied by similar quasi-sinusoidal Doppler shifts. However, no cases of Pi-1 associated Doppler shifts occurred in the absense of Pi-2. Consequently Pi-1 are dealt with as part of the Pt phenomenon under the next heading 4.1.5, Pi-2/Pt.

Examples of the type of Pi-1 directly associated with energetic particle precipitation [Milton et al. (1967)] were not identified in examination of the riometer a.g.c. and Westham Island micropulsation records, and are above the upper frequency resolution cut-off of the Doppler experiments. The VLF phase equipment was either not working or not sensitive enough to observe the (Pi-1) storm time pulsations of the type observed by Sechrist (1962).

4.1.5 Pi-2 and Pt Micropulsations

These usually occur mainly in the evening and at night during the so-called 'splash' precipitation regime with which they are associated in the auroral zone [Wilhelm (1967), Nishida (1964 b)]. In the auroral zone magnetic bays and Pi-1 accompany the Pi-2, while at lower latitudes the Pi-1 and bays are frequently absent [Saito (1966)].

One of the main results of this study is that Pi-2 events involving Pi-1 riders are almost invariably observeable ($\Delta f > 0.1$Hz) on HF Doppler signals reflected from the F region within one or two hours of sunset (sect. 3.5.C7) if they are observed on telluric potential records (with a sensitivity of 0.01Y sec.$^{-1}$). About 30 % of early evening hours exhibit Pi-2 associated Doppler events. At other times the majority of Pi-2 with Pi-1 events are seen on both E and F layer reflected waves. This leads us to conclude that virtually all Pt events are observeable using properly chosen HF frequencies and the Doppler sounding technique. (This is a much more specific conclusion than that of Lewis (1966) who referred to rapid variations and to Doppler frequency change in general, whereas here, specific similarity of waveforms between the Doppler shift and the magnetic H component is implied.)

When Pi-1 are not present it probably indicates that the magnetic signal has travelled further from its place of origin since ionospheric attenuation is greater for the higher frequencies [Rostoker (1966 a)] In fact, the low frequency Pi-2 components may be just the magnetic field due to distant, auroral zone electric currents. Consequently the poorer association with ionospheric motion in the absence of the

Pi-1 is understandable. The fact that the presence or absence of bays does not seem to effect the probability of seeing overhead Pi-2 ionospheric perturbations (table 3.5.4) tends to eliminate the modulation of ionospheric currents (5.3.2) as a mechanism to account for mid-latitude Pt's. [See also Kato and Watanabe (1956)]. In this regard it is to be noted that a special class of Pi2 Doppler events in the 90 - 110 sec. period range are frequently associated with bays at Victoria; (see section 4.1.8 for further discussion of these particular events.)

Since sensitive riometer records did not show absorption in association with Pt (section 3.3) it is unlikely that the mid-latitude Pt signals are produced directly by energetic particle precipitation. Since the sense of Doppler shift, or motion with respect to the sense of magnetic variation reverses both both within particular events, and from event to event, it would seem that the Hall drift mechanism is inappropriate for pi-1 + Pi2 (i.e.Pt) events. This is a conclusion to be tempered by consideration of the possibility of complex ionospheric electric current distributions, and consequent differences between the summed magnetic effect observed at the ground and the local ionospheric field at the height of radio reflexion.

The shorter period pulsations produce larger Doppler shifts [Section 3.5.C4, 3.5.C7, 3.7.1] which vary roughly as $\omega^{\frac{1}{2}}$ in agreement with Rishbeth's equation for Alfvén waves (5.4). However, the Δf magnitude is larger than this equation would predict.

The apparent horizontal propagation velocities observed by Herron (1966) and the polarisation and dispersion characteristics measured by Rostoker (1967) tend to rule out the horizontal propagation of sonic ($v \approx 300$ m sec.$^{-1}$) waves. Vertical downward propagation is not ruled out. However, in this regard the simultaneous 2.7 and 4.6 MHz Doppler records near sunset (section 3.5.C7) and sunrise (section 3.6.B1) show time displacements of 10 seconds, or less between the complex waveforms; consequently vertical apparent velocities must be of the order of 5 km/sec. (for 50 km. difference in 2.7 and 4.6 heights of reflexion) which is too high for vertical downward sonic wave propagation.

The time constants $(\frac{L}{R})$ for E region currents with auroral zone origins are too long (section 5.4) to enable such currents to account for the higher frequency components of Pt's. Moreover, the polarisation character of the lower frequency components cannot be accounted for by large current systems [Rostoker (1966a)]. Consequently electric currents originating in the auroral zone are not favoured to account for Pt's.

The association with radio scintillation (section 3.3) tends to indicate that the ionospheric perturbations extend above the peak of the F region, as scintillation producing irregularities are thought to do [Heissler (1967)]. It is probable that scintillations and spread F observed near midnight during magnetically (K_ℓ, and K_p = 0 to 2) quiet times at mid-latitudes are intimately related with Pt phenomena.

Finally it is concluded that electrodynamic drift (either Pedersen, parallel, or Hall) associated with ULF/EM waves in the ionosphere (which may originate from downcoming HM waves or from auroral zone pulsating precipitation) is probably responsible for the majority of Pt Doppler events observed at mid-latitudes.

The propagation velocities and dispersion characteristics and the $(\Delta f/\Delta H)$ dependence on $\omega^{\frac{1}{2}}$ all favour such waves. However, it has not been possible to rule out shock waves (5.4) which might propagate at velocities greater than the sound velocity, and further work with spaced HF reflexion points is desirable to clarify the dispersion characteristics of Pt disturbance.

4.1.6 Si, ssc

Magnetic sudden impulses and sudden commencements are roughly simultaneous all over the globe, and are frequently associated with riometer absorption increases (indicating precipitation) in the auroral zone [Sato (1963)]. Five sudden commencements were identified on the (1965) telluric potential records using published data from magnetic observatories. Of these, two exhibited direct association with 2.7 MHz Doppler impulses. [(3.6.A5) July 6, 0951z, Nov. 12, 1430z]. The Doppler traces were too disturbed on the other three occasions to be certain that the impulses really were associated with the SSC. On July 6, the $\Delta f/\Delta H$ ratio was 0.12 Hz/γ and the sense was that to be expected for Hall drift. The event occurred near midnight and involved F layer reflexion. On Nov. 12, the 2.7 MHz $\Delta f/\Delta H$

ratio was about 0.04 Hz/γ and again a ΔH increase was associated with a Δf decrease. Lewis (1967) found $\Delta f/\Delta H$ ratios or 0.01 to 0.04 Hz/γ for ssc events. It appears that larger ratios are possible. Moreover, the 2.7 MHz frequency was probably about the same 'distance' from the f_oF_2 at 0451z= 9PM, 120° W.LMT, as at 1430z (6:30 a.m.), so that the larger ratio was unlikely to have been due to the proximity to critical frequencies.

Eleven sudden impulses (reported in JGR) were selected on the 1965 telluric records. Of these, two definitely exhibited no associated Doppler shifts (Aug. 2, 0116z, Dec. 1, 1225z). Very clearcut associations were observed on Aug. 2, 0527z ($\Delta f/\Delta H$ 0.2 Hz/γ) and on Dec. 4, 1445z (0.05 Hz/γ). The other events showed more or less similar impulses but on noisy or confused complicated records. A very clean si was recorded (April 4, 1966) (section 3.6.A4) when $\Delta f/\Delta H_{2.7}$ = 0.4 Hz/γ , and $\Delta f/\Delta H_{4.6}$ = 0.6 Hz/γ. The $\Delta f/\Delta H$ ratios for si's appear to vary from 0.05 Hz/γ to 0.6 Hz/γ. However, the latter value was obtained when the 4.6 MHz frequency was quite close to the MUF. The sense of the Doppler shifts agreed with Hall drift theory.

The magnitude of the ($\Delta f/\Delta H_{2.7}$) ratio is smaller than that predicted for magnetospheric compression (5.4.f) by Jacobs and Watanabe (1966). The $\Delta f_{4.6}/\Delta f_{2.7}$ ratio was about 1.5:1 - 1.8:1 for the si, and it is concluded that the height of reflexion effects are favoured over the effects of the medium below the height of reflection considered by Jacobs and Watanabe which would give a 1/f variation in Δf

Riometer records were not available for these events and the presence or absence of precipitation of energetic particles remains an open question.

Of the various source mechanisms, magnetospheric compression or possibly an HM/EM shock wave are favoured. Currents induced in the auroral zone by precipitation [Sato (1963)] are also feasible. The singularity of the events and their widespread hemisphere-wide simultaneity, tend to rule out wind-borne irregularities and horizontally propagating sonic waves. As magnetic bays frequently do not occur, at the same time as the si or ssc, modulation of ionospheric currents by a (neutral or ion-acoustic) downcoming wave is not indicated.

4.1.7 Magnetic Bays and Magnetic Storms

a) Bays

By magnetic bays are meant variations (> 15 γ) in one or more of the magnetic components lasting for longer than 15 min. Smaller bay events of 5 to 15 min. period are difficult to distinguish from giant pulsations and long period Pi-2. The diurnal distribution of occurrence of bays at Victoria for 1964 has been published by Rostoker (1966 b). Virtually no bays were observed (4) between 11 a.m. and 4 p.m. in that year. Consequently it is not surprising that no examples of Doppler records exhibiting association with bays were found at noon (sect. 3.5.C4). However, at sunrise (± 2 h.) a number of bays (12) appeared on the magnetograms (1965) but not on the 2.7 MHz (or 4.6 MHz) Doppler records (3.5.C6). This absence may be due to the effect of recombination (sect. 5 .2)

as long period micropulsations were also absent in the daytime; or it may be due to the fact that the bays were not D 'transition' bays and hence probably did not involve current systems directly overhead. [vid. Rostoker (1966 b)]. Around midnight it was found that 15 percent of all the observed bays (section 3.5.C4) were accompanied by 2.7 MHz Doppler variations of similar form. Most of the associations occurred for transition bays. These account for about 25 percent of all bays seen at night. It is concluded that if the current producing a magnetic bay is concentrated in the overhead region, then F layer perturbations there are to be expected accompanying the transition bay, if the event occurs during the ionospheric night. In the daytime it is uncertain whether absence of overhead currents or recombination is responsible for the absence of association. Clear-cut associations with Sq variations were not observed but numerical filtering and correlation techniqes might bring out such variations, as the records were generally perturbed in the daytime (section 3.1.9).

The $\Delta f/\Delta H$ ratio for bays was usually in the 0.01 - 0.1 Hz / γ range (e.g. 3.6.A6) and the sense was usually that to be expected for Hall drift (ΔH inc. $\rightarrow$ Δf dec.). Consequently it is highly probable that electric fields, and Hall drift (5.3-4) associated with overhead currents (5.4a) (electrojets) are responsible for the majority of the bay associated Δf perturbations. It is also possible that Joule heating (5.3-7) which may lead to increased electron collision frequencies, in the presence of a gradient in density may result in detectable Doppler shifts.

Rüster (1965) suggests that Hall drift associated with a bay current system would give too high a velocity to explain his measurements. However, this conclusion depends on the assumed current distribution. Becker et al. (1965) observed a bay of 60γ and 4 hours duration accompanied by a vertical F region true height displacement of 200 km. (effectively a vertical velocity of 10 m/sec.$^{-1}$). The corresponding $\Delta f/\Delta H$ ratio for vertical incidence Doppler sounding using the moving mirror approximation is about 0,02 Hz/γ. [Rishbeth (1963) also favours electric fields associated with local ionospheric currents.]

b) Storms

The few ionospheric/geomagnetic storms occurring in 1965/1966 were invariably associated with perturbed Doppler and radiometer records. However, the interpretation of the records was usually impossible because they were too noisy. Moderate storm events such as that discussed in 3.6.A7 did however, exhibit long period ionospheric perturbations corresponding to the main H or D component excursions. $\Delta f/\Delta H$ ratios of about 0.01 - 0.1 Hz/γ were found. Computer analysis revealed an association extending to shorter period variations and the $\Delta f/\Delta H$ ratio varied roughly as $\omega^{\frac{1}{2}}$, which suggests HM/EM ULF waves, section 5.4.E. The 'noisy' character of the storm-time Doppler records was probably due to the presence of multiple transmission paths exhibiting differing Doppler shifts. Some of

the paths might simply be multiple echoes, between the ground and one region of the ionosphere; such echoes would suffer additional absorption on each pass. Therefore it is more likely that echoes from a number of ledges or 'tilts' occur during storms.

It is concluded that during storms, more and smaller 'reflecting' irregularities are present within the field of view (a region of horizontal scale size roughly 200 km.) Of course, diffraction and interference effects greatly complicate the picture and at storm times one cannot consider the size of an idealised planar first fresnel zone as being indicative of the size of the reflecting region.

4.1.8 90 - 120 Sec. Period Waves

Waves in the 90 - 120 sec. period range are occasionally observed in the Doppler records unaccompanied by any detectable magnetic disturbance. When two frequency channels are available, the larger effect is on the lower frequency one (e.g. 3.6.A8). This tends to favour the E region rather than the F region as the region of maximum disturbance (vid. equation 2.4.3), since a Δf dependence on $1/f$ is expected for electron density variations below the height of reflexion, and also since the lower frequency is reflected lower down in the ionosphere. This conclusion is further reinforced by the presence of dominant 90 sec. period components in Doppler signals reflected from sporadic E (e.g. 3.6.B2).

When these waves were observed without micropulsations there were no magnetic bays and the K indices were zero both at Victoria and in the auroral zone at College (e.g. 3.6.A8). However, during disturbed conditions, 90 - 120 sec. ionospheric 'waves' and micropulsations were frequently observed at Victoria (vid. figure 3.5.5). In fact the principal band of night-time pulsation activity associated with Doppler shifts is the 90 - 110 sec. band. This is in contrast to the observations reported by Wescott (1964) taken at Cold Bay, where little or no micropulsation activity was observed in this band. Cold Bay has a similar geomagnetic L value (3) to Victoria, but is at a higher geographic latitude; consequently atmospheric properties (density, temperature, temperature gradient) which depend more on geographic than on geomagnetic co-ordinates may be of importance. In this regard the event described in Section 3.6.C2 (Sept. 7, 1965, 0530z) is of particular interest. This event began with small 90 sec. period pulsations on the VLF (18.6 KHz) phase record presumably due to E region motions which were not accompanied by magnetic or telluric micropulsations. Then at 0930z, a magnetic bay occurred (see Fig. 3.6.21) and, simultaneously, 90 sec. period 2.7 MHz (F_2 layer) Doppler shift pulsations and magnetic micropulsations. It would appear that this is an example of an infrasonic wave modulating an ionospheric current. The high apparent vertical speed of the disturbance probably does not represent a speed but rather just the mapping of a varying electric field associated with the modulated electrojet up into

the F region along the inclined field lines. (There is also at least about 50 km. horizontal separation between VLF and HF reflexion regions.) A similar event was recorded at 0800z Sept. 7, 1965, and other events without VLF records but exhibiting smooth 90 - 100 sec. period sinusoidal simultaneous ionospheric and magnetic pulsations (without any Pi-1 or other high frequency components) were observed.

The characteristics of these waves which have been estimated (90 - 120 sec. period, height range 90 - 180 km.) agree very well with the theoretically predicted characteristics of infrasonic waves undergoing ducted propagation in the E region (vid. Fig. 4, Wickersham (1965), also appendix section 5.4.D).

4.1.9 5 - 15 min. Period Daytime Waves

The daytime Doppler records frequently (about 20 percent of all days) exhibited quasi-sinusoidal oscillations of 5 - 15 min. period lasting for an hour or more. These 'waves' were not accompanied by magnetic pulsations. An unusually fine example is shown and discussed in section 3.6.A9. Probably the most interesting aspect of these perturbations is that D, E and F layers seem to be moving in the same (vertical) direction at about the same speed. The period range is that of the Brunt/Väisälä resonance [MacDonald (1963)] and waves associated with this resonance (Helmholtz or surface gravity waves) are probably responsible for the observed phenomena. Internal gravity waves would not be expected to

exhibit almost unchanged vertical velocity throughout the ionosphere [Hines (1965 a) sect. 5.4]. If the motions are mainly of a vertical character, since the dip angle is 72°, only slight dynamo effects would result, and the absence of associated magnetic pulsations is not surprising. These waves were not observed in the company of magnetic bays (or for $K_{\lambda} > 2$) so that it is unknown whether they might modulate electrojets or not.

The findings in section .1 are summarised in Tables 4.1.1* & 2*
The symbols used in the main part of Fig. 4.1.2* mean as follows :

A) This process or phenomena is favoured strongly, by the results of this study.

B) This process is favoured weakly by this study.

C) Neither this study nor others rule this process out, but no definite support for it has been found.

X) This study does not rule this out, but other studies appear to.

Y) This study rules this out; other studies leave the matter open.

Z) Both this study and others rule this process out.

N.A. means not applicable.

