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Relationship Between Simultaneous Geomagnetic and Ionspheric Oscillations

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On rare occasions, mostly during severe geomagnetic disturbance, variations of phase of high-frequency radio waves reflected from the ionospheric *F* region are closely correlated with geomagnetic variations with periods in the range ½ to 30 minutes. Whatever the prime cause of the disturbances, the existence of the correlation poses an interesting problem in ionospheric dynamics. In this note, it is discussed in terms of the ionosphere "dynamo-motor" theory and in terms of hydromagnetic waves. Because only crude theoretical calculations are made, and because the HF phase and geomagnetic data refer to locations some thousand kilometers apart, only an order-of-magnitude agreement between the two types of observation can be expected, or is indeed found. Further observations with vertical incidence phase sounders and suitable magnetometers, and improved theoretical work, are required before the phenomenon can be satisfactorily understood.

1. Observations

This note discusses possible interpretations of correlated oscillations of the geomagnetic field and the height of the ionospheric *F* region, with periods of ½ to 30 min. Fluctuations of phase, or frequency, of high-frequency radio waves reflected from the *F* region have been described by Watts and Davies [1960]; Fenwick and Villard [1960]; and Davies [1962]. They are interpreted as Doppler shifts due to vertical motion of the reflecting layer. Chan, Kanellakos, and Villard [1962] compare these phase fluctuations with geomagnetic field variations associated with storm sudden commencements, main phases of storms and geomagnetic micropulsations. Sudden commencements are not dealt with here; no particular distinction between "field fluctuations during storms" and "micropulsations" is made, although more definite periods can be attributed to the latter and they may, of course, originate from different processes.

The radio observations comprise continuous frequency measurements of signals from stable cw senders, received via transcontinental paths which include multiple reflections at oblique incidence from the *F* region. These experiments have been described by Chan et al. [1962]; all the data used in the present paper refer to transmissions from WWV (20 Mc/s) and Puerto Rico (18 Mc/s) to a receiving station at Seattle. The magnetic data comprise rapid-run magnetograms from the United States Coast and Geodetic Survey stations at Fredericksburg and Tucson. The scale of the available records prevents the study of oscillations with shorter periods than about ½ min, whereas the longest periods that can be conveniently studied are 20 to 30 min.

A few good examples of correlated frequency variations and geomagnetic oscillations are shown in figures 2a to 3b of Chan, Kanellakos, and Villard [1962]; one example is reproduced here in figure 1. The present study utilizes Chan's phase records and further data kindly made available by D. P. Kanellakos. Twenty-three occurrences of phase oscillations were investigated, of which nine showed good correlation with oscillations recorded by the Fredericksburg or Tucson magnetometers, and a few more showed some correlation.

Details of several events are given in table 1. The magnetic data refer only to the horizontal (*H*) component, and all amplitudes are peak-to-mean values. The symbol * indicates that more than one period seemed to be present, so that the oscillations were somewhat confused. In example G, the magnetic oscillation was not detectable at Tucson.

A few comments may be made about the occurrences listed in table 1. The drawbacks of the oblique-incidence technique include the lack of precise knowledge concerning the number of hops of the HF propagation paths, and the fact that the reflection points are situated 1000 km or more from the magnetic observatories. On some occasions, the magnetic oscillations were detected at only one of the two continental United States stations, Fredericksburg and Tucson; on other occasions, they were detectable at both stations but showed rather different periods on the different magnetic traces. In at least three cases included in table 1 (B, E, F) the oscillations could be identified at very distant stations, Sitka or Guam, as well as at Fredricksburg and Tucson.

Most of the events listed, including the best examples, occurred during a very disturbed period in mid-November 1960. This in itself suggests a strong dependence on magnetic activity, and it is possible that the correlations occur only

