RADIO SCIENCE Journal of Research NBS/USNC–URSI
Vol. 68D, No. 3, March 1964

An Interpretation of Rapid Changes in the Phase of Horizontally Polarized VLF Waves Recorded at Night Over a Short Path in the Southwestern United States *

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(Received August 26, 1963; revised October 14, 1963)

Data are presented from a near vertical incidence cw VLF sounding system whose transmitter is located at Sentinel, Arizona. The configuration of the transmitting antenna is such that the vertically polarized groundwave pattern has deep nulls in which receivers may be located. The small groundwave allows the polarization components of the downcoming skywave to be measured with considerable accuracy. The sounding system was operated at four frequencies in the VLF range.

The observations show certain striking features. The records of receivers placed to the east of the transmitter are different in character from records of receivers placed in a corresponding position to the west of the transmitter. Characteristic records of components polarized in the plane of incidence are often very different from those of components polarized normal to the plane of incidence.

Rapidly moving features often pass over the triangle of receiving stations causing 180° to 360° phase changes.

A model is proposed which can explain the observational features of the data.

1. Introduction

It is well known from phase records obtained over both long and short paths (see for example Bracewell et al. [1951]; Hargreaves [1961]) that the *D*-region of the ionosphere shows considerably more irregular fluctuations at night than during the daytime. Various investigations have indicated different generating mechanisms depending on the observational techniques that have been employed. Measurements of phase fluctuations over short paths have certain inherent advantages compared, for example, with radar observations of meteor trails since they provide a continuous record. They also possess advantages over phase measurements obtained on long paths since they provide data from a fairly small region of the ionosphere while long-path measurements represent average conditions over a large area. It is the purpose of the present paper to discuss certain observational features of short-path phase measurements at VLF which have not been emphasized previously, and to discuss certain phenomenological mechanisms which may offer an explanation of the observations.

2. Observations

The use of short VLF paths for studying the ionosphere is not new. For example a group at Cambridge University has made extensive measurements in Great Britain [Bracewell et al., 1951]. They used the transmission from GBR at Rugby and were successful in obtaining a wide variety of information about the *D*-region. However, their experimental system had several inherent drawbacks. First of all, the GBR transmissions are vertically polarized and the groundwave pattern is horizontally isotropic. Consequently, receivers close to the transmitter received a large groundwave component which contaminated their records and made the skywave difficult to isolate and study. Secondly, only one frequency (16 kc/s) was available, and they were unable to carry out many experiments which frequency diversity would have permitted. In order to avoid the first difficulty, the Navy Electronics Laboratory has built two horizontal dipole antennas about 9 km long, oriented in the magnetic meridian and normal to the magnetic meridian. A horizontal dipole over a conducting plane has a radiation pattern with maximum signal radiated upward and has nulls in the vertically polarized component of the groundwave pattern normal to the axis of the antenna [Macmillan, Rusch, and Golden, 1960]. Figure 1 shows the average measured groundwave pattern for one of the antennas. The theoretical groundwave pattern is also shown for comparison. The measurements were made with a field strength meter which was installed in a helicopter and flown in a circle of 10-mile radius around the antenna about 200 ft above the ground. The measured nulls off the sides of the antenna were at least 20 db down from the field strength off the ends. It is not so easy to rule out possible contamination from the horizontally polarized component of the groundwave. The vertical component of the magnetic vector would not be detected because the plane of the receiver loops is vertical. However, a magnetic vector component

*This paper was presented at the VLF Symposium in Boulder, Colo., August 12, 1963.