U. means uncertain.

The interaction processes (1 - 7) are those discussed in appendis II section 5.3, while the source phenomena are those discussed in appendix II, section 5.4.

TABLE 4.1. 2*

SUMMARY OF CONCLUSIONS REGARDING MAGNETICALLY ASSOCIATED IONOSPHERIC PHENOMENA

(Key to symbols is on page 210 See also AppendixII)

	OCCURRENCE			HEIGHT			INTERACTION PROCESSES (6.3)							SOURCE PHENOMENA (6.4)					
	PERCENTAGE OF MAGNETIC $\Delta H, \Delta D$ EVENTS ACCOMPANIED BY SIMILAR HF DOPPLER Δf PULSATION WAVEFORMS	PERCENTAGE OF OBSERVING HOURS WHEN EVENTS ARE SEEN.		IONOSPHERIC HEIGHT REGION WHERE OBSERVED.															
		noon ± 2 h.	midnight ± 2 h.	F	E	E_s	1) PARTICLE INJECTION	2) MODULATION OF CURRENTS	3) PARALLEL DRIFT	4) HALL DRIFT	5) INDUCTION	6) DYNAMO ACTION	7) JOULE HEATING	a) CURRENTS	b) PRECIPITATION	c) WIND-BORNE IRREGULARITIES	d) NEUTRAL GAS WAVES	e) HM/EM WAVES	f) COMPRESSION INDUCTION (vid. sect. 6.4)
Pc-3 (5.1.2)	U 10	7	U 0	A	Y	Y	Y	Y	B	O	O	Z	O	O	Y	Z	O	A	Y
Pc-4, 5 (5.1.3)	U25	20	U 0	A	Y	Y	Y	Y	X	B	B	X	O	B	Y	X	X	O	X
Pt, Pi-2 (5.1.5)	U80	U 0	30	A	U	A	Y	Y	B	B	B	Y	O	X	Y	Z	Z	A	X
Si, ssc (5.1.6)	U 30	U 1	U 1	A	A	U	O	Y	B	B	B	Y	O	B	O	Y	Z	B	B
Bays (5.1.7)	15 (P.M.)	U 1	5	A	U	A	Y	Z	O	A	O	O	B	A	Y	O	Y	Z	O
90 - 120 sec. pulsations(5.1.8)	N.A.	U 1	U 1	U	A	A	Y	A	B	B	Y	B	O	Y	Y	O	A	Y	Y

4.2 Conclusions Regarding Measurement Techniques

4.2.1 HF Radiometer

It is concluded that :

i) while HF radiometers receiving ionospherically propagated signals record events directly associated with magnetic micropulsation events, the technique is not suited for providing quantitative information pertinent to the determination of the phenomena involved. [illegible] ons 4.2 and [illegible]4.

ii) HF propagation perturbations are more directly associated with micropulsation indices than with local K index.

4.2.2 Rapid Response Riometer

It is concluded that a sensitive riometer with wide bandwidth and rapid response time can be valuable in determining characteristics of mid-latitude ionospheric perturbations associated with magnetic micropulsations. See section 3.3.

The riometer can provide information with regard to the presence or absence of energetic particle precipitation,

and whether it is modulated at micropulsation frequencies. The riometer is quite sensitive to collision frequency perturbations, and less sensitive to electron density gradient effects, and consequently could be used to resolve an ambiguity in Doppler measurements (although amplitude or puse-type absorption measurements would also be desirable in this regard to localise the height of absorption). The riometer can be used to observe scintillations due (presumably) largely to irregularities above the peak of the F region, and consequently to determine whether perturbations observed below the F region peak by other techniques extend upwards. This is particularly important since most satellite records are intermittent. That scintillation was observed rather than ionospherically scattered interference, was concluded since commercial radio transmissions in the 30 MHz band are usually of an intermittent nature, while the 'scintillation' records exhibited a smooth envelope over periods approaching half an hour.

4.2.3 HF CW Doppler Sounding

Since even when four Doppler channels operated simultaneously, they involved reflexion from quite different

ionospheric locations, it was not possible to evaluate the relative contribution of the time perturbed gradient in electron density, vs. the time perturbed electron density at the height of reflexion. For the majority of events, Δf varies directly with carrier frequency. Sunrise and sunset events, however, exhibited higher than normal variations on the higher frequency (sections 3.5.C6, 3.5.C7. 3.6.B1). This could be attributed either to proximity to critical frequencies or possibly to an actual increase in ionospheric velocity with height. At sunrise the lowest ratio $\Delta f_{4.6} / \Delta f_{2.7}$ was 1:1, while at sunset the lowest ratio was only slightly below that. However at noon (sect. 3.5.C5) one event gave a ratio of 0.2:1. This might indicate an increased importance for the f^{-1} terms, or more likely the effect of recombination in damping motions at lower heights (sect. 3.6.B3).

Multiple echoes sometimes 'confuse' the Doppler records, particularly during magnetic storms, at sunrise and sunset, and during blanketing sporadic E events (sect. 3.6.B2). Under these circumstances the sonogram technique of Davies (1962) is superior to the frequency meter/FM discriminator technique. At other times, and particularly when circularly polarised antennas are used, the frequency meter technique yields a 'cleaner' record with somewhat better time resolution than the sonogram technique. The 2.7 MHz channel with the 50 Hz IF bandwidth gave a noticeably cleaner signal than the one with a 200 Hz bandwidth probably due to QRM reduction. It is not desirable to use high powered transmitters or any more gain

than necessary in the receivers, because of multipath broadening of the apparent Doppler bandwidth.

In the development of the Doppler equation (appendix III) it was assumed that vertical incidence was involved and that variations in ray path S could be interpreted as variations in the height of reflexion z_r (if the ray path is asymmetrical about the 'point' of reflexion then this will not be the case even at vertical incidence). At oblique incidence, especially for E-W propagation, horizontal as well as vertical ionospheric motions perturb the path length. Consequently it is not surprising that larger Doppler shifts should be associated with a given magnetic disturbance (0.6 Hz/γ vs. 0.1 Hz/γ, vid. sect. 3.6.B4) when oblique incidence signals are used. However, the additional complexities involved in determining the location and nature of the perturbations do not favour the use of oblique incidence sounding for studying magnetically associated events.

It was found that vertical speeds estimated using the time displacement between complex 2.7 and 4.6 MHz Doppler pulsation waveforms (which for reasonable distances between reflexion points generally were of the order of some km. sec.$^{-1}$) did not agree with velocities $v_z = \frac{dz_r}{dt}$ obtained using the simple moving mirror equation, which gave velocities the order of a few m.sec.$^{-1}$ or less. Horizontally moving disturbance of large vertical extent could account for this discrepancy . Or, it may simply arise because the Doppler velocity depends on the actual electron perturbations which are related to the

amplitude of any wave motion as well as to the group velocity of the disturbance. However, in the case of a sinusoidal disturbance approaching the Doppler sounder, one would expect the average value about which the pulsating frequency excursions occur to be shifted from the transmitted frequency. In general, such mean frequency displacements were not observed. Two or three examples of asymmetrical Doppler waveforms were found, but not when the 2.7 and 4.6 MHz channels were both operating.

Reinforcing the results of calculations in appendix III, concerning possible direct magnetic effects is the fact that Doppler shifts on 2.7 MHz and 4.6 MHz sometimes (e.g. Sect. 3.6.C1) exhibit (micropulsation) waveforms 180° out of phase with each other. It is unlikely that the magnetic disturbance field should reverse completely between the two heights of reflexion when both are above the E layer. This implies that the Doppler shifts are not merely direct magneto-ionic perturbations due to the varying magnetic field but rather involve electron distribution perturbations, and via the latter affect the radio-wave. (The distance is much smaller than the wavelength of any possible HM/EM ULF wave, and the peak conductivity region where disturbance currents flow is below both reflexion heights.)

4.3 Recommendations Regarding Further Theoretical Work

4.3.1 Theory of Measurement

Since vertical incidence Doppler sounding has proved capable of observing quite small ionospheric perturbations varying rapidly with time, and since no other technique is equally suitable for this purpose (integration times required for satisfactory S/N ratios using incoherent backscatter radar are too long to permit the study of rapid micropulsations) it is recommended that a theory for the calculation of Doppler shifts based on full wave theory be developed in a suitable form for numerical calculation having the magnetic field, collision frequencies, electron density gradients, and electron velocity divergences explicitly included as (possible) input variables. (An extension of the approach taken by Gill (1965) and that of Unz (1965) might prove fruitful.)

4.3.2 Theories of Ionospheric Processes

a) A theory predicting the amplitude and polarisation of magnetic perturbations to be expected due to the modulation of an E region sheet current by infra-sonic waves or ion-acoustic waves (or other gas motions not directly involving magnetic variations) is much to be desired (for the interpretation of results such as those shown in Fig. 3.6.20.

b) A computational theory of hydromagnetic wave propagation in the ionosphere with particular reference to the electron gas velocity [rather than to the electric and magnetic field components as has been done by Prince Bostick and Smith (1964)] would also be useful.

4.4 Recommendations Regarding Further Experimental Work

4.4.1

It has been established that several distinct types of low-frequency wave-like disturbances pass through the ionosphere quite often and that some of these are accompanied by directly associated magnetic variations.

Determination of the precise nature of these disturbances is within reach of current experimental techniques. By using the Doppler sounding technique it is possible to determine the vertical and horizontal components of the propagation velocity of the disturbances, while the extent to which the neutral atmosphere participates is measureable by vehicle-released chemical trail techniques. The disperion of electron gas waves in the ionosphere could also be readily measured using 3 Doppler channels.

Consequently the principal recommendation is that a suitable Doppler sounding facility be established in conjunction with an ionosonde at a projectile or rocket launching range.

While Doppler resolution of 0.05 Hz can be obtained for many disturbances and this corresponds to a velocity sensitivity of at least 5 m/sec., it may be objected that the interpretation of the Doppler shifts in terms of electron drift velocity is uncertain.

The uncertainties in interpretation can largely be eliminated using a number of practical techniques :

i) If ionograms are taken half-hourly, suitable sounding frequencies may be chosen to avoid critical frequencies and to reflect from known height levels. Moreover, the ionograms may be used to calculate the actual HF propagation paths.

ii) If three spaced receivers are used, and frequency and polarisation diversity employed, overlapping information on horizontal and vertical velocity components of a kind which would enable an estimation of the effects of electron density and velocity gradients to be evaluated, could be obtained. (In particular frequency diversity of the type suggested by Kiyanovisky (1964) involving two frequencies chosen such that the O wave of the lower frequency would be reflected at the same height as the X wave of the higher frequency, would prove valuable in this regard.)

iii) If the Doppler shift were compared with simultaneous measurements made on the drift of electrically charged chemical trails released from projectiles [Föpl et.al. (1967)] a direct evaluation of drift velocity and Doppler shift could be obtained.

iv) Higher order spectral processing may also provide velocity distribution information from a single Doppler channel. [Hasselman et al. (1963)]. Even without these techniques the relative drift velocities over time periods of the order of an hour can be measured very accurately.

v) In order to determine whether the 'speeds' measured by vertical incidence Doppler sounding are true vertical velocities rather than the effect of horizontal movements of tilted irregularities, it would be desirable to combine vertical incidence Doppler sounding with incoherent backscatter radar.

vi) Faraday rotation measurements from satellites could be compared with Doppler shift measurments to help resolve the ambiguity inherent in measurements of moving irregularities by moving satellites on the one hand, and the ambiguities concerning the relative importance of electron density and electron velocity changes in giving rise to Doppler shifts of reflected HF waves on the other.

vii) More sophisticated approaches to Doppler instrumentation might be employed: a 'chirp' or sawtooth frequency sweep over a selected range of frequencies

(with a sweep rate at least five times higher than the highest micropulsation frequency to be observed) might prove valuable in sorting out electron gasdensity gradient and velocity effects [Benjamin (1966)] . Alternatively the use of close spaced frequencies [Bello (1965)] has considerable advantages if tuned antennas are employed. The beat frequency in the Doppler receiver could be 'cleaned up' by using a correlation detector [Lee et alia (1950)]. Correlation analysis of the type used by McGee (1966) could be performed to determine dispersion and drift velocities.

4.4.2

A second recommendation is that the Doppler sounding technique applied to micropulsation and other magnetically associated motions be used to evaluate recombination rates in the ionosphere.

At night, magnetic bays are sometimes seen to be accompanied by Doppler shifts which follow the bay faithfully for two or three min. and then trail off although the bay may continue to deepen (see Fig. 3.6.7). This would tend to indicate loss of electrically transported ionisation through recombination.

In the daytime solar flare ionisation time-constant results could be supplemented by micropulsation Doppler results, (in particular solar flares involving magnetic impulses may give different Doppler shifts to those without.

4.4.3

A third recommendation is that vertical incidence Doppler sounding be employed at conjugate point stations in conjunction with micropulsation studies (particularly Pc-4, 5). One of the difficulties of micropulsation observations is that the geographic extent of regions of high coherence is rather large (1000 km.) so that it is difficult to associate micropulsations with field lines of a particular L shell. The vertical incidence Doppler technique is sensitive only to electron distribution charges occurring in a comparatively small region (5 - 50 km.) overhead and is inherently better suited to determining whether particular micropulsation periods are associated with particular magnetic field lines, (provided the Doppler perturbations are not simply the result of magnetic field changes alone.)

5.1 Appendix I

Bibliography

Abreviations of frequently cited Journal titles :

CJP	Canadian Journal of Physics
JATP	Journal of Atmospheric and Terrestrial Physics (U.K.)
J. Geomag and Aeron.	Journal of Geomagnetism and Aeronomy of the U.S.S.R. (English translation edition)
J. Geomag. and Geoelect.	Journal of Geomagnetism and Geoelectricity of the University of Kyoto, Japan
JGR	Journal of Geophysical Research (U.S.A.)
J. Plan. Sci.	Journal of Planetary and Space Science (U.K.)
Proc. I.E.E.E.	Proceedings of the Institute of Electrical and Electronic Engineers (U.S.A.) Formerly Proc. I.R.E.
Rad. Sci.	Radio Science (U.S.A.) Formerly Jour. Res. N.B.S.Part D
Rep. Ionos. Res.	Report of Ionospheric and Space Research in Japan

APPENDIX I

BIBLIOGRAPHY

Agy, V., Baker, D.M., and Jones, R.M. (1965), Studies of Solar Flare Effects and Other Ionospheric Disturbances with a High Frequency Doppler Techniques, NBS (ESSA/ITSA) Tech. Note 306.

Agy, V. and Davies, K. (1959), Ionospheric Investigations Using the Sweep-Frequency Pulse Technique at Oblique Incidence, J. Res. NBS 63D, 151 -

Akasofu, S.I. (1960), On the Ionospheric Heating by Hydromagnetic Waves Connected with the Geomagnetic Micropulsations, JATP 18, 160 - 173.

Akasofu, S.I. and DeWitt, R.M. (1965), Dynamo Action in the Ionosphere, Plan. Space Sci. 13, 737 - 744.

Allen, R.S., Aarons, J. and Whitney, H. (1964), Measurement of Radio Star and Satellite Scintillations at a Subauroral Latitude, IEE. Trans. Ant. and Prop'n. Ap12, 812 - 822.

Al'pert, Ya. L. (1960), Radio Wave Propagation and the Ionosphere, Eng. Trans. Consultants Bureau, N.Y. (1963).

Appleton, Sir E.A. (1953), A Note on the Sluggishness of the Ionosphere, JATP 3, 282 - 284.

Ashour, A.A. and Ferraro, V.C. (1962), Induction of Electric Currents in a Uniform Anisotropic Ionosphere, Nature 196, 260.

Axford, W.I., Cunnold, D.M. and Gleeson, L.J. (1966), Magnetic Field Variations in Temperate Zone Sporadic E Layers, Plan. Space Sci. 14, 909 - 919.

Barry, G.H., Griffiths, L.J. and Taenzer, J.C. (1966), HF Radio Measurement of High-altitude Acoustic Waves from a Ground-level Explosion, JGR 71, 4173 - 4182.

Bates and Nicolet (1962), vid. Nicolet (1962).

Becker, W. (1961), vid. Becker W. et alia (1965).

Becker, W., Rüster, R. and Klostermeyer, J. (1965), Experimental Results on the Dynamics of the F region, Radio Science 69D, 1083 - 1087.

Bello, P.A. (1965), Some Techniques for Instantaneous Real-time Measurement of Multipath and Doppler Spread, IEEE. Com. Tech. Trans. COM-13, 285 - 292.

Belrose, J. (1965), Private communication; see Straker (1955).

Bendat, J. (1958), vid. p. 128, Principles and Application of Random Noise Theory. J. Wiley, N.Y.

Benjamin, R. (1966), Modulation, Resolution and Signal Processing in Radar, Sonar and Related Systems, Pergamon London.

Blackman, R.B. and Tukey, W. (1958), The Measurement of Power Spectra, Dover, N.Y.