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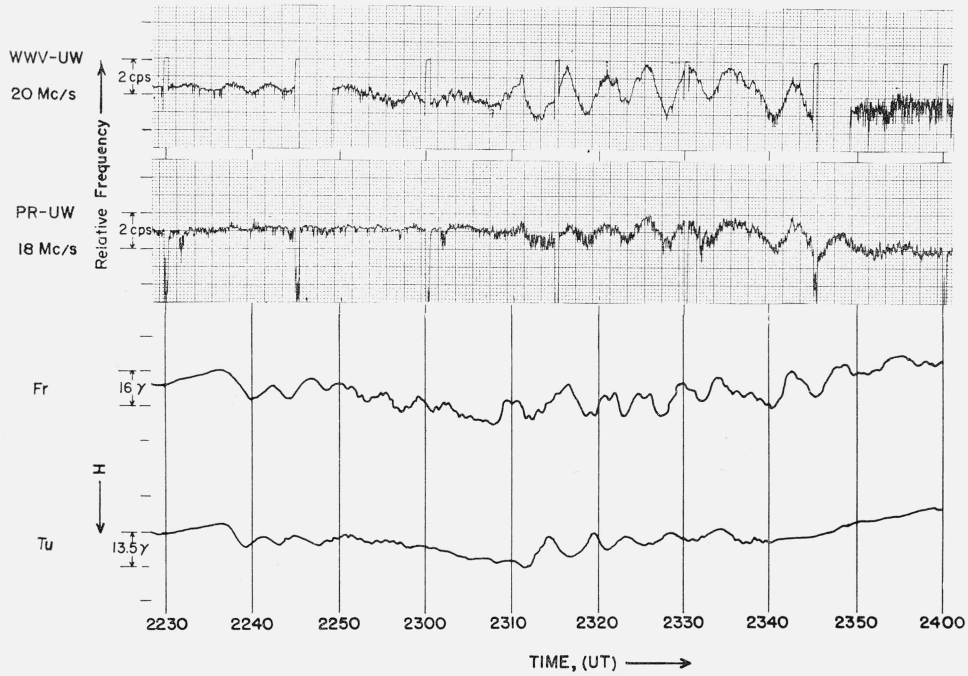

FIGURE 1. (*Taken from Chan [1962]*) *Correlated frequency and geomagnetic oscillations on 1960 November 16.*

The two upper charts show the variation of frequency of HF signals received at University of Washington, Seattle, from transmitters at Washington, D.C. (WWV) and Puerto Rico. The lower charts show the variations of the horizontal magnetic field H at Fredericksburg and Tucson.

TABLE 1

Ref.	UT date	UT approx. start end	HF sender	Oscillatory Period, min			Amplitudes			Mag Kp
							c/s	γ	γ	
				HF	FrH	TuH	HF	FrH	TuH	
A	1960 Nov. 12	1920–1950	PR	*2.1	2.5	3.3	0.6	2	2	8
B	1960 Nov. 12	2110–2130	PR	*3.2	3.2	3.4	.8	3.2	2	8o
C	1960 Nov. 16	0115–0130	PR	1.3	1.9	1.4	.5	0.5	0.5	8+
D	1960 Nov. 16	0300–0330	PR	3.7	3.5	3.3	.7	2	2	8+
E	1960 Nov. 16	1700–1715	WWV	0.56	0.57	0.56	.3	1.4	1.4	5−
F	1960 Nov. 16	2310–2345	WWV	4.7	4.7	4.8	1.1	2.4	2.4	3+
G	1960 Nov. 18	1800–1830	PR	*0.7	0.7	--------	0.4	0.4	--------	0+
H	1960 Dec. 1	0000–0040	WWV	*6	6	6	.8	1.5	1	6+
J	1961 May 23	0405–0445	PR	15	14	14	.6	1.5	2.5	4−

under very special conditions. For the remaining cases in table 1, some degree of magnetic disturbance was generally present.

The absence of events between 05^h and 17^h UT (about 23^h to 11^h local time) is presumably related to HF propagation conditions rather than to the cause of the phenomena, but it does appear that the period of the oscillations generally increases with advancing local time.

2. Possible Interpretations

There is no evidence that any general correlation exists between radio phase fluctuations and variations of the geomagnetic field. However, on rare occasions there is a correlation which is so close that it cannot be accidental. Both the magnetometers and the phase sounders are sensitive to a variety of phenomena; so according to the data presented above, whatever process is responsible for the correlation must either be rare, or else of very limited geographical extent. Probably it is associated with severe magnetic disturbance.

The geomagnetic field variations detected by the magnetometers must be caused by electric currents. These might be located, in principle, anywhere in the earth's environment, not necessarily in the ionosphere. The HF phase sounders respond to any vertical motion of the reflection level in the F layer and might detect the passage of small-scale irregularities and all kinds of traveling disturbance, changes of level of the F layer due to formation or decay of ionization or to motions of the neutral air, and bodily drifts produced by electromagnetic forces. Of these, the last appears most likely to be correlated with magnetic field variations.