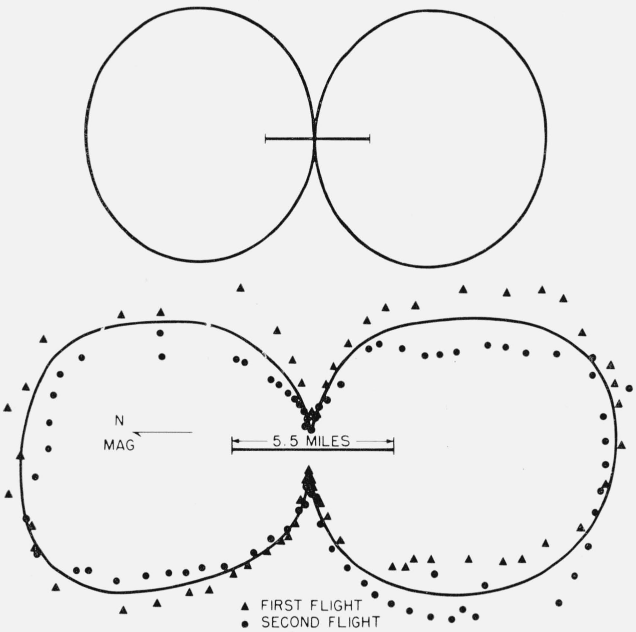

FIGURE 1. *Plan view of the theoretical (top) and measured (bottom) groundwave radiation pattern for a horizontal half wave dipole close to the ground.*

Measurements were made at 14 kc/s. The pattern is for the vertically, polarized component of electric vector.

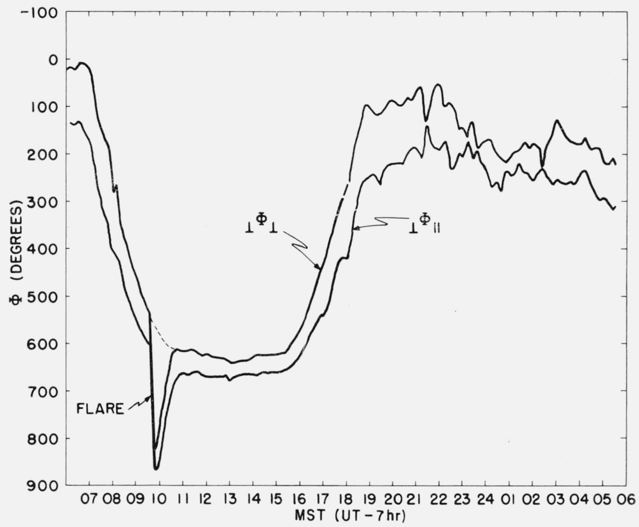

FIGURE 2. *Sample 24 hr record of phase of reflected $_\perp\Phi_\perp$ and converted $_\perp\Phi_{\parallel}$ skywave for 1 March 1962 from receivers placed in the null of the vertically polarized groundwave pattern.*

The site, Castle Dome, is 67 miles magnetic west of the transmitter. Record shows the response of the system to the class 2 flare of 1 March 1962. Note lack of correlation between polarization components at night in contrast to perfect correlation during flare.

in the direction of propagation would be detected by the loop and its possible importance depends on factors such as soil conductivity, soil dielectric constant and distance from the transmitter. Using theoretical analyses of the radiation pattern of a horizontal wire above a conducting plane by Wait [1961] and Norton [1937], it can be shown that the contribution from such a longitudinal component of the magnetic vector should not be large five wavelengths from the antenna even during daytime conditions so it is much smaller than the skywave at night. Many measurements were made in order to evaluate any vertically or horizontally polarized groundwave at the receiving sites and its contribution was found to be negligible at night compared with the skywave. The method used was that developed by the Cavendish group (loc cit) and employs a polar plot of the phases and amplitudes observed as the height of the reflecting layer varies through the day. If there is only a skywave present, the locus of the vector should approximate a spiral centered on the origin as the reflecting layer descends. If there is a constant groundwave component present, the spiral should be centered on the tip of the groundwave vector and its displacement from the origin will represent the magnitude and phase of the groundwave. Because of random variations with time, the method is not very sensitive but indicates that any groundwave component must be very small (see appendix). Therefore, by placing the receivers along a line normal to the axis of the antenna it is possible to measure the downcoming skywave reflected from the ionosphere at night with very little contamination from a groundwave.

Since VLF waves are reflected in the lower ionosphere they can be used as a sensitive detector of small changes of ionization in this region. At VLF it is difficult to sweep through a range of frequencies or use pulsed transmission as is done at higher frequencies, so an alternative was used. In the present system continuous wave transmission is employed and phase and amplitude are recorded at receivers located a short distance from the transmitter. This type of measurement is commonly made over long paths using standard VLF transmissions. However, the phase and amplitude variations observed over long paths are the integrated effect from a large area of the ionosphere. It is therefore impossible to measure small local features in the ionosphere, and it is difficult to isolate and study the mechanism of phase and amplitude changes. With a short path, not only is the area of the ionosphere which affects the signal relatively small, but because of the small angle of incidence, the phase and amplitude perturbations are more pronounced.