Bowles, K.L., Balsey, B.C. and Cohen, R. (1963), Field-aligned E Region Irregularities Identified with Acoustic Plasma Waves, JGR 68, 2485 - 2501.

Bowles, K.L., Cohen, R., Ochs, G.R. and Balsey, B. (1960), Radar Echoes from Field-aligned Ionisation Above the Magnetic Equator and Their Resemblance to Auroral Echoes, JGR 65, 1853 - 1855.

Boyd, G. (1966), Solar Eclipse Observations and Pc-1 Geomagnetic Micropulsations, Earth and Plan. Sci. Letters 1, 333 - 334.

Briggs, B.H. (1965), The Relation Between Spread F and Magnetic Disturbance, JATP 27, 991 - 994.

Brown, R.R. and Campbell, W.H. (1962), An Auroral-zone Precipitation Event and its Relationship to a Magnetic Bay, JGR 67, 1357 - 1366.

Budden, K.G. (1961), Radio Waves in the Ionosphere, Cambridge Univ. Press; also Lectures on Magneto-ionic Theory, Gordon and Breach, N.Y. (1964).

Burrows, K. and Hall, S.H. (1965), Rocket Measurements of the Geomagnetic Field above Woomeda, South Australia, JGR 70, 2149 - 2158.

Cahill, L.J. (1959) Magnetic Exploration of the Upper Atmosphere. p12 IGY ROCKET REPORT #4.

Campbell, W.H. (1961), Auroral Couscations and Geomagnetic Micropulsations, JGR 66, 41 - 55.

Campbell, W.H. and Matsushita, S. (1962), Auroral Zone Geomagnetic Micropulsations with Periods 5 to 30 Seconds, JGR 67, 555 - 573.

Caner, B. (1966) Private communication. Also see: Lambert & Caner (1965) Can.Jour.Earth Sci. 2, 485-509.

Chan, K.L., Kanellokos, D.P. and Villard, O.G. (1962), Correlation of Short-period Fluctuations of the Earth's Magnetic Field and Instantaneous Frequency Measurements, JGR 67, 2066 - 2072.

Chapman, S. (1963), Solar Plasma Geomagnetism and Aurora, in Geophysics, the Earth's Environment, eds. DeWitt, H.C., Hieblot, J. and LeBeau, A., Gordon and Breach, N.Y.

Chapman, S. and Akasofu, S.I. (1964), On the Asymetric Development of Magnetic Storm Fields in Low and Middle Latitudes, Plan. and Space Sci. 12, 607 - 626.

Chapman, S. and Bartels, J. (1940), Geomagnetism, 2 vols., Oxford Univ. Press.

Cole, K.D. (1962), Atmospheric Blow-up at the Auroral Zone, Nature 194, 761.

Cole, K.D. (1964), A Theory of the Dst Main Phase and Certain Associated Phenomena Based on Geomagnetic Fluctuations, contribution No. 20 in USA/NBS report number 8815, Symposium on Ultra Low Frequency Electromagnetic Fields, Boulder, Colo.

Cummings, W.D. Dessler, A.J. (1967) Field Aligned Currents in the Magnetosphere. JGR 72 1007-1042.

D'Angelo, N. and Michelsen, R. (1967), The Fine Structure of the Ionosphere, JGR 72, 2045 - 2097.

Davies, K. (1962 a), Doppler Studies of the Ionosphere with Vertical Incidence, Proc. IRE 50, 94 - 95; vid. also Davies (1962 c).

Davies, K. (1962 b), The Measurement of Ionospheric Drifts by Means of a Doppler Shift Technique, JGR 67, 4909 - 4913.

Davies, K. (1962 c), Correction to 'Doppler Studies of the Ionosphere with Vertical Incidence', Proc. IRE 50, 1544.

Davies, K., Watts, J.M. and Zacharisen, D.H. (1962 d), A Study of F_2 Layer Effects as Observed with a Doppler Technique, JGR 67, 601 - 609.

Davies, K. (1963), Doppler Studies of Ionospheric Effects of Solar Flares, Proc. Int. Conf. on the Ionosphere, London, 1962, Institute of Physics and the Physical Society, London.

Davies, K. (1965) , Ionospheric Radio Propagation, U.S. Dept. of Commerce, Nat. Bu. Stds., Monograph 80.

Davies, K. Baker, D.M. Solar Flare Effects and the Relaxation Time of the Ionosphere. JGR 71 2840-2842.

Davies, K. and Baker, D. (1966b), On Frequency Variations of Ionospherically Propagated HF Radio Signals, Rad. Sci., 1, 545 - 556.

Dessler, A.J., Francis, W.E. and Parker, E.N. (1960), Geomagnetic Storm Sudden-commencement Rise Times, JGR 65, 2715 - 2720.

Donnelly, R.F. (1966), An Investigation of Sudden Frequency Deviations Due to the Immediate Ionospheric Effects of Solar Flares, (Feb. 21, 1966), Ph.D. Thesis, Univ. Illinois, May 6, 1966, to be pub'd. as ESSA Tech. Report.

Duffus, H.J., Kinnear, J.K., Shand, J.A., Wright, Sir C.S. (1962) Spatial Variations in Geomagnetic Micropulsations Can. Jour. Physics 40, 1133 -1152.

Duffus, H.J. (1960), A Connexion Between Pc and the F Region, Nature 188, 719 - 721, Nov. 26, 1960.

Duffus, H.J. and Kinnear, J.K. (1962), Spatial Variations in Geomagnetic Micropulsations, CJP 40, 1133 - 1152.

Duffus, H.J. and Boyd, G.M. (1967), Geomagnetic Coupling in the Ionosphere, JATP in press.

Duffus, H.J., Boyd, G.M., and Kinnear, J.K. (1965), Radio Fading and the Natural Electromagnetic Background, CJP 43, 1951 - 1961.

Dungey, J.W. (1955), Electrodynamics of the Outer Atmosphere, p. 299 in Report of the Physics Society Conference on Physics of the Ionosphere (1955), London, 1956.

Evans, P.J. (1960) Technical report B427, and laboratory notes: 60-11, and 63-1. Pacific Naval Laboratory DRB. Canada. CFB. Victoria B.C.

Farley, D.T.N. (1960), A Theory of Electrostatic Fields in the Ionosphere at Non-polar Latitudes, JGR 65, 869 - 877.

Farley, D.T.N. (1963), A Plasma Instability Resulting in Field-aligned Irregularities in the Ionosphere, JGR 68, 6083 - 6098.

Fatkulin, M.N. (1963), Dynamo Field Heating of the Ionosphere, Geomag. and Aeronomy, 3, 620 - 621.

Fatkulin, M.N. (1964), Electrical Conductivity of the Ionosphere, Geomag. and Aeronomy 4, 86 -

Findlay, J.W. (1951), The Phase and Group Paths of Radio Waves Returned from Region E of the Ionosphere, JATP 1, 353 - 366.

Findlay, J.W., et alia (1961), Vertical Incidence Doppler Ionogram (correspondence), Proc. IRE 49, 1220.

Föpl , H., Haerendel, G., Haser, L., Loidl, J., Lütjens, P., Lüst, R., Melzner, F., Meyer, B., Neuss, H. and Rieger, E., (1967), Artificial Strontium and Barium Clouds in the Upper Atmosphere, J. Plan. Space Sci. 15, 357 - 372.

Fooks, G. (1962), Ionospheric Irregularities and the Phase-paths of Radio-waves, JATP 64, 937 - 947.

Fooks, G. and Morgan, D.P. (1967), Power Spectra of Geomagnetic Micropulsations, JATP 29, 201 - 206.

Francis, W.E., Karplus, R. and Dragt, A.J. (1962), The Attenuation of Hydromagnetic Waves in the Ionosphere, Plan. and Space Sci. 9, 771 - 785.

Friedman, J.P. (1966), Propagation of Internal Gravity Waves, in a Thermally Stratified Atmosphere, JGR 71, 1033 - 1054.

Georges, T.M. (1967), Evidence for the Influence of Atmospheric Waves in Ionospheric Motions, JGR 72, 422 - 425.

Gill, T.P. (1965), The Doppler Effect, Logos Press, London 1965.

Gledhill, J.A., Torr, D.G., Torr, M.R. (1967), Ionospheric Disturbance and Electron Precipitation from the Outer Radiation Belt, JGR 72, 209 - 214.

Goodman, N.R. (1957), On the Joint Estimation of the Spectra, Cospectrum and Quadrature Spectrum of a Two Dimensional Stationary Gaussian Process, Scientific Paper Number 10, Engineering Statistics Laboratory, New York Univ., N.Y.

Goodwin, G.L. (1966), The Dimensions of Some Horizontally Moving E_s Irregularities, Plan. and Space Sci. 14, 759 - 772.

Grigor'Yev, G.I. (1964), Geomag. and Aeronomy IV, 140 - 141.

Greifinger, C. and Greifinger, P. (1965), Transmission of Micropulsations Through the Lower Ionosphere, JGR 70, 2217 - 2332.

Haerendel, G., Lüst, R. and Rieger, E. (1967), Motion of Artificial Ion Clouds in the Upper Atmosphere, Space Res. 7, 78 - 86.

Hansen, W.B. ; McKibbon, D.D. and Sharpe, G.W. (1964), Some Ionospheric Measurements with Satellite-borne Ionisation Traps, JGR 69, Number 12, 2747 - 2763.

Harang, L. (1939), Pulsations in an Ionized Region at a Height of 650 - 800 km. During the Appearances of Giant Pulsations in the Magnetic Records, Terr. Mag. 44, 17 - 19.

Hasselmann, K., Munk, W. and MacDonald, G. (1963), Bispectra of Ocean Waves, pp. 125 - 139 in Time Series Analysis, ed. Rosenblatt, M., Wiley, N.Y. (1963).

Heissler, L.H. (1967), Travelling Ionospheric Disturbances, Space Research 7, 55 - 66.

Heppner, J.P. (1958), A Study of Relationships Between the Aurora Borealis and the Geomagnetic Disturbances Caused by Electric Currents in the Ionosphere, Report DR 135, Defence Research Board of Canada.

Herron, T.J. (1966), Phase Characteristics of Geomagnetic Micropulsations, JGR 71, 871 - 890, see also Lawrie,(1963)

Hewish, A. (1952), The Diffraction of Galactic Radio Waves as a Method of Investigating the Irregular Structure of the Ionosphere, Roy. Soc. Lond. Proc. A 214, 494 - 514.

Hill, G.E. (1963), Sudden Enhancements of F Layer Ionisation in Polar Regions, J. Atmos. Sci. 20, 492 -

Hines, C.B. (1963), Geomagnetism and the Ionsophere, in Proc. of the Int. Conf. on the Ionosphere, London, 1962. Phys. Soc. and Institute of Physics, London.

Hines, C.O. (1964), Ionospheric Movements and Irregularities, Chap. XII in Research in Geophysics, Vol. 1, ed. Odishaw, H. MIT, Cambridge, Mass. (1964).

Hines, C.O. (1965 a), Motions of the Neutral Atmosphere, Chapter 6 in Physics of the Earth's Upper Atmosphere, ed. by Hines, Paghis, Hortz, Fejer, Prentice Hall, (1965).

Hines, C.O. (1965 b), Hydromagnetic Resonance in Ionospheric Waves, JATP 7, 14 - 30.

Hines, C.O. (1967), Tidal Oscillation, Shorter-period Gravity Waves, and Shear Waves, Space Res. 1, 30 - 41.

Hines, C., Paghis, I., Hartz, C. and Fejer, J. (1965 a), Physics of the Earth's Upper Atmosphere, Prentice Hall, N.J., 1965.

Hutchinson, R. and Shuman, B. (1961), Rocket Measurements of the Magnetic Field Above New Mexico, JGR 66, 152 - 158.

Jacobs, J.A. (1962), Characteristics of Geomagnetic Pulsations, Jour. of the Phys. Soc., Japan, 17, Supplement A - II, Part II, 55 - 63.

Jacobs, J.A., Kato, Y., Matsushita, S. and Troitshaya, V.A., (1964), Classification of Geomagnetic Micropulsations, JGR 69, 18P - 181.

Jacobs, J.A., Rostoker, G. and Watanabe, T. (1965), World Wide Propagation of Impulsive Micropulsation Activity Through the Ionosphere, Nature 215, 61 - 62.

Jacobs, J.A. and Watanabe, T. (1966), Doppler Frequency Changes in Radio Waves Propagating Through a Moving Ionosphere, Rad. Sci. 1, 257 - 264.

Jacobs, J.A. and Westphal, K. (1962), Oscillations of the Earth's Outer Atmosphere and Micropulsations, The Geophysical Journal of the Royal Astronomical Society 6, 360 - 376.

Jasik, H. ed. Antenna Engineering Handbook McGraw Hill N.Y. (1961)

Jones, D. and Maude, A.D. (1965), Evidence for Wave Motion in the E Region in the Ionosphere, Nature 206, 177 - 179.

Jones, T.B. (1964), Ionospheric Disturbances Observed by Means of Standard Frequency Transmissions at Oblique and Vertical Incidence, JATP 26, 1294 - 1298.

Kamiyama, H. (1956), Ionospheric Changes Associated with Geomagnetic Bays, Sci. Rep't., Tohoku Univ., (Ser.5) 7, 125 - 135.

Kato, S. (1962), Joule Heating and Temperature in the Upper Atmosphere, Plan. and Space Sci. 9, 939 - 946.

Kato, S. (1964), Movement of Ionised Irregularities in the Upper Atmosphere, Plan. and Space Sci. 12, 1 - 10.

Kato, Y. and Sato, Y. (1965), Effect of the Anisotropic Ionosphere on the Hydromagnetic Oscillations, Sci. Rep. Tohoku Univ. 16, 123 - 145.

Kato, Y. and Tamao, T. (1962), On a Possible Mechanism for the Rules of Polarisation of Pc-5 Geomagnetic Pulsations, Sci. Rep't. Tohoku Univ. (Ser.5) 16, 15 - 36.

Kato, Y. and Watanabe, T. (1956), Studies on PSC, Rep. Ionos. Res. Japan, 10, 69 - 80.

Kavadas, A. and Johnson, D.W. (1963), Electron Densities and Electric Fields in the Aurora, Space Res. 4, 365 - 370.

Kazmirovsky, E.S. (1963), F Region Drifts and Dynamo Theory, Geomag. and Aeronomy, 3, 726 - 731.

King, G.A.M. (1966), The Ionosphere Disturbance and Atmospheric Waves, JATP 28, 957.

Kiyaovsky, M.P. (1963), A Method for Determining Drift Rate in the Ionosphere, Geomag. and Aeronomy USSR, 3, 563 - 565.

Kiyanovskiy, M.P. (1964), Measurement of Ionospheric Drift, Geomag. and Aeronomy 4, 751.

Kokurov, V.D. (1963), Relationships Between Some Ionospheric Characteristics and Geomagnetic Activity, Geomag. and Aeronomy 3, 800 - 801.

Lambert, A. and Caner, B. (1965), Geomagnetic Depth Sounding and the Coast Effect in Western Canada, Can. Jour. of Earth Sci. 2, 485 - 509.

Lauter, E.A. (1967), Present Research Aspects in Ionosphere-Stratosphere Coupling Effects, Space Res. VII, 212-227.

Lawrie, J.A. (1963 a), The Spatial Distribution of Rapid Geomagnetic Fluctuations, Geomag. Jour. Royal Astronomical Soc. 7, 102 - 130 and 328 - 360.

Lee, Y.W., Cheatham, T.P. and Wiesner, J.B. (1950), Application of Correlation Analysis to the Detection of Periodic Signals in Noise, Proc. IRE 38, 1165 - 1171.

Lehnert, B. (1956), Magneto Hydrodynamic Waves in the Ionosphere, Tellus 8, 241 - 251.

Lewis, T. (1964), The Correlation of Geomagnetic Field Changes with Ionospheric Motions, Determined by a Doppler Technique, M.Sc. Thesis, Univ. British Columbia, Geophysics Dept.

Lewis, T.J. (1967), The Association of Phase Changes of Ionospheric-propagating Radio Waves and Geomagnetic Variations, CJP 45, 1549 - 1563.

Lichtenstein, P.R. (1966), 18 mc/s Auroral Absorption in Middle Latitudes, JGR 71, 1899 - 1910.

Little, C.G. and Leinbach, H. (1959), The Riometer, a Device for Continuous Measurement of Ionospheric Absorption, Proc. IRE 47, 315 - 320.

McCrary, D.R. (1966), Recombination Co-efficient of the Night-time F Region from Incoherent Scatter Measurements, Ionosphere Research Laboratory, Pennsylvania Sate Univ., Sci. Rep't. No. 279.

McGee, C.R. (1966) On the Nature of Movements in the Ionosphere. JATP 28 861-869.

McNish, A.G. (1937) Terrestrial Magnetic and Ionospheric effects associated with Solar Flares. Terrestrial Magnetism 42, 109-122.