Various tentative suggestions might be made as to the origin of the simultaneous ionospheric and magnetic oscillations. Quite possibly they are hydromagnetic disturbances originating in the outer atmosphere and propagated downwards through the ionosphere. On the other hand, they might be driven from lower levels by alternating emf's in the E region, which could be generated *in situ* by "dynamo" action from oscillations of the neutral air, or by remote sources located perhaps at high latitudes.

The present paper, however, does not deal with these possible causes, but only with the linkage between the geomagnetic and ionospheric oscillations implied by the observations. This linkage might be described in two alternative ways; one being in terms of currents and electric fields analogous to those of the well-known "dynamo-motor" theory, and the other being a hydromagnetic description in terms of wavelike displacements of geomagnetic field lines. In the present case, the wavelengths of these displacements are much greater than the vertical extent of the ionosphere. The two approaches are of course related in principle, but will be treated separately for simplicity of discussion.

In the F region, the geomagnetic induction $\mathbf{B}$, the electric field $\mathbf{E}$ and the drift velocity $\mathbf{V}$ of the ionization are mutually perpendicular and related by the vector equations

$$0=\mathbf{E}+\mathbf{V}\times\mathbf{B} \tag{1}$$

$$\mathbf{V}=\mathbf{E}\times\mathbf{B}/B^2. \tag{2}$$

These equations apply to both descriptions, but at this point more specific models must be introduced and the two approaches then diverge. For the "motor" approach, it is worth using only the simplest model used in the "dynamo and motor" theory developed by Baker and Martyn [1953]. The E layer is visualized as a thin sheet in which the electric current is represented by a vector $\mathbf{J}$ and the d-c conductivity by a tensor $\mathbf{\Sigma}$. Both $\mathbf{J}$ and $\mathbf{\Sigma}$ are integrated with respect to height throughout the sheet. The very large conductivity in the direction parallel to $\mathbf{B}$ above the E layer insures that the F layer electrostatic or "polarization" field is, to a good approximation, equal to that in the E layer. Denoting "eastward" and "upward" components by suffixes Y and Z respectively, and the magnetic dip angle by I, the vertical component of the "motor" eq (2) gives

$$V_Z=(E_Y/B)\cos I. \tag{3}$$

In principle, V_Z can be computed by combining magnetic observations at ground level with estimates of the tensor conductivity. There are several complications, such as the earth currents induced by the ionospheric currents, which may contribute an appreciable fraction (perhaps one-third) of the ground-level magnetic variations. Another difficulty arises if the currents originate from "dynamo" action of an oscillating wind (velocity $\mathbf{W}$) in the neutral air. For in this case $\mathbf{J}=\mathbf{\Sigma}\cdot\mathbf{E}_t$, and the "total" electric field $\mathbf{E}_t$ contains an "induced" or "dynamo" component $\mathbf{W}\times\mathbf{B}$, in addition to the "electrostatic" or "polarization" field which alone appears in the "motor" equations (2) and (3). This difficulty does not arise if the currents and electric fields originate from some cause other than "dynamo" action. The "induced" field is neglected in the calculations of section 3 in which velocities calculated from (3) are compared with the HF data.

For the "hydromagnetic" approach, it is convenient to picture the disturbance as a hydromagnetic wave traveling along the geomagnetic field lines, which are distorted into a sinusiodal form. In the most idealized case of a simple Alfvén wave, the electronic and ionic collision frequencies are entirely neglected. The phase velocity is the Alfvén speed V_A, which is analogous to the velocity of waves in a vibrating string, and depends on the ratio of the magnetic energy density B^2/μ_0 to the plasma density Nm_i, N being the electron or ion concentration and m_i the ionic mass [e.g., Dungey, 1958]. Consider the undisturbed magnetic field to be directed along the ζ-axis of a Cartesian coordinate system (ξ, η, ζ), and suppose the magnetic vector of the wave to point in the ξ-direction and to vary sinusoidally with amplitude B_ξ and angular frequency ω. The lateral displacement of the lines of force is also in the ξ-direction and is quadrature with B_ξ; but its velocity of motion V_ξ is in antiphase with the variation of B_ξ, so that $+B_\xi$ and $-V_\xi$ vary as $\cos(\omega t-\zeta\omega/V_A)$. Their amplitudes are related by the equations

$$-V_\xi/B_\xi=V_A/B=(\mu_0 m_i N)^{-1/2}. \tag{4}$$

There are small differences between the motions of electrons and ions which set up the electric field E_η which enters (1) and (2).