The small groundwave at the receiver sites makes it possible to obtain reliable measurements of the phase difference between downcoming polarization components of the skywave and of the ratios of their amplitudes. The most convenient components to measure are those normal to the plane of propagation and in the plane of propagation. The phase and amplitude of the polarization components were measured continuously through the night and the phase difference and amplitude ratio were then compared with the theoretical results predicted by the full wave solution for a continuous lower ionosphere computed by a high speed digital computer using numerical methods developed by Budden and Barron [1959]. The method requires very careful

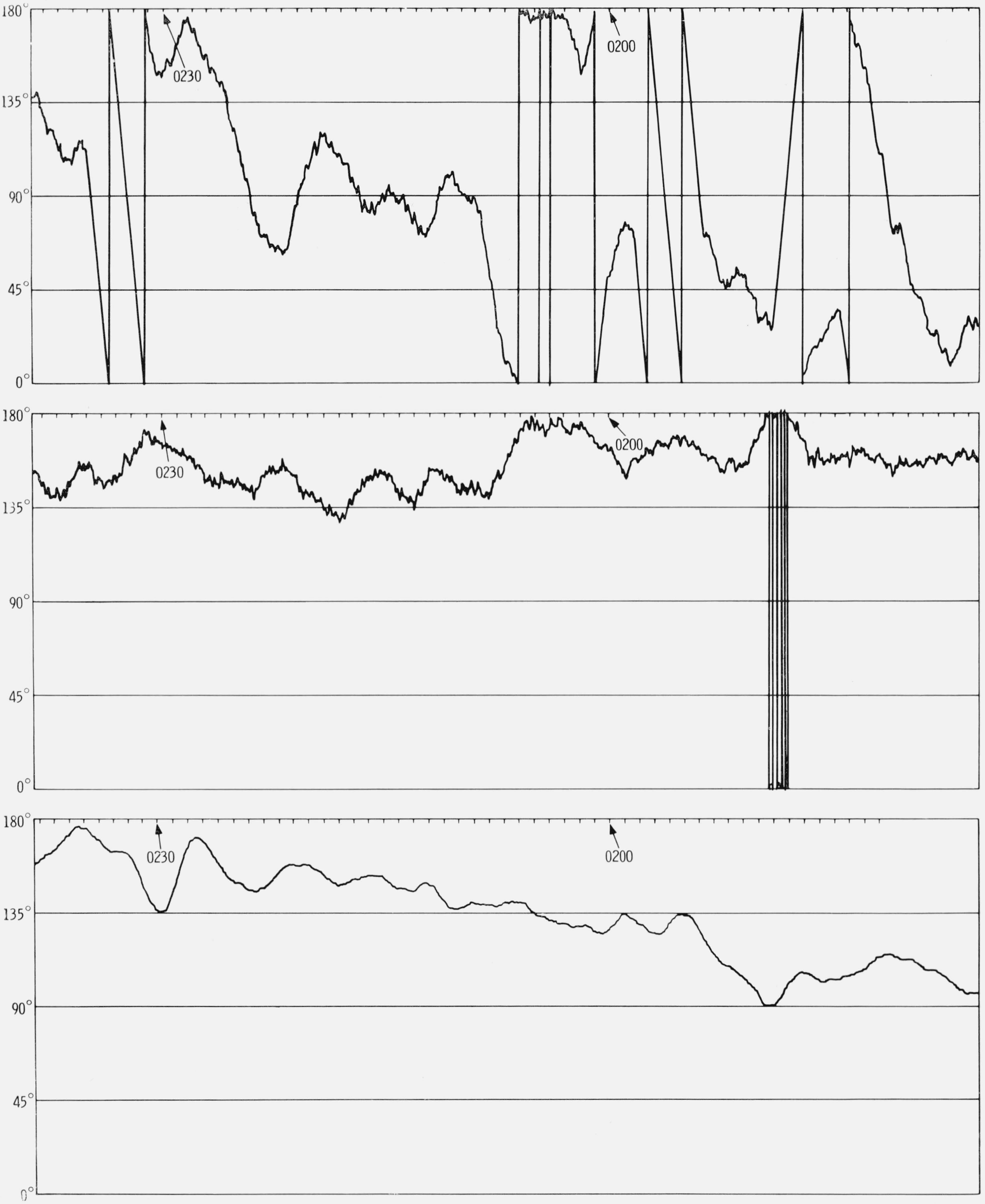

FIGURE 3. *Typical phase records at 13 kc/s for a summer night to the east of the transmitter (top) and to the west of the transmitter (bottom) for polarization normal to the plane of propagation.*

The middle record is from the station to the east of the transmitter for polarization parallel to the plane of propagation.

calibration of the experimental system with particular attention to exact location of the receivers in the groundwave null.