MacDonald, G.J.F. (1963), Motions in the High Atmosphere, pp. 591 - 624 in Geophysics The Earth's Environment, ed. DeWitt, H.C., Hieblot, J. and LeBeau, A., Gordon and Breach, London (1963).

MacLeod, M.A. (1966), Sporadic E Theory. 1. Collision-Geomagnetic Equilibreum, J. Atmos. Sci. 23, 96 - 109.

Maeda, H. (1959), Horizontal Winds and Ionisation Drifts in the Ionosphere, Rep. Ionos. and Space Res. Japan, 13, 79 - 89.

Maeda, K. (1953), The Vertical Distribution of Electrical Conductivity in the Upper Atmosphere, Jour. of Geomag. and Geo-electricity, 5, 94 - 104.

Maeda, K. (1965), Infra-sonic Waves from Aurorae, Nature 205, 279 - 281.

Maeda, K and Watanabe, T. (1963), Infra-sonic Waves from the Auroral Zone, Goddard Space Flight Centre, Technical Rep't. X 640 - 63 - 247.

Maeda, K. and Watanabe, T. (1964), Pulsating Aurorae and Infrasonic Waves in the Polar Atmosphere, Jour. Atmos. Sci. 21, 15 - 29.

Maple, E. (1959), Geomagnetic Oscillations at Middle Latitudes, JGR 64, 1395 - 1409.

Martyn, D.F. (1954), Interpretation of Observed F_2 'Winds' as Ionisation Drifts Associated with the Magnetic Variations, p. 163 in Report of the Physics Society Conference on the Physics of the Ionosphere, Phys. Soc. London, (1954).

Matsushita, S. (1965), Ionospheric Perturbation (The Roles Played by the Ionosphere in Geomagnetic Pulsations), Radio Science 69D, 1149 - 1159.

Matuura, N. (1959), Some Remarks on Motion of Ionospheric Irregularity, Rep't. Ionos. and Space Res. Japan 13, 4 - 20.

Meecham, V.C. (1965), Simplified Normal Mode Treatment of Long-period Acoustic-gravity Waves in the Atmosphere, Proc. IEEE, 53, 2079 - 2087.

Megill, L.R. and Carleton, N.P. (1963), Excitation by Local Electric Fields in the Aurora and Airglow, JGR 69, 101 - 121.

Milton, D.W., McPherron, R.L., Anderson, K.A. and Ward, S.H., (1967), Direct Correspondence Between X-Ray Micro-bursts and Impulsive Micropulsations, JGR 72, 414 - 417.

Mirektam, S.F. and Drachev, L.A. (1959), Phase-method Study of Large-scale Inhomegeneities in the Ionosphere, Canada DRB Translation T314R.

Mitra, S.K. (1952), The Upper Atmosphere, Asiatic Soc. Calcutta.

Mitra, S.N. (1952), Spaced Receiver Technique for the Study of Ionospheric Drifts, Jour. of Sci. and Industrial Res. India, 11, 453 - 454.

Moffat, H.K. (1962), Intensification of the Earth's Magnetic Field by Turbullence in the Ionosphere, JGR 67, 3071 - 3073.

Mozer, F.S and Brustan, P. (1967), Electric Field Measurements in the Auroral Ionosphere, JGR 72, 1109 - 1117.

Muldrew, D.B. (1959), An Ionospheric Ray-tracing Technique and its Application to a Problem in Long Distance Radio Propagation, IRE Trans. Ant. and Prop'n. AP-7, 393 - 396.

Muldrew, D.B. (1965), F Layer Ionisation Troughs Deduced from Allouette Data, JGR 70, 2635 - 2650.

Munk, W.H., Snodgras F.E., Tucker, M.J. Spectra of low Frequency Ocean Waves. Bulletin of the Scripps Institution of Oceanography 7, 283-362. (1959)

Nagata, T., Kokubon, S. and Lijina, T. (1963), Geomagnetic Conjugate Relations of Giant Pulsations at Syowa Base Antarctica, JGR 68, 4621 -

Nathan, K.V.S.K. (1966), Particle Heating Effects in the Upper F Region, Plan. and Space Sci. 14, 717 - 730.

Nelms, G.L. and Lockwood, G.E.K. (1967), Early Results from the Topside Sounder in the Allouette II Satellite, pp. 604 - 624 in Space Research VII, North Holland Pub. Co. Amsterdam (1967).

Nicolet, N. (1962), Composition and Constitution of the Earth's Environment, pp. 201 - 280 in Geophysics of the Earth's Environment, ed. by DeWitt, C., Hieblot, J., and LeBeau, A., Gordon and Breach, N.Y. (1963).

Nishida, A. (1964a) Theory of Irregular Magnetic Micropulsations Associated with a Magnetic Bay, JGR 69, 947 - 954.

Nishida, A. (1964b) Ionospheric Screening Effect and Storm Sudden Commencement, JGR 69, 1861 - 1874.

Norton, R.B., Vanzandt, T.E. and Denison, J.S. (1963), A Model of the Atmosphere and Ionosphere in the E and F_1 Regions, pp. 26 - 34 in Proceedings of the International Conference on the Ionosphere 1962, The Institute of Physics and the Physics Society, London (1963).

Obayashi, T. (1963), The Electrical State of the Upper Atmosphere, Univ. of British Columbia, Institute of Earth Sciences, Sci. Rep't. No.7, Sept. 23, 1963.

Ogawa, T. (1960), Ionosphere Observations by Doppler Effect, Rep't. Ionos. Res. Japan 14, 133 - 147.

Ohl, A.I. (1962), Pulsations During Sudden Commencements of Magnetic Storms and Long Period Pulsations in High Latitudes, Jour. Phys. Soc. Japan, 17, Supplement A - II, pp. 24 - 26.

Osborne, D.G. and Skinner, N.J. (1963, Equatorial Drift and the Electrojet, JGR 68, 2441 - 2444.

Parasarathy, R. and Hessler, V.P. (1964), Periodic Covariation of Radiowave Absorption, Earth Currents, and Other Associated Phenomena in the Auroral Zone, JGR 69, 2867 - 2871.

Patel, V.L. (1966), A Note on the Propagation of HM Waves in the Magnetosphere, Earth and Plan. Sci. Letters 1, 282 - 283.

Paulsen, K.V. and Shepherd, G.G. (1966), Fluctuations in Brightness from Quiet Form Auroras, CJP 44, 837 - 866.

Petrie, L.E. and Stevens, E.E. (1965), An F_1 Layer MUF Prediction System for Northern Latitudes, IEEE Trans. Antennas and Propagation, AP - 13, 542 - 546.

Pfeffer, R.L. (1962), A Multi-Layer Model for the study of Acoustic-Gravity Wave Propagation in the Earth's Atmosphere, Jour. Atmos. Sci. 19, 251-255.

Pitteway, M.L.V. and Hines, C.D. (1965), The Reflection and Ducting of Atmospheric Acoustic Gravity Waves, CJP 43, 2222 - 2243.

Poeverlein, H. (1967) Characteristic Heights of Hydromagnetic Processes in the Atmosphere. JGR 72 251-256.
-See also Papa, R.J. Basic Relaxation Times Characterizing Electromagnetic Field-Plasma Interactions. Proc. IEEE (1966) 54 1188-1189.

Press, F and Harkrider D. (1962), Propagation of Acoustic Gravity waves in the Atmosphere, JGR 67, 3889 - 3908.

Price, A.T. (1965), Effects of Induced Earth Currents on Low Frequency EM Oscillations, Radioscience 69D, 1161 - 1168.

Prince C.E. and Bostick, F.X. (1963), General Dispersion Relations for a Partially ionised Gas, Report No. 129, Electrical Engineering Research Laboratory, The University of Texas.

Prince, C.E., Bostick, F.X. and Smith, H.W. (1964), A Study of the Transmission of Plane Hydromagnetic Waves Through the Ionosphere, Report No. 134, Electrical Engineering Research Laboratory, University of Texas.

Rao, N.N., Swarm, H.M. and Harrison, A. E., (1964), Experimental Determination of the Absolute Phase Path of Radio-Waves Reflected from the Ionosphere at Normal Incidence, Proc. I.E.E.E., 858 - 859.

Radoski, H.R. (1966) Uncoupled Magneto-Acoustic Propagation in a Dipole Field. Geomag.&Geoelect. 18 pp 431-436.

Ratcliffe, J.A. (1959 a), Magneto-Ionic Theory, Cambridge Univ. Press.

Ratcliffe, J.A. (1959 b), Ionisations and Drifts in the Ionosphere, JGR 64, 2102 - 2111.

Ratcliffe J.A., and Weekes, K. (1960) A Summary of Ionospheric Dynamo and Drift Theory. p392 et seq. in Physics of the Upper Atmosphere Academic Press N.Y.

Rishbeth, H. (1963), Ionospheric Storms and the Morphology of Magnetic Disturbance, Plan. and Space Sci. 11, 31 - 43.

Rishbeth, H. (1967), A Review of Ionospheric F Region Theory, Proc. IEEE 55, 16 - 35.

Rishbeth, H. and Garriott, O.K. (1964), Relationship Between Simultaneous Geomagnetic and Ionospheric Oscillations, Radio Science 68D, 339 - 343.

Rostoker, G. (1965), Propagation of Pi-2 Micropulsations Through the Ionosphere, JGR 70, 4388 - 4389.

Rostoker, G. (1966 a), The Characteristics and World-wide Propagation of Pi-2 Micropulsations, Ph.D. Thesis, Univ. of British Columbia Geophysics Dept.

Rostoker, G. (1966 b), Mid-latitude Transition Bays, JGR 71, 79 - 95.

Rostoker, G. (1967), The Polarisation Characteristics of Pi-2 Micropulsations and Their Relation to the Determination of Possible Source Mechanisms for the Production of Night-time Impulsive Micropulsation Activity, CJP 45, 1319 - 1335.

Rosenberg, N.W. and Edwards, H.D. (1964), Observations of Ionospheric Wind Patterns Through the Night, JGR 69, 2819 - 2826.

Rothwell, P. (1963) , Diffusion of Ions Between F Layers at Magnetic Conjugate Points.

Rüster, R. (1965), Height Variations of the F_2 Layer Above Tsumeb, JATP 27, 1229 - 1245.

Saito, T. (1966), A Review of the Research on Geomagnetic Pulsation in Japan, USA/ESSA Tech. Rep't. IER 15-ITSA 15.

Saito, T. and Matsushita, S. (1967), Geomagnetic Pulsations Associated with Sudden Commencements and Sudden Impulses, Plan. and Space Sci. 15, 573 - 587.

Sato, T. (1956) Disturbance in F_2 Region Associated With Magnetic Storms. Rept. Ionos. Res. Jap. 10, 35-48.

Sato, T. (1963), The Evidence of Charged Particles into the Upper Atmosphere and Relations to Sudden Commencements, Geomagnetic Storms and to Giant Pulsations at High Latitudes, pp. 155 - 162 in Proc. of the International Conference on the Ionosphere London 1962, The Inst. of Phys. and the Phys. Soc. London.

Scarf, F.L., Crook, G.M. and Fredricks, R.W. (1965), Preliminary Report on Detection of Ion-Waves in the Magnetosphere, JGR 70, 3045 - 3060. See also D'Angelo and Maeda, JGR 72, No. 7, 2045 - 2047.

Sechrist, C.F. Jr. (1962), Very Low Frequency Phase Perturbations Observed During Geomagnetic Storms, JGR 67, 1685 - 1686.

Sessler, G.M. (1964), Propagation of Longitudinal Waves in a Weakly Ionized Gas, Physics of Fluids 7, 90 - 95.

Shepherd, R. and Lomax, J.B. (1967), Frequency Spread in Ionospheric Radio Propagation, IEEE Trans. Com Tech. COM-15, 268 - 275.

Shrestha, K.L. (1967), Observation of Infrasonic Waves in the F Region of the Ionosphere, JATP 29, 107 - 112.

Stegelman, E.J. and Kenschitski, C.H. (1964), On the Interpretation of the Sudden Commencement of Geomagnetic Storms, JGR 69, 139 - 155. Vid. also 'Author's reply to the Preceding Discussion', JGR 69, 3748.

Stix, T.H. (1962), The Theory of Plasma Waves, McGraw Hill N.Y.

Straker, T.W. (1955), The Ionospheric Reflection of Radio-waves of Frequency 16 Kc/s over Short Distances, Proc. IEE 102, P't. C., 396. (UK)

Suguira, M. (1953), The Solar Diurnal Variations in the Amplitude of Sudden Commencements of Magnetic Storms at the Geomagnetic Equator, JGR 58, 558 - 559.

Swift, D.W. (1965), A Mechanism for Energising Electrons in the Magnetosphere, JGR 70, 3061 - 3073.

Thomas, J.A. (1962), Report on Recent E_s Work in Brisbane, in Ionospheric Sporadic E, ed. E.K. Smith, and S. Matsushita, Pergamon Press, N.Y. (1962).

Thomas, J.A. and McNichol, R.W.E. (1955), Automatic Recording of the Direction of Arrival of Radio Waves Reflected from the Ionosphere, Proc. of the Institute of Electrical Engineers, Great Britain, Part 3, 102 793 - 799.

Titheridge, J.E. (1967), Calculation of the Virtual Height and Absorption of Radio Waves in the Ionosphere, Radio Science 2, 133 - 138.

Tintner, G. (1965), Some Topics in Time Series Analysis, Part 3, in Econometrics, Science Editions, John Wiley, N.Y. (1965).

Tsedilina, Ye. (1962), The Doppler Effect in the Magneto-active Ionosphere, Geomag. and Aeronomy II, 717 - 723.

University of Alaska (1966), Geophysical Institute, ed. Hessler, V.P., High Latitude Geophysical Data, Continuing Series.

Unz, H. (1965), Drifting Plasma Magneto-ionic Theory for Oblique Incidence, IEEE Trans. Ant. and Prop'n., AP-13, 595 - 600.

Walker, C.G. (1966), Electric Field Heating of D-region Electrons, Plan. and Space Sci. 14, 987 - 990.

Watanabe, T. (1957), Electrodynamical Behaviour and Screening Effect of the Ionosphere, Sci. Rep. Tohoku Univ. (Ser.5) 9, 81 - 98.

Watanabe, T. (1959), Hydromagnetic Oscillation of the Outer Ionosphere and Geomagnetic Pulsation, Jour. Geomag. and Geo-electricity, Kyoto, 10, 195 -

Watanabe, T. (1961 a), Wave in a Rarefied Ionized Gas Propagated Transverse to an External Magnetic Field, CJP 1044 - 1057.

Watanabe, T. (1961 b), Alfvén Waves in Partially Ionized Gases, CJP 39, 1197 - 1211.

Watanabe, T. (1962), Law of Electric Conduction for Waves in the Ionosphere, JATP 24, 117 - 125.

Watt, T.M. (1964), Phase Height Oscillations in the Ionosphere, Stanford Electronics Labs. Radioscience Tech. Rep't. No. 7, SU-SEL-64-061.

Weaver, P.F., Tsunoda, R.T. and Yuen, P.C. (1967), Detection of Abrupt Changes in the Ionosphere Using a Doppler Technique, paper given at the Spring URSI meeting in Ottawa, 1967.

Wescott, E.M. and Hessler, U.P. (1962), The Effect of Topography and Geology on Telluric Currents, JGR 67, 4813 - 4823.

Wescott, E.M. and Mather, K. (1964), An Investigation of Solar Induced Phenomena at Conjugate Points, Univ. Alaska Geophysicist Report, AFCRL-64-274, 2 Vols.

Whitham, K. (1960), Measurement of the Geomagnetic Elements, pp. 104 - 167 in Methods and Techniques in Geophysics Vol. I, ed. Runcorn, S.K., Interscience, N.Y.

Whitten, R.C. and Poppoff, I.G. (1965), Physics of the Lower Atmosphere, Prentice Hall, N.J.

Wickersham, A.F. (1965), Comparison of Velocity Distributions for Acoustic Gravity Waves and Travelling Ionospheric Disturbances, JGR 70, 4875 - 4883.

Wilhelm, K. (1967), Geomagnetic Pulsations and Electron Gremsstruhlung in the Northern Auroral Zone, JGR 72, 1995 - 1999.

Willmore, A.P. (1966), Ionospheric Irregularities, in Progress in Radio Science 1963 - 1966, URSI Munich (1966).

Ziauddin, S. (1960), Simultaneous Observations of Pulsations in the Geomagnetic Field and in Ionospheric Absorption, CJP 38, 171.

5.2 Appendix II A

The Continuity Equation for the Electron Gas (or Fluid) in the Ionosphere

The theory which is relevant to a study of association between geomagnetic variations and ionospheric radiowave propagation perturbations is that which pertains to the electron density distribution and collision frequency distribution, and relates them to electric currents, or magnetohydrodynamic waves in the ionosphere. In particular processes which can result in rapid changes in electron density and velocity, are of interest.