Even at F region heights, the ion-neutral collision frequency ν_{in} is large enough to modify appreciably the phase velocity of the wave, and a complex dispersion equation must be used. This may be obtained from (47) of Hines [1953], by assuming that a single species of positive ion is present and that the density of neutral matter, multiplied by ω/ν_{in}, greatly exceeds the density of charged matter (i.e., that, in Hines' notation, $N_r M_r K_r = K_r \delta \ll \omega\rho$). Multiplication of the equation throughout by c^2/ω^2, with appropriate changes of notation, yields

$$n^2 = 1 + (c^2/V_A^2)(1 - j\nu_{\text{in}}/\omega). \tag{5}$$

In the daytime F layer, V_A is estimated as ~ 300 km/s and is therefore much less than c. Moreover $\nu_{\text{in}} \sim 1$ sec^{-1} at 300 km altitude, which is much greater than the angular frequency of the oscillations under discussion (e.g., for a period of 1 min, $\omega = 0.1$ sec^{-1}). Hence n^2 is nearly a pure imaginary number so that the real and imaginary parts of the refractive index are comparable: in spite of this, the attenuation of the wave is not too severe because the thickness of the ionosphere is a small fraction of a wavelength. In this case, the phase of the transverse velocity V_ξ is shifted by $\pi/4$ from the case of the simple Alfvén wave described by (4), and its magnitude is now given by

$$|V_\xi / B_\xi| = (\mu_0 m_i N)^{-1/2} (\omega/\nu_{\text{in}})^{1/2}. \tag{6}$$

In the ionosphere, the ζ-axis of the coordinate system (ξ, η, ζ) is inclined downwards at the dip angle I in the northern hemisphere, and the η-axis is assumed to point towards magnetic east and thus coincides with the Y-axis of the system (X, Y, Z) used for the "motor" calculation. The ξ-axis then points northward and upward at an angle I to the vertical. The vertical velocity of the ionization then oscillates with amplitude $V_\xi \cos I$, and the horizontal component of the magnetic induction B oscillates with amplitude $B_\xi \sin I$. In the calculations of section 3, the latter is equated with the displacement of the horizontal magnetic intensity observed at the ground, but this of course neglects the attenuation and partial reflection of the hydromagnetic wave which must occur in the conducting E layer, and reflection at the ground of the electromagnetic wave transmitted through the E layer. It should be noted that according to Karplus et al. [1962], hydromagnetic waves of period $\gtrsim 1$ min are not greatly attenuated in the ionosphere, so that the amplitudes of the magnetic vectors in the waves above and below the E layer may be approximately equal.

3. Numerical Calculations

In this section, some illustrative calculations are made using the data of table 1. The frequency deviations Δf from the mean radiofrequency f are used to calculate apparent vertical velocities of the reflecting layer, V_{ZR}; then the "motor" and "hydromagnetic" approaches are used to calculate vertical velocities V_{ZM} and V_{ZH} from the displacements of the horizontal magnetic induction observed at the ground. In the equations, these displacements are denoted by ΔH (the conventional geomagnetic notation) and the relation $1\gamma = 10^{-9}$ weber m^{-2} used to express ΔH in mksa units of magnetic induction.

Although the equations are not derived in detail, those for V_{ZM} and V_{ZH} follow naturally from the equations given in section 2 and that for V_{ZR} may be derived from first principles. Several simplifying assumptions are made in these calculations, some of which are so serious that only order-of-magnitude agreement can be expected between the different velocities.

The "vertical velocity from radio Doppler data," V_{ZR}, is calculated by assuming that the vertical oscillations of the F region are of equal amplitude at each of the m reflection points, m being the number of hops of the propagation path. The value $m=2$ is used for the numerical calculations in table 2, since it is (in most cases) consistent with the prevailing $F2$ layer critical frequencies. The values of V_{ZR} would be almost doubled if it were instead assumed that $m=1$, and almost halved if the value $m=3$ were used. According to Chan [1962], if θ_m is the angle of incidence at the $F2$ layer,

$$V_{ZR} = \frac{c\Delta f}{2mf \cos \theta_m}. \tag{7}$$

TABLE 2

Table 1 ref.	Approx. local time	Period of osc. T	Freq. devn. Δf	Horiz. mag. devn. ΔH (Fr)	V_{ZR}	V_{ZM}	V_{ZH}
	hr	*min*	*c/s*	γ	*m/s*	*m/s*	*m/s*
E	11	0.56	0.3	1.4	5	0.6	1.3
G	12	.7	.4	0.4	5	.2	0.4
A	13	2.1	.6	2	8	.9	.7
B	15	3.2	.8	3.2	11	2.0	1.1
F	17	4.7	1.1	2.4	8	5	0.7
H	18	6	0.8	1.5	6	4.5	.6
C	19	1.3	.5	0.5	6	1.0	.4
D	21	3.7	.7	2	10	12	1.3
J	22	15	.6	1.5	8	9	0.4