The experimental system has been operated periodically since November 1961. The terminal equipment is identical with that which has commonly been used at the U.S. Navy Electronics Laboratory for long path measurements for about a decade. The receivers employ phase coherent detection and use a precision crystal oscillator stable to about five parts in 10^{10} over 24 hr. A slow oscillator drift is sometimes apparent in the records, but our concern in the present paper is with rapid phase changes sometimes observed at night.

A sample 24-hr record of both polarizations obtained over a 67 mile path in Arizona is shown in figure 2. The record of the well-known class 2 flare of 1 March 1962 has been chosen for this purpose since the flare provides a convenient impulse for system diagnosis. The apparent almost-complete absence of interference phenomena during the flare and during the sunrise-sunset periods should be noted in connection with possible groundwave and second hop effects. In fact, polar plots of the records during sunrise and sunset indicate that the second hop skywave is somewhat less than one-fifth of the first hop at these times. The appearance of figure 2 is in sharp contrast to some records obtained at night on a receiver 74 miles to the magnetic east of the transmitter during June and July of 1962. It is the purpose of this paper to discuss and interpret the June–July records.

Several characteristic features of the records were noted which must be explained by any acceptable model.

1. The amount of variability observed on any given frequency depended strongly on the location of the receiver relative to the transmitter. In the June–July measurements of 1962, the receiver site 74 miles to the east of the transmitter exhibited much more phase "noise" at 13 kc/s than similar sites to the west of the transmitter.

2. When the transmission was in the magnetic east-west direction and was horizontally polarized, the phase of the horizontally polarized component of the received wave exhibited much more fluctuation than the vertically polarized component, as shown by the records in figure 3.

3. Occasionally, large rapid changes in phase occurred, and there was a tendency for these changes to be approximately 180° or 360°. These large rapid changes were accompanied by a sharp drop in signal level and they occurred almost simultaneously (within a few minutes) over a comparatively large horizontal area (receiver separations of 40 miles).

4. There is some evidence that the large rapid phase changes are biased toward increasing phase (apparent shortening of the radio path) as shown by the occasional occurence of records such as figure 4 in which the phase through the night accumulated many cycles.

3. Models

In the past, attempts have been made to interpret various observational data in terms of turbulence, and statistical techniques have been developed [Briggs, Phillips, and Shinn 1950] suitable for analyzing observational data in terms of ionospheric drifts on which random motions are superimposed. More

FIGURE 4. *Phase record for the night of 29–30 October 1961.*

Times are in mountain standard time (UT-MST=7 hr). Radiofrequency is 23 kc/s. An oscillator drift amounting to a total of about three cycles is evident in the record, but the events of principle interest are the abrupt phase changes that occur periodically with a bias toward phase increase.

recently Hines [1960] has suggested that the large scale irregularities may be the result of freely propagating internal gravity waves. Such wave trains may possibly be generated by tropospheric weather phenomena [Gossard, 1962]. Axford [1962] has suggested that ionized layers may be created in the neighborhood of shearing zones created by internal gravity waves by a modification of the mechanism originally proposed by Dungey [1959]. Computations by Storey [1962] indicate that such a mechanism should be effective down through the E-region but not far below it. The presence of internal waves in the neighborhood of the bottom of the thermosphere (about 80 km) has been impressively verified photographically by Witt [1962].

The tendency of the large rapid phase changes to be approximately 180° or 360° strongly suggests interference between two or more reflectors moving relative to each other either horizontally or vertically. Since the observations indicate the presence of a small number of discrete reflectors, one possible model consists of a reflecting layer with perturbations moving horizontally. Reflecting facets would occasionally occur off-path producing reflected rays that interfere with the on-path reflection.