In general, the electron density distribution is given by the equation of continuity :

$$\frac{\partial N_e}{\partial t} = q - L(n) - D \nabla^2 (N) - \vec{v} \cdot \nabla(N\vec{v}) \qquad (5.2.1)$$

(Similar equations apply to the ions and neutral particles; however, at this juncture, only the electron gas equation is considered.)

In this equation :

N is the ion or electron number density

q is the rate of production by photo-ionisation

$L(N)$ is the rate of loss by dissociative recombination, and by attachment to neutral molecules

$D \nabla^2 (N)$ represents loss by (isotropic) diffusion

$\vec{v} \cdot \nabla(N\vec{v})$ represents transport by various drift processes

There are two types of terms involved in the continuity equation; those which represent possible interactions between magnetic field changes and the electron density distribution and those which merely affect the rate of such changes. The processes which control q , $L(N)$ and $-D\,\nabla^2(N)$ are in general only subject to second order interaction with the magnetic and electric fields and consequently these may be regarded as response-limiting terms. Many of the processes which effect the term $\vec{v}\,.\overrightarrow{\nabla(N\vec{v})}$, that is to say lead to ordered motion or drift of charge density or directly dependent on electric and magnetic fields, are possible interaction terms in fact.

The limiting terms will be considered first. They are as follows :

i) q , the production of electrons by photo-ionisation at a rate of q electrons m^{-3} sec.$^{-1}$. Production by precipitation when it occurs must be treated separately [Lichtenstein (1966)].

q depends on the cosine of the solar zenith angle and therefore attains its maximum value near noon, and at a height of about 150 km. For sunspot minimum and mid-latitude, q max. is about 10^9 e m^{-3} sec.$^{-1}$. [Al'pert (1960)]

A sudden increase in q of 10^7 e m^{-3} sec.$^{-1}$ would result in a new equilibrium value of N_e in about 30 min. in the E region [Lichtenstein (1966)]. Equilibrium is reached largely because of the second term $L(N)$, the loss rate.

ii) L(N) . Below 200 km. the loss coefficient is approximately equal to $a N^2$ since dissociative recombination with coefficient a , is the dominant loss mechanism.

The relaxation time for ionisation decay will be approximately $\tau = \frac{1}{a N}$. (However, Appleton (1953) derives a time constant $\tau = \frac{1}{2aN}$. This represents the time lag between the moment of maximum ionisation production and the moment when maximum ionisation is observed.)

Effective Recombination Coefficients and Relaxation Times

TABLE 5.2.1*

Layer	Time	N/m^3	α	τ_α	Source
D	Day		$3 \times 10^{-12}\ m^3\ sec^{-1}$	33 sec	Belrose (1965)
D	Night	No value available			
E	Day	10^{11}	$1.1 \times 10^{-13}\ m^3\ sec^{-1}$	100 sec	Norton (1963)
E	Night	3×10^5	$10^{-14}\ m^3\ sec^{-1}$	3×10^4 sec	Estimate considering that α varies inversley with temp.
F_1	Day	5×10^{11}	$0.6 \times 10^{-13}\ m^3\ sec^{-1}$	33 sec	Norton (1963)
			$2 \times 10^{-15}\ m^3\ sec^{-1}$	10^3 sec	Belrose (1965)
			Solar flare studies [Davies et alia] tend to favour Norton's value.		
F_1	Night	6×10^9	$5 \times 10^{-15}\ m^3\ sec^{-1}$	3×10^4 sec	Al'pert (1960)
F_2	Day	10^{12}	$1 - 2 \times 10^{-16}\ m^3\ sec^{-1}$	10^4 sec	Al'pert (1960) p. 101
F_2	Night	10^{11}	$1 \times 10^{-15}\ m^3\ sec^{-1}$	10^4 sec	Al'pert (1960) p. 106

Attachment Coefficients and Relaxation Times $\tau_\beta = \frac{1}{\beta}$

Layer	Time	β	τ_β	Source
F_2	Day	2.5×10^{-4} sec^{-1}	4×10^{3} sec	Bates and Nicolet (1962)
F_2	Night	5×10^{-5} sec^{-1}	2×10^{4} sec	McCrary (1966)

TABLE 5.2.3*

It is apparent from these relaxation times that irregularities produced by quasi-sinusoidal motions of the electron gas with periods longer than about 100 seconds in the daytime E region will be attenuated; while at night or in the F_2 region irregularity motions with periods longer than about ten minutes will be attenuated by electron loss through recombinations.

iii) Not only will loss processes tend to smooth out moving irregularities but diffusion will also do so. The ion loss rate by diffusion is estimated to be only 5% of the loss rate by recombination at 150 km. However, at higher altitudes, diffusion becomes more important than recombination [Whitten and Poppoff (1965)].

The characteristic time for diffusion is given by $\frac{L^2}{D} = \tau_D$ where L is a characteristic length for irregularity and D is the diffusion coefficient in the direction concerned. In the E region D is about 4×10^2 m^2 sec^{-1}

[Al'pert (1960)] and an irregularity 5 km. in diameter of twice the ambient electron density will diffuse away in about three hours. Rothwell (1963) gives decay times for F region ionisation due to diffusion along the magnetic field lines at middle and high latitudes, They are : at 250 km. $\tau_D = 400$ sec., at 450 km. $\tau_D = 1$ hour, at 550 km. $\tau_D = 10$ hours. Diffusion across the field lines is less effective than along them. In the D region and in the F region up to 105 km., turbulence frequently appears to occur, leading to the rapid formation and dispersal of irregularities.

In summary : transport with characteristic time of 10 sec. or less is virtually unaffected by these processes. Transport perturbations with a period of 100 sec. will be somewhat attenuated at E and F_1 heights in the daytime. Transport with a period of a thousand seconds will be severely attenuated in the middle ionosphere in the daytime and somewhat attenuated in the E and the F_2 regions. Transport with a characteristic time longer than an hour will be damped everywhere in the ionosphere in the daytime, and in the lower ionosphere even at night.

Ordered Motion

The ordered motion is represented by the $\vec{v} \cdot \nabla(N\vec{v})$ term in the continuity equation. In the F region the electron motions consist of gyrations about the magnetic field upon which drift motions are superimposed; under these

circumstances, only the motion of the guiding centres is important in the estimation of transport effects. Lower in the ionosphere the collision frequencies approach and exceed the gyro frequencies and gyrations are incomplete.

This term may be expanded :

$$\nabla . (N\vec{v}) = \vec{v} . \nabla\vec{N} + N \vec{\nabla} . \vec{v}$$

$\vec{v}_e . \vec{\nabla}\vec{N}$ represents the transport of (∇N) irregularities or other gradients (e.g. vertical motion of an ionospheric layer as a whole).

$N \vec{\nabla} . \vec{v}_e$ represents compressions and rarefractions such as those encountered in (magnetosonic, hydromagnetic or ion-acoustic) wave propagation.

No general relationship between $\frac{\partial N_e}{\partial t}$ as given by the continuity equation and $\vec{v}_e$ can be written since different phenomena involve entirely different dependencies on $\nabla\vec{N}_e$. For example, a vertical drift velocity in the downward direction may attenuate irregularities above the peak of the F layer, where the $\vec{\nabla N_e}$ is negative, and attenuate irregularities on the underside of the F layer where the $\vec{\nabla N_e}$ is positive (Martyn's Theory).

5.3 Appendix II B

Interaction Mechanisms

(Refer to table 1.4.1*)

The interaction mechanisms through which the various source phenomena act to bring about directly associated perturbations of (N_e , $\vec{v}_e$, J, ϑ_e , T_e) the variables characterising the observed phenomena, are as follows :

1) Direct electron gas motion,
2) Modulation of quasi-steady ionospheric currents
3) Pedersen, and parallel (to B_o), electric-field induced drifts,
4) Hall field induced drifts,
5) Induction of E fields, and currents,
6) Dynamo effect, and
7) Joule (I^2R) heating.

It is very difficult to prove that any of these mechanisms do occur. However, various types of observations are strongly indicative of the non-occurrence of particular mechanisms. The strongest contra-indicative observation is mentioned in connexion with each mechanism. Consequently it is possible by process of elimination to estimate which mechanisms are most likely.

(1) Direct Motion

Precipitation (or other non-electrodynamic transport) of electrons and ions into the region between 70 and 130 km. altitude where the electrons are more mobile than the positive ions ($\omega_{He} > \nu_{en}$ but $\omega_{Hi} < \nu_{in}$) can result in electric currents and consequently in magnetic field perturbations. If the influx of electrons is large enough it will constitute a directly observable perturbation in electron distribution. [Maeda and Watanabe, section 4.3.2 (1964), estimate a wave pressure of $p \doteq .10^{-5}$ dyne cm^{-2}.

If a reversal of the sense of motion with height is observed then it is unlikely that direct motion along the field lines is involved. If there is no evidence of absorption (riometer) of a pulsating nature then it is unlikely that injection of energetic particles is occurring.

(2) Modulation of a Steady Ionospheric Current.

A fluctuation in ionospheric conductivity would modulate slowly varying electric currents (such as the Sq current flowing in the ionosphere in the 70 - 200 km. height range, and lead to magnetic perturbations [Matsushita (1965)].

Ionospheric conductivity depends on the density and mobility of the electrons and ions. Consequently any process (wave motion, wind-borne impulse) which injects or redistributes

electrons in a region where currents are flowing will tend to modulate the currents. Presumably perturbations in electron density of a few percent would produce perturbations of the S_q and other currents of the order of a few percent, and a 'steady' magnetic variation of about a hundred γ could then exhibit observeable pulsations of a γ or so in amplitude.

If the local K_ℓ index is zero, or if there are no magnetic bays occurring then there are no ionospheric electric currents of sufficient magnitiude to be modulated and give a measurable disturbance and this mechanism can be ruled out.

(3)Electric Field Drifts, Pedersen Drift, and E Parallel to B_o Drift

If a disturbance electron field is applied parallel to $\vec{B}_o$ the magnetic field has no effect and a force given by $e\vec{E}N_e$ is applied to the electron gas. If $\vec{E}$ is perpendicular to $\vec{B}_o$ this force still exists and results in Pedersen drift, but Hall drift (vid. ff. section) also occurs.

In the case of parallel drift due to an applied E field alone the equation of motion is :

$$\frac{\partial \vec{v}_e}{\partial t} N_e m_e = -e\vec{E}N_e + \nu_{en}(\vec{v}_e - \vec{v}_n)N_e m_e + \nu_{ei}(\vec{v}_e - \vec{v}_i)N_e m_e \qquad (5.3.1)$$

Terms are dropped that represent second order effects, only. (For instance, electron gas pressure (P_e) which depends on perturbations in N_e and T_e which arise from $\vec{v}_e$ which is obtained from the electric acceleration process.)

Under conditions particularly relevant to the experiments (sunspot minimum, night time, 150 km. altitude) ν_{ei} is about $4 \times 10^{-1} sec^{-1}$ (600° K and 10^{9} electrons/m^3, which is very much less than ν_{en}, the latter being about 10^3 sec^{-1} [Nicolet (1962)]. Consequently the ν_{ei} term may be omitted. (This is quite important since the positive ions are also accelerated by the applied electric field.) The equation of electron fluid motion for parallel drift is then :

$$\frac{\partial \vec{v}_{e\parallel}}{\partial t} N_e m_e = -e\vec{E} N_e + \nu_{en} (\vec{v}_e - \vec{v}_n) N_e m_e \qquad (5.3.2)$$

If a sinusoidal component is considered and $\vec{v}_n$ is taken as zero, then :

$$v_{e\parallel} = \frac{-e E_{\parallel}}{m_e (\omega - \nu_{en})} \approx 1.8 \times 10^{8} E_{\parallel} \qquad (5.3.3)$$

(for $\omega \ll \nu$ and at 150 km altitude)

Electron drift produced by an electric field parallel to the ambient magnetic field can occur at any height in the ionosphere. Pedersen drift, however, is only effective below an altitude of about 180 km., where the collision frequency is appreciable relative to the ion or electron gyro frequencies.

According to Mozer and Brustan (1967) electric fields parallel to $\vec{B}_o$ as large as 20 mv/m have been measured. At 150 km. altitude such a parallel $\vec{E}$ field would result in a vertical electron drift velocity of the order of 3,000 km/sec. Typical $\vec{E}$ fields in the F region at night are more likely to be of the order of 1 - 3 mv/m. in a horizontal direction and less than that vertically [Haerendal et al (1967)].

If the sense of motion of the ionospheric electron gas is observed to reverse with height, or if larger motions occur in the E region than in the F region it is unlikely that electric fields acting parallel to the magnetic field, or in the Pedersen mode are involved, because an electric field reversing with height is unlikely (wavelengths of EM/HM waves are too long) and because the higher collision rates in the E region reduce the effectiveness of $\vec{E}$ field induced drift there.

(4) Hall (Perpendicular) Drift

If an electric field $\vec{E}$ is applied normal to $\vec{B}_o$ then an electron drift normal to both $\vec{E}$ and $\vec{B}_o$ will result. (The electron gyro orbits are translated so that the particles follow cycloidal paths.)

Except near boundaries, the motion of the guiding centres of the orbiting electrons is equivalent to the drift motion of the electron gas. Consider the equation of motion in the absence of collisions $(\nu_{en} = \nu_{ei} \equiv 0)$

$$\frac{\partial \vec{v}_e}{\partial t} N_e m_e = -e E N_e - e N_e (\vec{v}_e \times \vec{B}_o) \qquad (5.3.4)$$

For slowly varying fields $\left|\frac{\partial \vec{v}_e}{\partial t}\right| \ll \left|\frac{e}{m}(\vec{v}_e \times \vec{B}_o)\right|$

(in fact $\left|\frac{\partial \vec{v}_e}{\partial t}\right| \ll 10^7 |\vec{v}_e|$ imposes no restriction in the micropulsation period range.)

The LHS $\simeq 0$ and it can be seen that $\vec{v}_e = \frac{\vec{E} \times \vec{B}_o}{|B_o|^2}$

is a solution since $\left(\frac{\vec{E} \times \vec{B}_o}{|B_o|^2}\right) \times \vec{B}_o = -\vec{E}$

In the presence of collisions equation (5.3.4) may be split into two equations : one in the direction normal ($\hat{n}$) to $\vec{v}_e$ and $\vec{B}_o$ (i.e. the $\pm \vec{v} \times \vec{B}$ direction.)

$$0 \approx \frac{e}{m} E_{(\hat{n})} + \frac{e}{m} v_{e\perp} B_o \qquad (5.3.5)$$

and one in the direction parallel ($\hat{p}$) to $\vec{v}_e$

$$0 \approx \frac{e}{m} E_{(\hat{p})} + \nu_{en} (\vec{v}_{e\perp} - \vec{v}_n) + \nu_{ei} (\vec{v}_{e\perp} - \vec{v}_n) \qquad (5.3.6)$$

(Note that the subscript $\perp$ means $\perp$ to $\vec{B}_o$)

The solution of (5.3.5) is that already obtained for the Hall drift :

$$v_{e\perp} = \frac{E_{(\hat{n})} \times \vec{B}_o}{|B_o|^2} \approx 2 \times 10^4 E_{(\hat{n})} \, m \, sec^{-1} \qquad (5.3.7)$$

while the solution for (5.3.6) is a Pedersen drift velocity similar to that discussed in the previous section. Apparently there is a constraint between $E_{(\hat{n})}$ and $E_{(\hat{p})}$. In the simple case where $\nu_{ei} \approx 0$ and $\vec{v}_n = 0$.

$$\frac{e}{m} \frac{|E_{(\hat{p})}|}{\nu_{en}} = |v_{e\perp}| = 2 \times 10^4 |E_{(\hat{n})}| \quad \text{(HALL EFFECT)} \qquad (5.3.8)$$

The principal effect of collisions is to add a Pedersen drift component to the drift velocity and as ν_{en} = approaches (f_{He}) the electron gyro frequency, to attenuate the Hall drift. Consequently below 70 km. where $\nu_{en} \approx f_{He}$ Hall drift is not effective for electrons. (For ions $\nu_{in} \approx f_{He}$ occurs at 120 km.)