The "vertical velocity from the motor calculation," V_{ZM}, has been calculated from the horizontal (H) component of magnetic induction only. This amounts to treating the conductivity Σ as a scalar quantity in the calculation of electric fields from E layer current density. Larger velocities V_{ZM} would be obtained if the complete tensor equation $\mathbf{J} = \mathbf{\Sigma} \cdot \mathbf{E}$ were used instead, and the oscillations in magnetic declination included in the calculation. No attempt is made to do this, because the declination variometer traces are not sufficiently sensitive to yield the required information. The conductivity Σ is estimated to be 15 $N_m E$ mhos, if the peak E layer electron density $N_m E$ is expressed in units of $10^{11} m^{-3}$ and magnetic effects of induced ground currents are ignored, as are dynamo fields in the ionosphere. Then it may be found from (3) that

$$V_{ZM} = \frac{2\Delta H \cos I}{\mu_0 B \Sigma}. \tag{8}$$

The "vertical velocity from the hydromagnetic calculation," V_{ZH}, is derived from the equations for a plane hydromagnetic wave in a uniform medium: reflection of waves from the E region and the ground are neglected. The electron density N is assumed to be N_mF2, even though the HF reflections may take place at a lower level in the F region. For this very idealized situation, it is found from (6) that the magnitude of the oscillation is

$$V_{ZH}=\Delta H \cot I(\omega/\nu_{\text{in}}\mu_0 m_i N)^{1/2}. \tag{9}$$

Equations (7), (8), and (9) are used to calculate the vertical velocities corresponding to the data of table 1; results are given in table 2 where the events are arranged in order of local time. The electron densities N_mE and N_mF2 are taken from Washington data for the appropriate dates, but displaced by 2 hr to allow for the longitude difference between Washington and the midpoints of the propagation paths. For nighttime events, rough estimates of N_mE are made for the calculation of V_{ZM}. Values of B and I appropriate to the midpoints of the propagation paths were used.

In table 2, it is seen that the "hydromagnetic" and "motor" velocities V_{ZH} and V_{ZM} are of the same order, except at night when the latter becomes large on account of the small values assigned to the conductivity. The results do not especially favor either model, for both V_{ZH} and V_{ZM} are generally smaller than the "radio Doppler" velocity V_{ZR}. In the case of V_{ZM}, the deficiency may be attributed to the inclusion of only one component of the magnetic field variations, mentioned in connection with (8). In the case of V_{ZH}, the discrepancy could be attributed to the inadequate treatment of hydromagnetic wave propagation. But even the order-of-magnitude agreement actually obtained is of interest, and suggests that it is worthwhile to pursue the topic further. Clearly, some of the major uncertainties in the calculations arise from the length of the oblique-incidence propagation paths and their unfavorable situation in relation to the regular magnetic observatories; they could be avoided in a suitably designed experiment using vertical-incidence sounding.

4. Conclusion

Variations of the phase of high-frequency radio waves reflected from the F region are occasionally correlated with geomagnetic field variations. This correlation may be rather rare, but a few occasions have been recorded on which there is no doubt as to its reality. It may indicate some coupling between the F region and lower levels in the E region where electric currents associated with magnetic variations are thought to flow. Such coupling has often been invoked in theories of the F region, and any experimental demonstration of its existence is of great interest to ionospheric theory. The present paper does not attempt to trace the origin of the disturbances, as this does not appear to be vital to the question of coupling between the E and F regions.

In this paper, the linkage implied by the experimental data has been discussed in two ways: as hydromagnetic disturbances, and in terms of the ionospheric "motor" effect. In numerical calculations it is found that the vertical velocities in the F region, computed from the magnetic data by either of the two approaches, are generally smaller than are required to account for the radio phase oscillations. The differences are not regarded as especially significant, in view of the crude theoretical models used and because of the distances between the magnetic observatories and the ionospheric reflection points for the radio waves, amounting to 1000 km or more.

Further theoretical work is required before the validity of either model can be fairly assessed. On the observational side, many of the uncertainties could be removed if vertical-incidence phase sounders were used in conjunction with suitable magnetometers at nearby locations.

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