However, there appears to be one important requirement that this model cannot satisfy. Since the phase changes are assumed to occur only because of geometrical changes, it cannot explain the striking difference in appearance of the phase changes of the

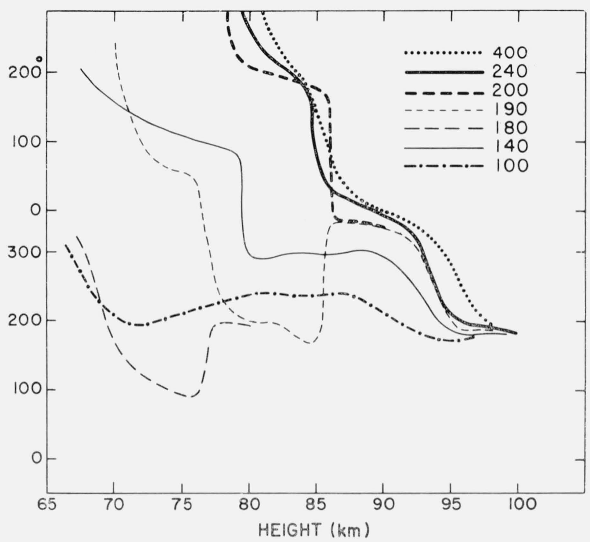

FIGURE 5. *Radio phase as a function of height of the base of the lower layer in a "step" model of the ionosphere.*

Collision frequency is assumed to be given by $0.4303 \times 10^{12} \exp(-0.1622h)$ where h is height in kilometers. Polarization is normal to the plane of propagation. The radiofrequency is 13 kc/s. The assumed angle of incidence is 31° corresponding to an assumed reflection height of 90 km for East to West propagation. Curves are for various electron densities. Note the very abrupt change in phase that occurs at 86 km for electron densities of 190 to 200 el/cm³.

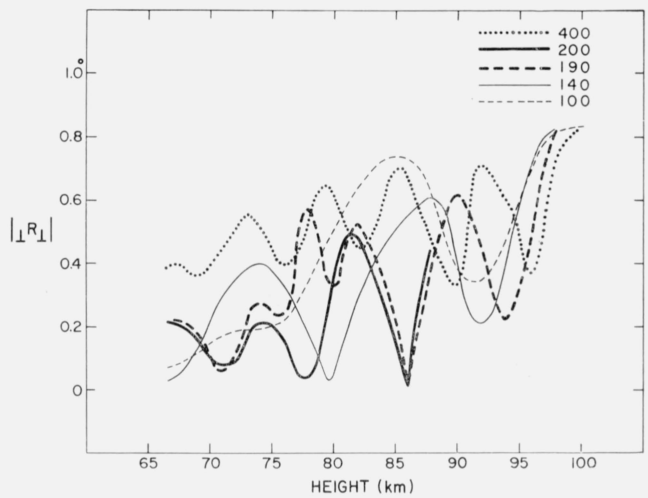

FIGURE 7. *Magnitude of reflection coefficient versus height of the base of the lower layer in a "step" model of the ionosphere.*

Polarization is normal to the plane of propagation. Frequency is 13 kc/s. Other conditions as in figure 5.

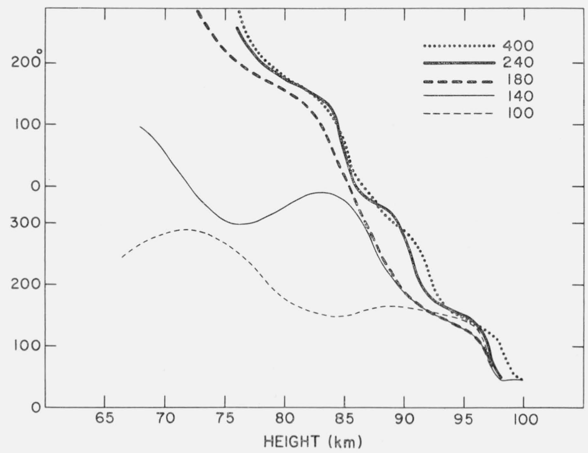

FIGURE 6. *Radio phase versus height of the base of the lower layer in a "step" model of the ionosphere.*

Polarization is parallel to the plane of propagation. Frequency is 13 kc/s. Other conditions as in figure 5.