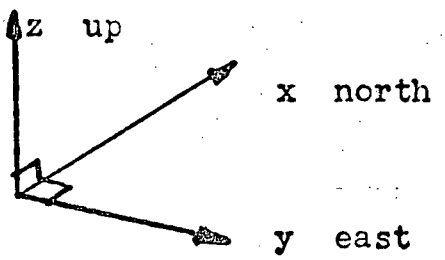
The most complete treatment of the relationship between Hall drift motions in the ionosphere and the Doppler shift to be expected with HF vertical incidence sounding is that given by Jacobs and Watanabe (1966). Another treatment of the problem is that of Rishbeth and Garriott (1964) who make the simple assumption that the ionosphere acts like a moving mirror and the electron velocity is equated to the velocity of change in reflection height. Jacobs and Watanabe (1966), on the other hand, deal with the more complex case in which it is assumed that changes of the integrated electron distribution below the height of reflection have an important effect on the observed Doppler shift of HF radio-waves reflected from the ionosphere. Both effects are to be expected under certain conditions, (vid. Chapter II)

According to Rishbeth and Garriott (1964), the vertical electron velocity is given (approximately) by

$$V_z = \frac{E_y}{B_o} \cos I \qquad (5.3.9a)$$

or

$$V_z \approx \frac{2 \Delta B \cos I}{\mu_o B_o \Sigma_y} \qquad (5.3.9b)$$



I = dip angle

Σ_y = E-W conductivity in mho m^{-1}

$\approx \frac{15 N_e}{10^{11}}$ (MKS units)

The vertical velocities to be expected depend mainly on the E-W electric field. As an upper bound, consider the horizontal electric fields observed by rockets passing through active aurorae which are about 80 mV/m [Kavadas and Johnson (1963)]. Such a field would lead to a vertical velocity of 480 m s^{-1} at 72° dip angle. On the other hand a typical micropulsation event at mid-latitudes is only about 5γ peak to peak (at 200 sec. period) and this would yield a vertical velocity of about 7 x 10^{-3} m s^{-1}. The 'sense'

of the motion of course, remains constant with height if the electric field sense does not change.

If the sense of the ionospheric motion (up/down) is observed to reverse with respect to the N-S magnetic or E-W electric potential disturbance, then it is unlikely that Hall drift is involved in such events.

If the sense of ionospheric motion reverses with the height (up in the F_2 layer down in the F_1 layer say) then it is also unlikely that Hall drift is involved since it is unlikely that the E field would reverse direction with height (except possibly during major disturbances located in the auroral zone. [Hutchinson and Shuman (1961)].)

(5) Induction

If a magnetic field variation occurs (due for example to compression of the magnetosphere by the varying solar wind pressure) it can induce electric fields and hence electron drift motions in the ionosphere [Ashour and Ferraro (1962)]. The process is represented most simply by Maxwell's equation

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

If a (horizontal) scale length L characterising the region of the ionosphere effected can be specified then :

$$|\vec{E}| \approx -\left|\frac{\partial \vec{B}}{\partial t}\right| L$$

(Induction will also result in ionospheric electric currents which will modify the magnetic disturbance as observed below the ionosphere.)

If no magnetic disturbance is observed, this mechanism is, of course, ruled out. Otherwise, as the actual motions are due to Hall drift or Pedersen drift, the considerations applying to those mechanisms are the relevant ones.

An upper limit on the electric fields produced by this mechanism is set by the maximum observed rates of magnetic field change (0.1 γ/sec.) and the maximum scale of a disturbance region ≈ 1000 km. (except for worldwide Sc, Si events), consequently for magnetic induction.

$$E_{max} \approx 1 \text{ mVm}^{-1}$$

(6) Dynamo Effect

If conducting ionospheric plasma is moved across the magnetic field lines (for instance transported by winds or waves of the neutral gas) then an electric field will be set up and dynamo (Hall and Pedersen) currents will flow [Akasofu and De Witt (1965)]. The electron velocity and density distributions will be perturbed, and the currents will result in magnetic perturbations.

If $\vec{v}_e$ is supplied (by collision coupling from $\vec{v}_n$ say)

$$\vec{E} = \vec{v}_e \times \vec{B}_0$$

or

$$|E| \approx 5 \times 10^{-5} v_{e\perp}, \quad \text{Vm}^{-1}$$

This process is effective in the E region.

Mechanisms E and F are, as it were, intermediate between the source phenomena and the other interaction mechanisms, because they lead to electric fields which then produce drifts by mechanisms C and D. See chart in Chapter I., Fig. 1.2.

An upper limit on the electric fields produced by this mechanism is set by the maximum wind velocities observed which are of the order of 500 m/sec.

$$E_{max} \approx 25 \text{ mVm}^{-1}.$$

(7) Joule Heating

A further mechanism which should be mentioned is Joule heating [Cole (1962)], which may be important in connexion with auroral electrojets (but see : Fatkullin (1963)]. It is less likely to be important in connexion with hydromagnetic wave energy dissipation [Akasofu (1960)].

Perturbations of the recombination process have also been considered of possible interest in connexion with ionospheric irregularities and mid-latitude red aurorae [King (1966)].

If no magnetic disturbance is observed, Joule heating is ruled out. According to Walker (1966), "an electric field greater than 3.5×10^{-2} Vm^{-1} is needed to raise the electron temperature significantly, even at high altitudes".

Such an electric field would be associated with (Pedersen or Hall) currents of the order of 10^{-6} amp m^{-2} [Obayashi (1963)]. A line current 20 km. square of 400 amperes at 150 km. would give a magnetic field disturbance of 1/2γ.

$$\Delta f(\text{gammas}) = \frac{0.21\ (\text{amp})}{R\ (\text{km})}$$

As most currents would not be confined to a 20 km. horizontal width this is the extreme lower limit on the size of magnetic disturbance likely to bring about detectable heating in the ionosphere.

TABLE
5.3.1 Observations Tending to Eliminate Interaction Processes

1)	Particle Injection	-- reversal of sense of Δf with height, -- absence of (riometer) absorption.
2)	Modulation of Currents	-- absence of magnetic bays. -- $K_\ell = 0$.
3)	Parallel and Pedersen Drift	-- reversal of Δf sense with height, -- Δf, E layer greater than Δf, F layer.
4)	Hall drift	-- reversal of Δf sense with respect to ΔH sense, -- Δf increase for ΔH increase, -- reversal of Δf sense with height.
5)	Induction	-- absence of magnetic disturbance, (otherwise vid. (B) and (C).
	and	
6)	Dynamo Action	
7)	Joule Heating	-- absent or small magnetic disturbance, and absence of (riometer) absorption.

54 Appendix II C

Source Phenomena

By 'source phenomena' is meant the phenomena which have been identified as possible sources for ionospheric disturbances and magnetic micropulsations observed at mid-latitudes. These phenomena are related to the observations through interaction mechanisms (table 1.4.1* and appendix 5.3). They are :

a) ionospheric electric currents
b) charged particle precipitation
c) wind-borne ionisation irregularities
d) neutral gas waves and ion-acoustic waves
e) hydromagnetic and ULF EM waves
f) magnetospheric compressions.

A brief description of the phenomena including the most helpful recent references and the types of observations which tend to rule-out the possibility of a particular phenomenon being involved in a particular event are given in this appendix.

5.4.a) Ionospheric Electric Currents

i) Horizontal Currents

These may be set up by electric fields applied in the auroral zone by precipitation or induction effects occurring there. [Ashour and Ferraro (1962)]. The electric field associated with a given current is

obtainable from a generalised Ohm's law involving the tensor conductivity of the ionosphere [Obayashi (1963)]. To a rough approximation σ horizontal is about 10^{-4} mho m^{-1} so that $E \approx 10^{4}$ J. MKS (5.4.1) The rate of buildup and decay of such currents may be estimated by considering a current loop of radius b and cross section radius a. The inductance

$$L \approx B_o \ln \frac{8b}{a} \quad \text{(MKS units)} \qquad (5.4.2)$$

For a 1000 km. radius loop of 100 km. X-section radius, L ≈ 8 Hy. The resistance of such a loop is

$R = \frac{\pi}{\sigma}\frac{2b}{a^2} \approx 2$ ohms so that the time constant $\frac{L}{R} = 4$ sec. This provides an upper limit on the rate at which a large ionospheric current may be set up by an applied electric field. Consequently magnetic or ionospheric disturbances with time constants less than about 5 seconds are not likely to be due to auroral return currents.

ii) Currents between the magnetosphere and the ionosphere.

Semi-vertical field-aligned electric currents may flow in loops between the magnetosphere and the ionosphere [Swift (1965 a), Cummings and Dessler (1967)]. Such currents may involve observeable electron drifts and observeable magnetic perturbations of a spatially localised character.

Currents of 10^5 amperes distributed over an area of about 10^{16} m^2 (i.e. F region vertical current densities of about 10^{-10} amp/m^2) are needed to account for observed 100 sec. period pulsations of 10Y amplitude. If F region electron drifts are to be 'seen', then about 10^9 electrons m^{-3} must be in motion (assuming a background Ne of 5×10^9 e/m^3). Taking $\vec{j} = eN_e\vec{v}_e$ then $|\vec{v}_e| = 0.6$ m/sec. which is just observeable. However, the current density could easily be higher if the current is more confined. Using (5.4.1 and 5.4.2) and taking an average $\sigma = 10^{-6}$ mho m^{-1} and b = 5,000 km. the time constant for a current loop between the magnetosphere and the ionosphere is possibly about 2,000 sec. Probably only rather long period magnetic disturbances could be set up by a magnetospheric electric field.

5.4.b) Charged Particle Precipitation

In this case energetic particles capable of producing secondary electrons and of penetrating at least to the lower F region (particle energies > 0.2 kev) are discussed. Precipitation of 2 -3 kev electrons may lead to detectable heating effects [Nathan (1966)]. There is also evidence that current systems causing magnetic bays may be triggered by a sudden intensification and expansion of electron precipitation. [Brown and Campbell (1962) , This event resulted in clearly identifiable 30 db. riometer absorption.] Mirroring

periods for precipitating particles at a (60° geomagnetic latitude) sub-auroral latitude are given by Paulsen and Shepherd (1966) for various particle energies and heights of penetration. These periods are all 13 sec. The time for the mirror point to drift around the earth is found (the drift velocity is 0.19 km./sec.) to be about one day. If magneto-hydromagnetic waves are involved in the particle acceleration [Cole (1964)] then other periodicities might occur in the precipitation.

If a sensitive riometer fails to detect any pulsating absorption, the likelihood of occurrence of the required minimum precipitated flux of particles energetic enough to produce appreciable secondary ionisation (and thereby affect ionospheric currents) is small [Gledhill et al (1967)]. The critical flux a appears to be of the order of 10^4 electrons cm^{-2} sec^{-1} of 40 kev energy in order to produce disturbed values of f min. and h'F at L = 4.

5,4,C Wind-borne Ionisation Irregularities

If ν_{en} is large enough so that horizontal gradients in electron density can be transported horizontally by neutral particle winds, then variations in radio propagation characteristics will occur, as will magnetic perturbations due to dynamo action and possibly due to the modulation of steady ionospheric currents.

In the F region ν_{en} is not great enough for the winds to be capable of transporting irregularities [Maeda (1959)]. In the E region the motion of irregularities has been more successfully associated with internal gravity waves [Hines (1963)] than with winds [Goodwin (1966)]. Below 100 km. turbulence may generate magnetic fluctuations [Moffat (1962)].

Winds in the E region have speeds of about 50 - 150 m sec^{-1} [Föpl et al (1967)]. According to Megill and Carleton (1963) these winds may lead to dynamo fields of the order of 5 mVm^{-1} and may give measureable magnetic effects in the daytime.

An upper limit on the periodicity of associated ionospheric and magnetic pulsations caused by wind-borne irregularities may be estimated. The smallest observeable irregularity will be of the order of 10 km. (the size of the first Fresnel zone) for a reflected radiowave, and the maximum wind velocity is about 150 m sec^{-1} so that a 70 sec. scale time, or 140 sec. period is about the shortest that can be expected.

5.4d) Neutral Gas and Ion-acoustic Waves

The various types of neutral gas waves (acoustic or infrasonic waves, Brunt-Vaisala waves, thermobaric or internal gravity waves, Helmholtz waves) are grouped together with ion-acoustic waves since none of these waves intrinsically involve magnetic perturbations. They may generate magnetic perturbations by moving ionisation if ν_{en} is large enough

(i.e. in the E and F_1 layers) either by setting up dynamo currents or by modulating existing currents.

i) Acoustic/infra-sonic waves

The relationship of these waves to auroral disturbance has been discussed by Maeda and Watanabe (1964). The propagation characteristics of the waves have been discussed by Press and Harkrider (1962) and by Pfeffer (1962) and Meecham (1965). Observations of waves taken to be infrasonic waves have been reported by Maeda (1965), Shrestha (1967),Georges (1967) and others. Compressional waves, for which the particle motion may be in the direction of propagation, can propagate in the E and F regions of the ionosphere [Pfeffer (1962)]. If the waves depend mainly on the elastic collision of neutral particles for their restoring force, they are acoustic or infrasonic waves. If they involve ions and the ambient magnetic field is important in determining propagation characteristics, then we speak of magnetosonic, or magneto-acoustic hydro-magnetic waves [Stix (1962)].

ii) Characteritstic of Sonic Waves

The range of heights at which these waves occur limits the range of wave frequencies. Around 300 km. the ion-neutral collision frequencies are of the order of one collision per sec. and consequently only waves of considerably lower frequencies can

propagate. Below 70 km. the ions and electrons are tightly coupled to the neutrals and only infrasonic waves occur in the 10 - 100 sec. period range. Between 70 and 120 km. electron-sound waves may propagate.

The positive temperature/height gradient above 100 km. and the negative gradient below 80 km. should result in the ducting of waves (of a hundred sec. period or less) in the lower ionosphere. [Meecham (1965)]. The most favourable frequencies for such ducting lie between 0.014 and 0.006 Hz. The lower frequency limit for infrasonic waves in the ionosphere occurs when gravity begins to become important in the equation of motion. The Väisälä or Brunt resonance frequency (which is about 0.004 Hz but varies with height, time of day, and temperature) is near the lower frequency limit for infrasonic waves : somewhat below this frequency, internal-gravity, or thermobaric waves may propagate [Maeda (1965)].

At a given height a particular period and wave-length of infrasonic waves are favoured. For instance, if pressure waves are excited in an isothermal atmosphere, similar to the night-time sub-auroral-zone-latitude atmosphere, at 140 km. 100 sec. period waves are favoured, while at 100 km. altitude 10 sec. waves are favoured [Maeda and Watanabe (1963)].

The magnitudes of group velocities of infrasonic waves and magnetosonic waves at 100 to 200 km. altitudes are in the neighbourhood of 270 to 320 m/sec. The group velocity decreases with increasing frequency. Phase velocities also are of the order of 300 m/sec. for propagating waves, and also decrease with increasing frequency. These velocities are, however, strongly temperature dependent and higher speeds may occur in the daytime ionosphere particularly above 300 km. [Meecham (1965)]. Shock waves moving faster than the speed of sound may also be possible.

Sonic waves may be produced by electric currents or by hydromagnetic waves, either of which may independently result in observable micropulsations, or sonic waves may perturb existing electric currents and thereby produce magnetic pulsations, or sonic waves may themselves produce dynamo effects or charge motions, resulting in magnetic perturbations. Depending on which mechanisms are involved the relationship between magnetic pulsations and ionospheric electron gas motions will vary.

If magnetosonic waves are generated by an electric current no wave motions will be detectable until the current reaches a certain threshold value [Farley (1963)]. This threshold current is higher the higher the frequency of the waves. The observed required electron gas velocity is about 360 m/sec. [Bowles et al (1963)] and the corresponding magnetic

disturbance at the Earth's surface is about 80γ [Osborne and Skinner (1963)]. Consequently this mechanism can only be expected in the presence of a large bay or magnetic storm. (High frequency waves would probably only be generated in the auroral zone.)

If infrasonic waves are the result of downcoming hydromagnetic waves in the auroral zone, [Maeda and Watanabe (1964)] or are the remains of distantly originating magneto-sonic waves [Sessler (1964)] the observed magnetic disturbance will propagate independently of the sonic waves and no simple relation need prevail between wave characteristics and the observed magnetic disturbance.

If the sonic waves perturb overhead magnetic currents again no simple relationship between wave amplitude and magnetic disturbance is to be expected. If the wavelength of the sonic waves is less than a hundred km. and the width of the current sheet is greater than that, perturbation probably won't be observeable at ground level. (A 100 km. wavelength corresponds to a period of about 200 sec.) Also in this case the pre-existing current will result in a magnetic bay whose amplitude is many times greater than that of the pulsations.

If sonic waves result in dynamo effects these may be treated in the same way as dynamo effects due to winds or internal gravity waves, i.e.

$$\vec{E} = \vec{v} \times \vec{B}_o \quad , \left|\vec{E}\right| \text{ (volts/m)} = (0.05)\, E \left|\vec{v}\right| \quad \text{(km/sec.)} \qquad (5.4.3)$$

This electric field may then be taken as the electric field for the calculation of the perturbation magnetic field and the Hall drift of electrons as in section (5.3); however, the interaction is actually very complicated. [See Macleod (1966)]. A useful expression for the change in phase-path of radio waves to be expected from an infra-sonic wave has been given by Barry, Griffiths and Tanzer (1966).

Diurnal and seasonal effects on magnetosonic wave propagation are largely due to temperture variation in the ionosphere; an eleven year solar cycle variation should also occur.

iii) Brunt/Väisälä Resonance Waves

These waves are characterised by mainly vertical particle motion, and by a frequency which varies linearly with the temperature gradient and inversely with temperature [Macdonald (1963)]. At 100 - 125 km. altitude the Väisälä frequency is about 4 min. or the Brunt period is about 250 sec. but may vary considerably, according to Macdonald. The Brunt resonance occurs at a frequency between the frequency ranges of infra-sonic and internal gravity waves.

Since the particle motion is largely vertical, Brunt resonance waves should not be as effective in producing electric fields and currents of detectable magnitude

at this latitude (magnetic dip angle 72°) as acoustic or internal gravity waves involving horizontal gas motions.

iv) Internal Gravity or Thermobaric Gravity Waves. Much of the discussion concerning sonic waves and wind-borne irregularities also applies to internal gravity waves. The distinctive characteristics are as follows :

Internal gravity waves may propagate throughout the atmosphere ; however, waves of period less than about five min. are confined to the lower atmosphere. [Pitteway and Hines (1965), Macdonald (1963)]. The high frequency cut-off in the ionosphere is approximately at the Väisälä or Brunt frequency. Using the formula of Hines and Pitteway, the cut-off period for the mid-latitude night-time ionosphere at 150 km. is about 450 sec. At 300 km. it is about 2×10^{5} sec. [Friedman (1966)].

The group velocity is usually somewhat less than the phase velocity which has a magnitude of about 300 m/sec. Gravity waves may generate currents by dynamo action in the E region, in which case only very small magnetic perturbations would occur. They may perturb existing current systems in which case the size of the disturbance would depend on the magnitude of the electrojet current as well as on the gravity wave characteristics.

Internal gravity waves show a downward phase progression (when energy is propagating upward) and characteristic relationships between vertical and horizontal wave-lengths and period. They are mainly velocity waves and affect the density of the medium very little. According to Goodwin (1966) ionisation irregularities in the form of long (thousands of km.) fronts or ridges only about 9 - 24 km. in width and frequently extending up into the F region, are observed at mid-latitudes. The fronts sometimes occur in groups spaced about 20 km. apart and move (N-S) away from the auroral zone and perpendicular to their long (E-W) dimension.

Velocities are of the order of magnitude 12 - 75 m/sec^{-1} consequently the apparent period of a multiple front disturbance would be about 200 to 2000 sec. Goodwin suggests that internal gravity waves could be responsible for these disturbances. Since they occur in the E region, both dynamo currents and modulation of pre-existing (Sq electrojet) currents should be possible. Another example of ionospheric motions which may be attributed to internal gravity waves is presented by Georges (1967).

Waves of ionisation in the F_2 layer are not likely to be produced by internal gravity waves, because of poor neutral-electron coupling. Waves with periods shorter than about four min. or with true group

velocities appreciably higher than the local speed of sound (~ 300 m sec^{-1}) are not likely to be internal gravity waves, nor are waves involving predominantly vertical motions or predominantly density fluctuations.

v) Ion-Acoustic Waves

Ion-acoustic waves may occur in the ionosphere due to vertical gradients in electron density [D'Angelo and Michelsen (1967)], or to other causes [(Scarf, Crook and Fredricks (1965) p. 3047.]

Like neutral gas waves, ion-acoustic waves do not directly involve magnetic perturbations; but unlike the neutral waves, they may be associated with electron density variations high in the ionosphere and in the magnetosphere. In the region 150 - 250 km. where the Pedersen conductivity is appreciable, ion-acoustic waves may perturb any prevailing horizontal ionospheric currents, thereby leading to magnetic pulsations.

54.e) Hydromagnetic and ULF Electromagnetic Waves in the Ionosphere

i) Hydromagnetic Waves

The propagation of hydromagnetic waves in the ionosphere has been discussed by Lehnert (1956) and by Watanabe (1962). The range of periods for which true HM waves can propagate at various heights in the ionosphere is limited. Over much of the spectral range of principal interest (0.001 - 0.1 Hz) and in the lower E region

and the lower F region the ionosphere behaves like a metallic conductor and most modes of hydromagnetic waves do not propagate but rather may set-up ULF electromagnetic waves. The calculation of actual propagation parameters and dispersion equations for a given ionospheric model may only be carried out numerically and by linearising the essentially non-linear equations describing the motions of the various ionic and neutral constituents of the ionosphere. An excellent development of the theory is that of Prince and Bostick (1963). However, they do not emphasize the major difficulty which results from the fact that the wavelengths of hydromagnetic waves in the 0.01 Hz range are of the order of 10^4 km. while the scale heights of the ionosphere (T_e, N_e variation) are of the order of a few tens of km. at most. Consequently refraction and mode coupling problems are severe.

Rishbeth and Garriott (1964) assume a highly idealised situation involving a simple down-coming Alfvén wave and show that the vertical velocity of ionisation coupled to such a wave (Hall drift) in the F region is given by :

$$v_{e_z} = \Delta B \cot I \left(\frac{\omega}{\nu_{en} \mu_0 m_p N_e} \right)^{\frac{1}{2}} \qquad (5.4.4)$$

where ΔB is the amplitude of the magnetic disturbance in the northward direction $\perp$ to B_o, i.e. the 'H' direction, $\vec{V}$ the velocity in the same direction, m_i the average ion mass, N_e the electron number density, ν_{en} the frequency of collisions of an electron with neutral particles, and ω the angular frequency of the hydromagnetic wave. This equation gives $\omega^{1/2}$ dependence on ΔB, but the actual dependence of v on ω is related to the dispersion characteristics of the meduim, and varies with height and direction of propagation in a complicated fashion. The complexity of the variations in phase velocity and attenuation may be gathered from Prince and Bostick (1964) and Greifinger and Greifinger (1965).

In addition to the 'fast' HM waves there are also waves which propagate more nearly at the speed of sound in the meduim [Watanabe (1961b)] and invoke magnetic field perturbations.

An attempt was made to derive more accurate relationships between electron irregularity drift velocity and the magnetic perturbation field of HM waves of various types, but it was found that no general relations could be derived and each case requires a very full and explicit specification of parameters.

ii) ULF / EM waves

It appears more likely that electromagnetic waves, in the 0.01 Hz range may propagate in the ionosphere, than HM waves. [Watanabe (1962)]. Both ordinary EM waves, and EM surface waves depending on the

transverse Hall conductivity peak occurring near 120 km. may propagate. [Rostoker (1965) (1966)]. However, the wavelengths are again long compared with the scale heights and consequently refraction and mode coupling may be quite important in determining relationships between electric fields in the ionosphere and magnetic fields observed at ground level.

If observations show low propagation velocities (less than 300 m/sec. [Lehnert (1956)] or absence of dispersion, then it is unlikely that either EM or HM waves are involved.

Since the wavelengths of these waves are very great it is also unlikely that electron motion should reverse direction with height within the ionosphere if such waves are responsible for the electron drifts.

5.4.f) Sudden Commencement Induction

A sudden increase in solar wind pressure may produce an electric field in the ionosphere by induction due to the compression of the field lines of the magnetosphere. [Dessler, Francis and Parker (1960)].

An approximate value for the average electric field may be estimated by taking the line integral around a parallel of latitude. [Jacobs and Watanabe (1966)].

$$\oint \vec{E} \cdot \vec{ds} = \iint \Delta \left(\frac{\partial \vec{h}}{\partial t}\right) \cdot \vec{dA} \qquad (5.4.5)$$

$$E_y = -i \frac{R}{2c} \omega h \cos \lambda_0$$ [after Jacobs and Watanabe (1966)]

R is the radius of the earth, λ_0 is the magnetic latitude

Where : $\vec{h}$ is magnetic perturbation,

$\vec{E}$ is the induced eastward ionospheric electric field,

$\vec{ds}$ is an element of path length,

$\vec{dA}$ is an element of area,

$\vec{V}_e$ is electron drift speed,

$\omega = \frac{2\pi}{4T}$, where T is the time scale of the sudden compression.

This electric field varies as $\frac{\partial h}{\partial t}$

or considering a Fourier component $|\vec{E}| \propto (\omega |\vec{h}|)$

Consequently, using the Hall drift relation that

$|\vec{V}_e| \propto |\vec{E}|$ we get $\frac{|\vec{V}_e|}{|\vec{h}|} \propto \omega$ (5.4.6)

for this sudden commencement model.

(However, other types of model, invovling hydromagnetic waves, have been proposed for sudden commencement effects. [Stegelman and Kenschitzki (1964)]. After Jacobs and Watanabe the expected Doppler shift at 54° latitude would be about :

$\delta f = \frac{2.5}{T} \Delta B$ (in gammas) (5.4.7)

TABLE
5.4.1 Observations Tending to Eliminate Source Phenomena

a)	currents	- Δf period short compared to L/R time constant of hypothetical current. - no magnetic disturbance.
b)	energetic-particle precipitation	- absence of riometer absorption. - absence of fading (sounding or other) of received signal strengths.
c)	wind-borne irregularities	- Δf change too rapid for smallest observeable (1st Fresnel zone) irregularities to pass by at the highest probable wind speed.
d)	neutral gas waves and ion-acoustic waves	- simultaneous high (>1 km. sec^{-1}) vertical and horizontal propagation velocities. - absence of magnetic bay for mechanism (2) app. 6.3.
	also for various types:	
	internal gravity waves	- periods less than 5 min. - absence of dispersion with height.
	Brunt/Väisälä resonance	- period less than 2 min. or - greater than 10 min. - reversal of Δf with height.
	infrasonic waves	- periods longer than 10 min. - F region disturbance only.
	ion-acoustic waves	- Δf, E layer greater than Δf, F layer.
e)	HM/EM ULF waves	- low (<1 km. sec^{-1}) vertical propagation velocity. - reversal of Δf with height. - absence of dispersion.
f)	compression induction effect.	- geographically localised (500 km.) magnetic disturbance. - reversal of Δf with height.
g)	Propagation between the earth and the Ionosphere.	- Δf,F layer, greater than Δf,E layer if period shorter than E layer recombination time.

APPENDIX III

a) Detailed Specifications of the Telluric Potential System

Separation of electrodes N-S 440 m., E-W 510 m.

Source resistance (E-W) 285 Ω

Normal DC potential (E-W) 120 mV

Input impedance of filter 4000Ωc.t.

DC attenuation before amplifier 32 db.

60 Hz attenuation before amplifier 95 db.

Amplifiers : Liston Becker model 14, serial numbers :

320, 441, 446

Maximum possible gain (for 1:1 S/N ratio) 110 db.

As normally used (C4, F10) gain overall from line to output is 50 db. (The amplifiers are used well within their drift, noise level, and gain capabilities.)

The frequency response of the system is given in Fig. 5.5.1

The phase shift in Fig. 5.5.2.

The impulse response in Fig. 5.5.3

The frequency response of the slow-speed tape record-play-back system is shown in Fig. 5.5.4

The telluric potential amplitude as a function of the D and H component disturbance amplitudes recorded at the Dominion observatory is given in Fig. 5.5.5

The performance capabilities of this system are more than adequate for monitoring rapid geomagnetic variations, and locating dominant spectral peaks, and determining their order of magnitude.

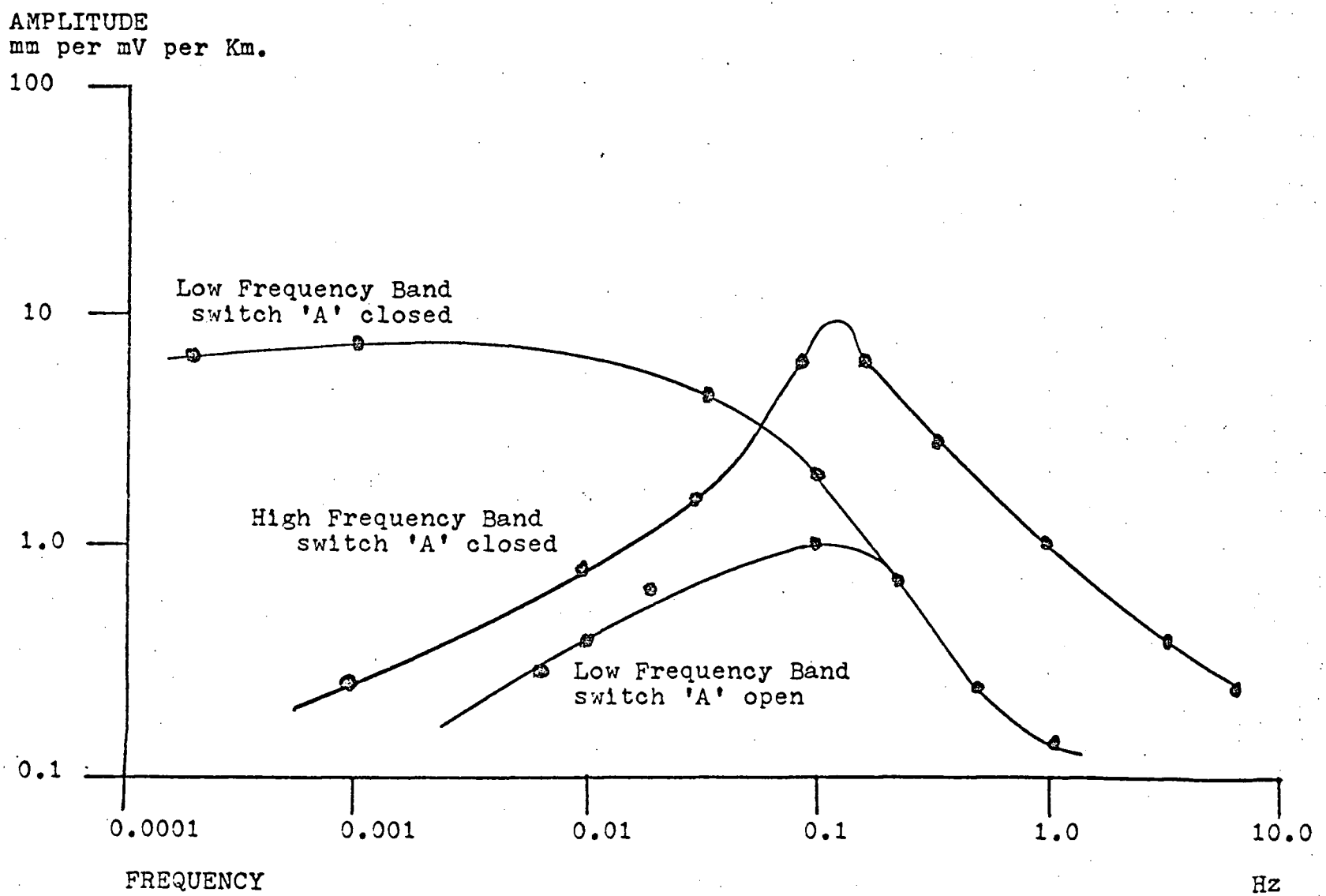


Fig.5.5.1. Frequency Response of the Telluric Potential Chart -recording system

The two bands are recorded separately to aid in distinguishing micropulsation classes . Switch 'A' is shewn in Fig.2 .2.3. It is used to attenuate magnetic storms and diurnal electrochemical potential variations.