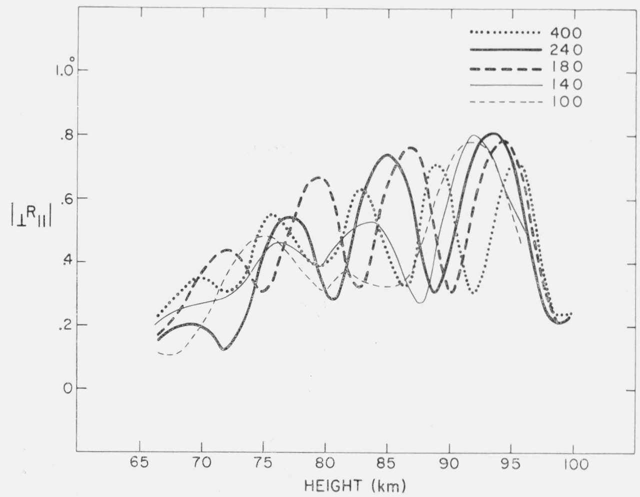

FIGURE 8. *Magnitude of reflection coefficient versus height of the base of the lower layer in a "step" model of the ionosphere.*

Polarization is parallel to the plane of propagation. Frequency is 13 kc/s. Other conditions as in figure 5.

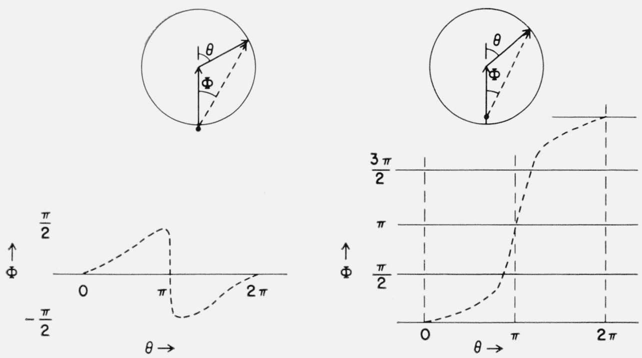

FIGURE 9. *Schematic drawing illustrating why very abrupt changes of 180° or 360° can occur for certain layer spacings and electron densities in a "step" model of the ionosphere.*

Φ is the phase angle measured, and Θ is the supposed phase of a varying component.

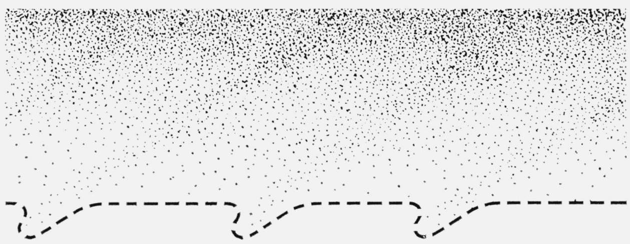

FIGURE 10. *Schematic drawing showing the effect of a wave train of the type discussed by Hines on the electron density of the lower ionosphere.*

The density of dots represents electron density. The dashed line represents a typical contour of electron density.

polarization component in the plane of propagation and that normal to the plane of propagation. This is probably a fatal defect of this model.

We now consider the problem of vertically moving reflectors. It is interesting to consider what pattern of phase fluctuation might occur if a partially reflecting layer were to descend a short distance below the *E*-region before attachment and recombination completely dissipated it. The computed phase and magnitude changes resulting from such a model are shown in figures 5, 6, 7, and 8. For simplicity a "step" model has been assumed for the height dependence with a region of 4200 electrons/cm^3 based at 100 km, and below it a region of various electron densities extending downward to various heights as indicated on the horizontal scale of the figure. It is seen that the phase of the $\perp\perp$ component [1] can rapidly change approximately 180° in either direction when the reflected signals from the two layers are comparable but out of phase. The direction of change depends on whether the electron density in the lower region is less or greater than a certain critical value at the critical height. Furthermore, the curves show that abrupt phase changes are much more pronounced on the $\perp\perp$ polarization than on the $\perp\|$ polarization.

[1] The symbol $\perp$ means "perpendicular to the plane of propagation" and $\|$ means "parallel." The first symbol refers to the transmitted wave and the second refers to the received wave. They apply to the electric vector.