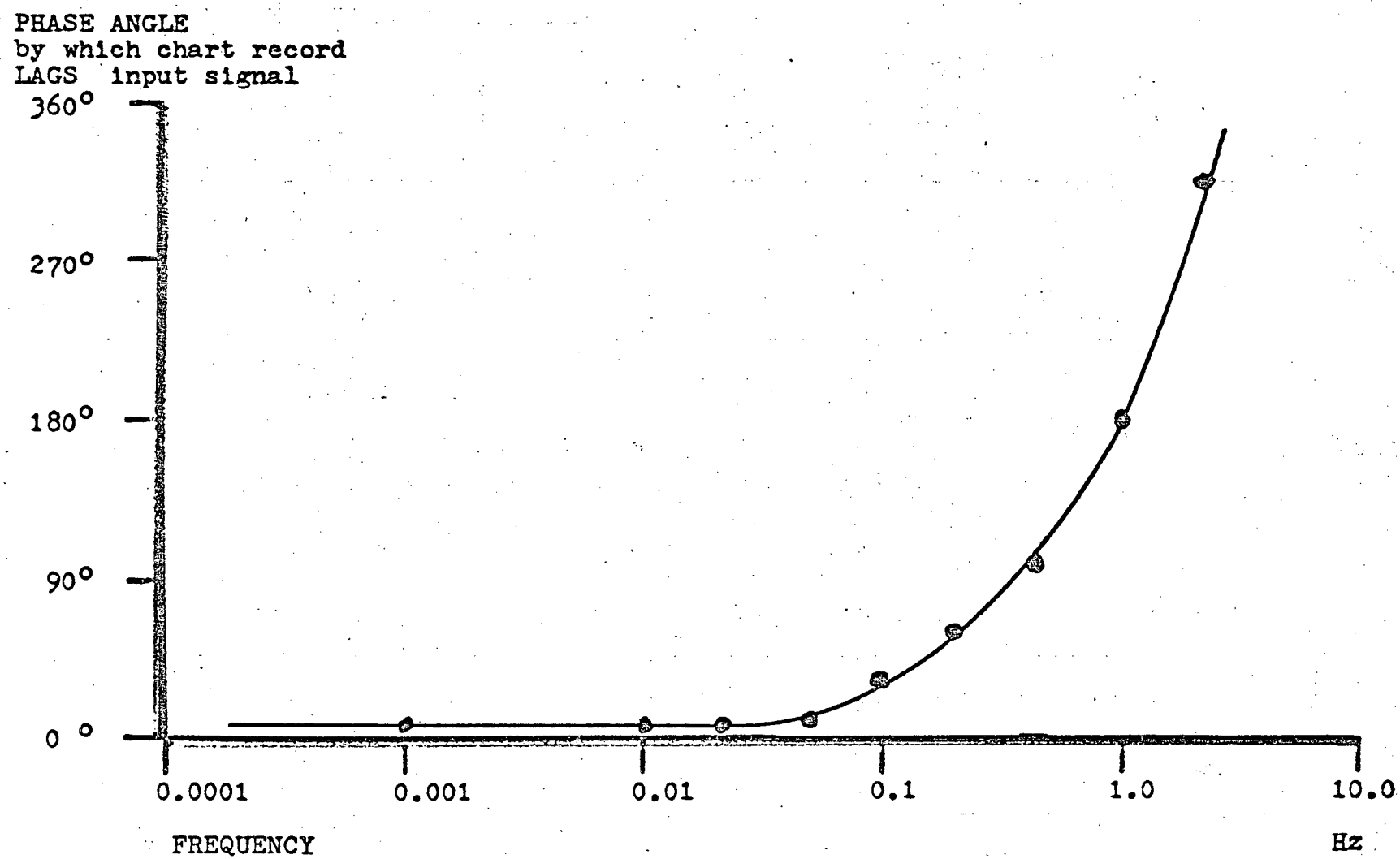


Fig. 5.5.2. Phase Shift as a function of micropulsation frequency
Telluric potential chart records Low Frequency Band channel.
(switch 'A' closed)

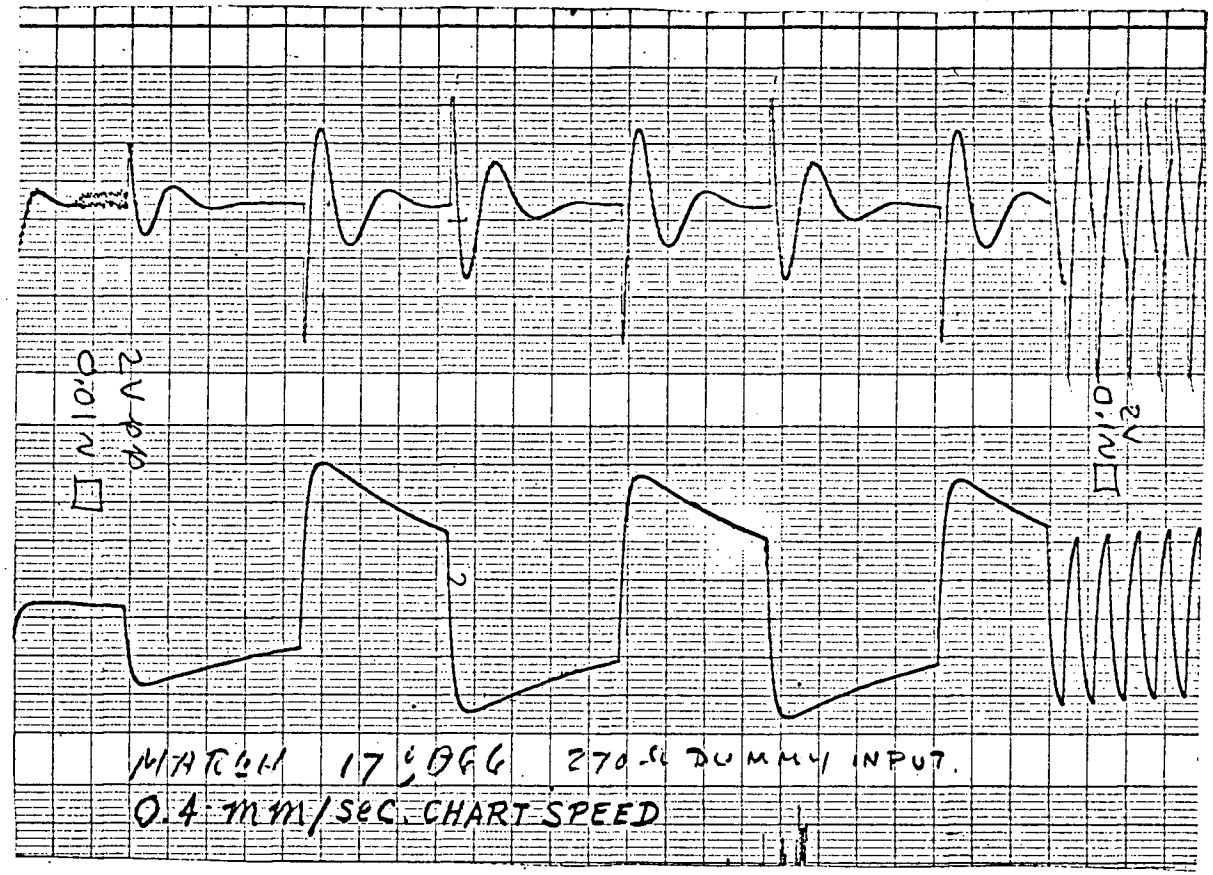


Fig. 5.5.3. Transient Response of the Telluric Potential recording system. A square wave of 0.01 Hz and 2.0V pp. amplitude was applied to the calibration pad input.

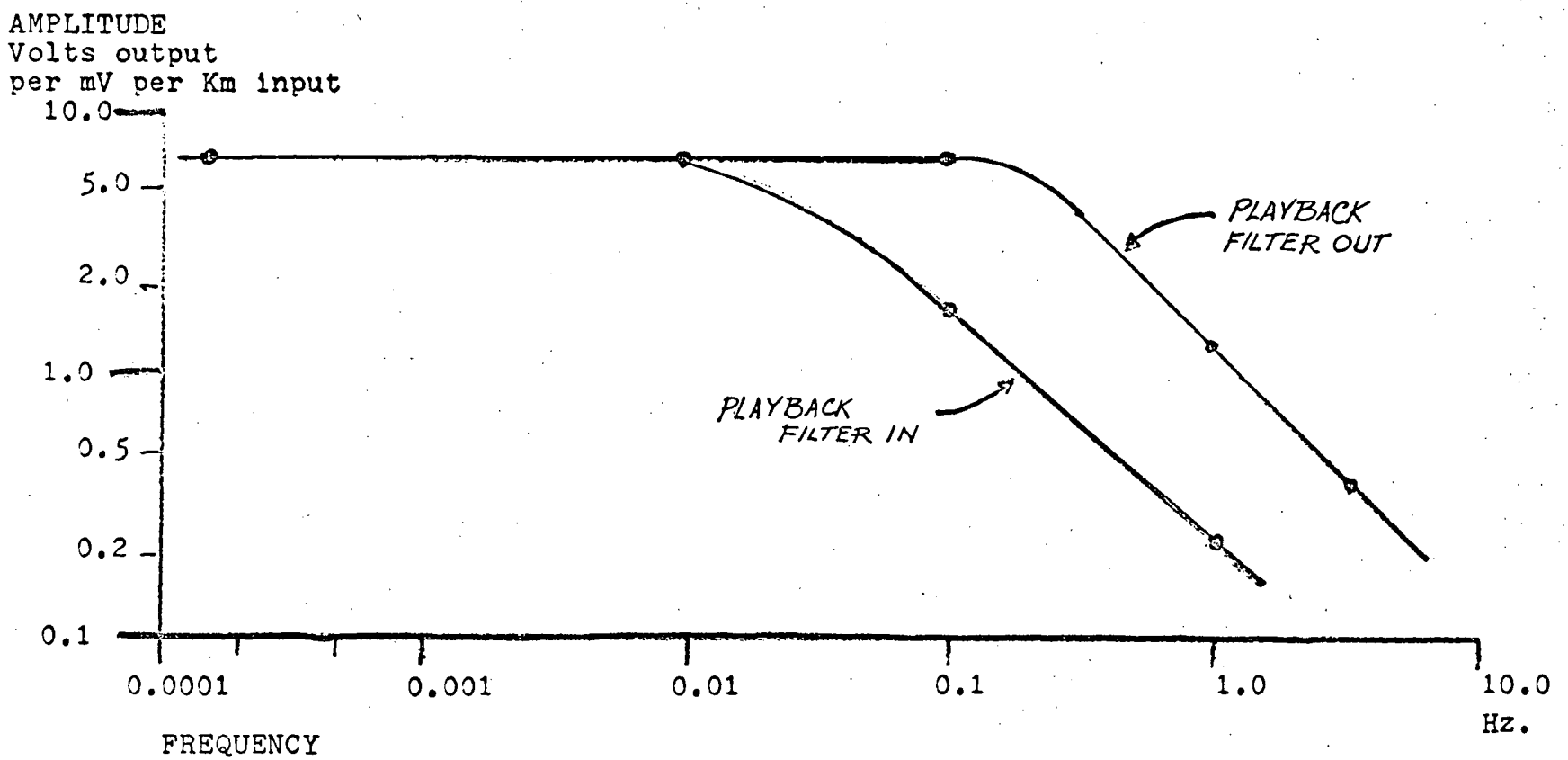


Fig. 5.5.4 Frequency Response of the FM slow speed Tape Recorder (Measured from record input 5.6 inches per minute to playback output 7 ½ inches per second; input frequencies are used in the plot, output frequencies are 80X input frequencies.)

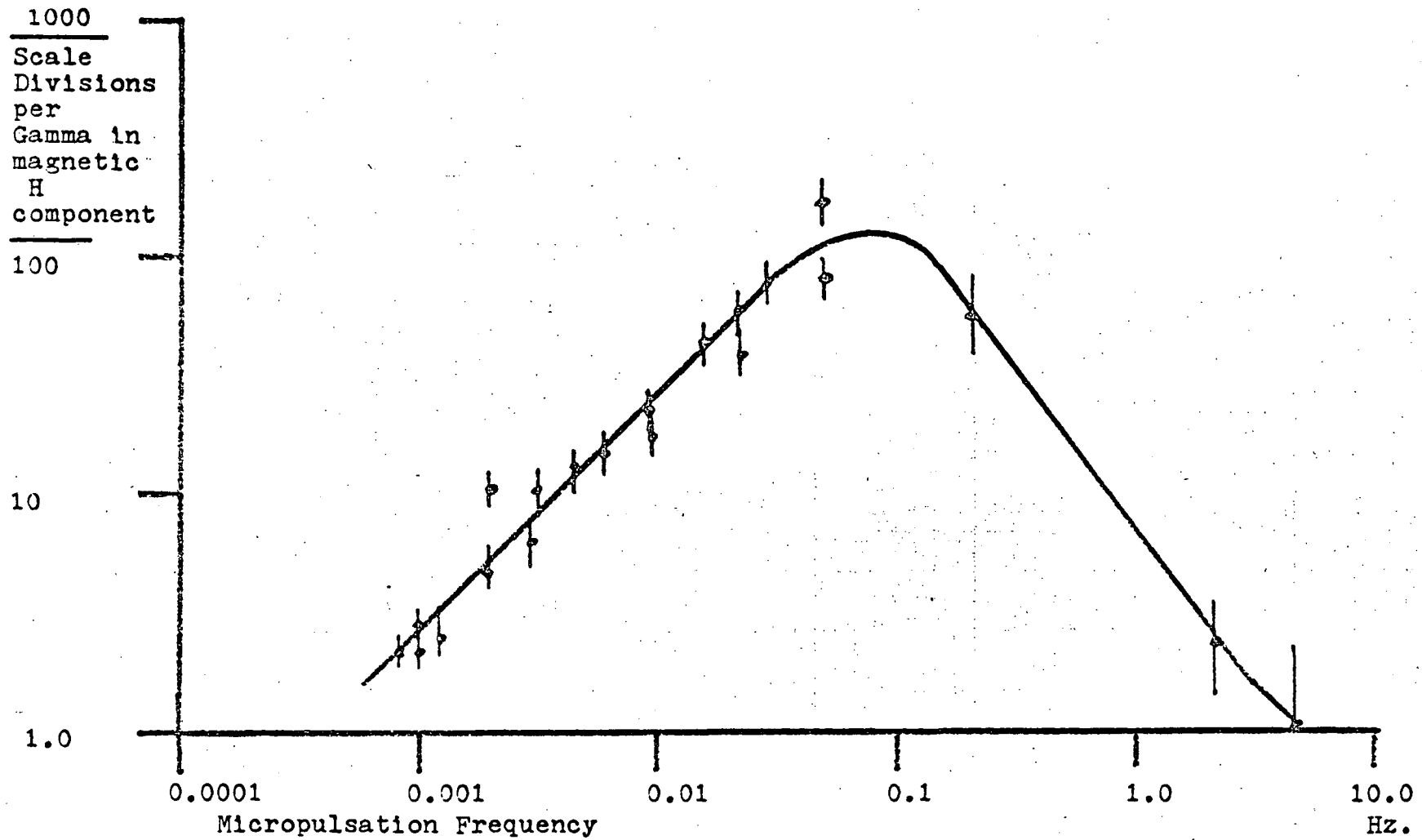


Fig. 5.5.5 Calibration Curve for E-W Telluric potential records in terms of N-S (H component) magnetic records from the Victoria Magnetic Observatory. Twenty events occurring in June and July 1965 were used.

b) Specifications of the Varian Rubidium Vapour Magnetometer.

(Used at Royal Roads, and on the eclipse project)

Type : Varian, model : X49-530, Serial No. 4.

Sensitivity 0.01 γ max., 0.1 γ as used.

Time resolution $\pm$ 5 seconds (20 cm./hr. chart speed)

$\pm$ 0.2 seconds magnetic tape record.

(The noise level of the instrument is 10^{-2} γ R.M.S.)

Eclipse - Calibration = 2 γ full scale Varian chart.

Royal Roads calibration = 20 γ full scale brush chart.

c) Specifications of the U.B.C./P.N.L. Westham Island Station

i) magnetic induction micropulsation equipment :

References :

D.R.B. Canada, P.N.L. Tech. Rep. B 427.

P.J. Evans (1960) Lab. note: 60-11.

Specifications :

3 component mu-metal cored coils.

Frequency range 0.02 - 5.0 Hz.

Amplitude resolution better than 0.001 γ / sec.

Time resolution : 1 sec. Esterline Angus chart.

Record at 6"/hr.

ii) Fluxgate 3 component magnetometer

PSC Type T 613

Amplitude resolution 2 γ

Time resolution 9 sec. L and N chart recorder

8"/hr.

5.6 Appendix IV

Data Reduction

Some data reduction was performed using analogue spectral analysis equipment.

Some of the data was digitised and fed into the PNL Raytheon 250 computer and various statistics computed. [The program was written by Lokken, J.E., Maunsell, C.P. and Van Andel, H.W.H. and is described in PNL Laboratory Note 61 -11, (1961)]. The approach is based on the methods of Blackman and Tukey (1958) and Goodman (1957). [See also Tintner (1965) part 3.]

The program is used to compute the autocorrelation and spectra of two input signals and then the cross-spectra and the coherencies.

The output variables are :

k ——— the lag number or frequency band index number,

A_k ——— the autocorrelation function for channel 1,

X ——— the power/Frequency spectrum for channel 1,

Log X ——— the logarithm of the above,

B_k ——— the autocorrelation function for channel 2,

Y ——— the spectrum for channel 2,

Log Y ——— log spectrum for channel 2,

$E = \frac{C + D}{2}$ — the covariance of 1 and 2 with 1 lagging = C plus the covariance of 1 and 2 with 2 lagging = D

$F = \frac{D-C}{2}$ ——— the sign of F indicates the direction of skewness of the cross correlation function.

Z_k ——— the co-spectrum (X Y) given by

$$Z_k = \frac{\delta_k}{m}\left[\sum_{l=0}^{m-1} E_{(l)} \left(1 + \cos\frac{l\pi}{n}\right)\left(\cos\frac{kl\pi}{m}\right) + E_{(o)}\right]$$

W_k ——— the quadrature spectrum (same as Z above, except incorporating sines instead of cosines.

$$\left\{ P = \frac{Z_k}{X_k Y_k} \qquad Q = \frac{W_k}{X_k Y_k} \right\}$$ Fourier transformed correlation coefficients

R ——— the coherence as a function of frequency band

$$R = P^2 + Q^2$$

Φ — the phase angle as a function of frequency band

$$\Phi = \tan^{-1}\frac{W_k}{Z_k}$$ (Phi = 0 if the cross correlation is symetrical about 0 lags.)

l = lag number. δ_k = 1/2 for k = 0 and m

= 1 otherwise

m = maximum lag.

The coherence function peaks, whenever the same frequency components are present in the two records. The phase angle (Φ) indicates the phase difference between such associated components.