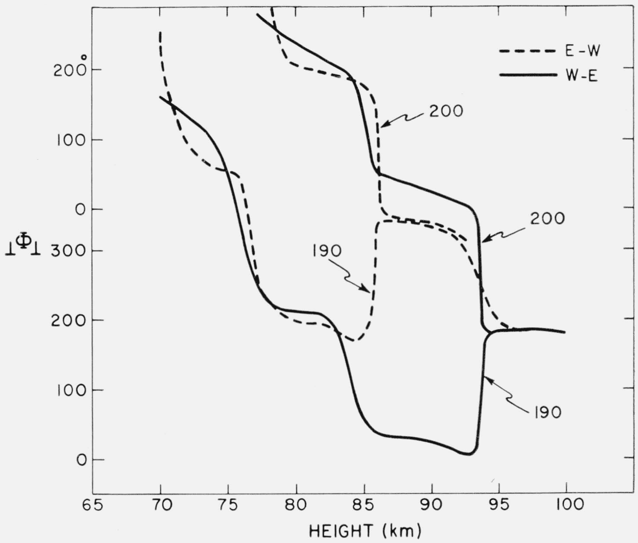

FIGURE 11. *Theoretical phase versus height of the base of a lower layer in a "step" model of the lower ionosphere for east to west propagation (dashed) and west to east propagation (solid) for polarization normal to the plane of propagation.*

Radiofrequency is 13 kc/s. Angle of incidence for W to E propagation is assumed to be 34° in accordance with the path geometry. The 3° difference in angle of incidence causes negligible modification in the pattern of the curves.

The abrupt phase change occurs because of interference between the reflected energy from the 100 km level and reflection from the second layer at various heights below 100 km. The situation is shown schematically in figure 9. While this model can account for the difference between the two polarizations, it cannot, alone, account for the bias toward 360° increases in phase or the difference in "noise" on records of receivers to the east and to the west of the transmitter.

The model that seems to account for all of the observational requirements is a "step" model with perturbations of either the lower or upper boundary. Suppose, for example, that the average electron density versus height distribution is a step profile whose lower step is a region with an electron density and thickness such that partial reflection from it is nearly equal to and out of phase with the reflection from the upper region. If horizontally asymmetrical perturbations of ionization were to occur as shown schematically in figure 10 due to the wind shear zones discussed by Hines and Axford it might be expected that the height of reflection of the lower boundary would decrease as the ionization irregularity crosses the link. At some time during its passage the electron density in the lower region would pass through a maximum and begin to decrease. After the "bulge" in the lower boundary crosses the link, the phase should begin to decrease and quickly return to its original value before the ionization irregularity occurred. If this phenomenology were to occur and if the ionization density in the lower region were slightly greater than critical during passage of the irregularity, the resultant vector from the two reflectors would trace a locus which could completely encircle the origin as the (relatively minor) ionization irregularity crossed the link. Furthermore, the direction of the 360° phase change would be toward increasing phase. It should be noted at this point that although ionization irregularities moving horizontally are required in this model the interference phenomenon arises from 2 layers rather than from multiple reflecting facets as considered in the first model discussed.

3.1. Nonreciprocal Character of the Records

The above model appears to explain the observational features listed at the beginning, especially those indicative of interference phenomena. For example, the bias towards increasing phase now appears to be reasonable. However, the most convincing feature of the model is its ability to explain the strikingly different character of the records received 74 miles to the east of the transmitter at Gu Komelik from those received 67 miles to the west of the transmitter at Castle Dome. At 13 kc/s the records at Castle Dome were comparatively quiet during June and July. On the other hand, the records at Gu Komelik showed wild fluctuations in both phase and amplitude with many 180° and 360° changes biased toward increasing phase. Typical examples of the phase records are shown in figure 3. It is inconceivable that the ionosphere is sufficiently inhomogeneous from east to west over a period of months to account for such different received signals with such a small receiver separation. Apparently the only remaining possibility is the nonreciprocal character of east-west propagation at low radio frequencies. This effect can normally be considered to be quite small. However, figure 11 shows a plot of phase versus height of the base of a lower layer near the critical electron density in a step model for east-west propagation and west-east propagation. It is seen immediately that the critical height is higher for west to east propagation since no abrupt phase jump occurs for any electron density at the 92 to 94 km level for east to west propagation. Therefore, if the separation of the two layers is about 7 km, the two reflections would destructively interfere for west-east propagation, and erratic phase fluctuations would occur while east-west propagation would show fairly minor phase fluctuations. Assuming that two layers with this separation must have existed in June and July and assuming an electron density of about 180 electrons/cm^3 for the lower region, it seems probable that the lower layer can be identified with the *D*-layer observed in propagation over long VLF paths. It should therefore be placed at about 93 km while the upper layer must then be placed at 100 km. However, it should be noted from the figures that other height differences can lead to destructive interference also.

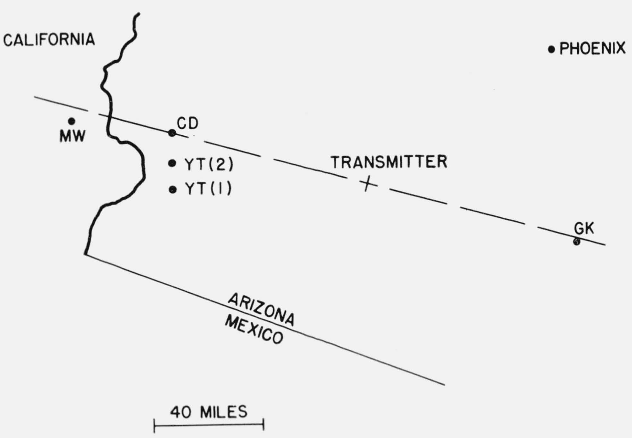

FIGURE 12. *Map of the transmitter and receiver sites.*

Dashed line is east-west (magnetic). CD is Castle Dome, Arizona; MW is Midway Wells, California; and YT(1) is the Yuma Test Station, Arizona.

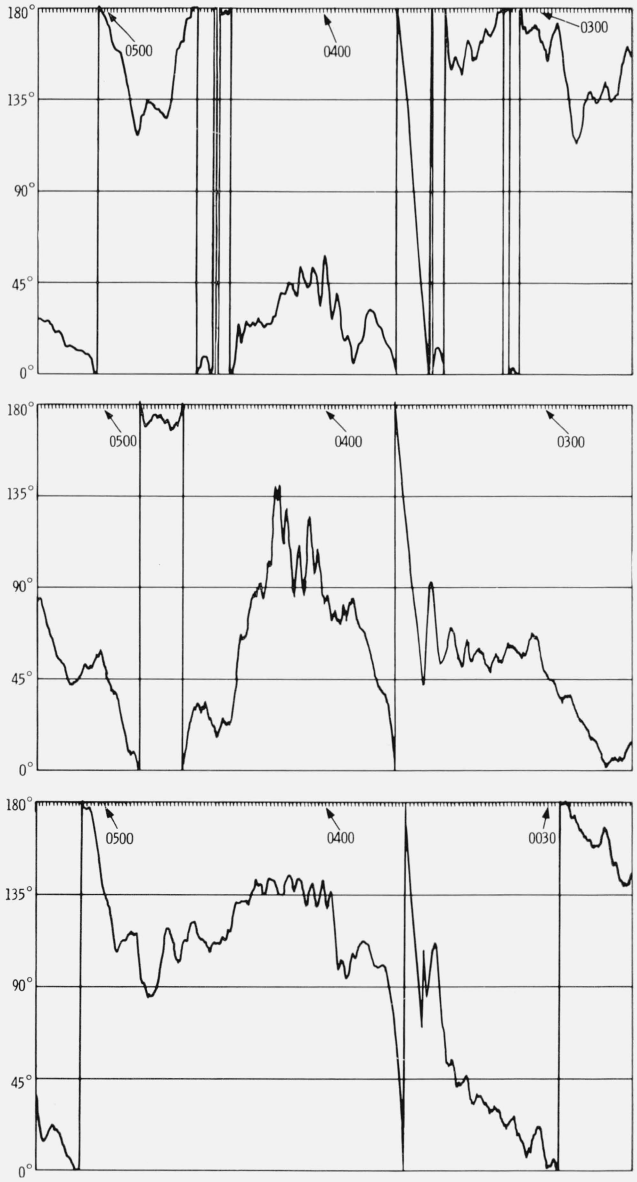

FIGURE 13. *Phase records at Castle Dome (top), Midway Wells (middle) and Yuma Test Station (1) (bottom) showing a large and very rapid phase change of 180°.*

Chart width is 180°. Radiofrequency is 23 kcs.

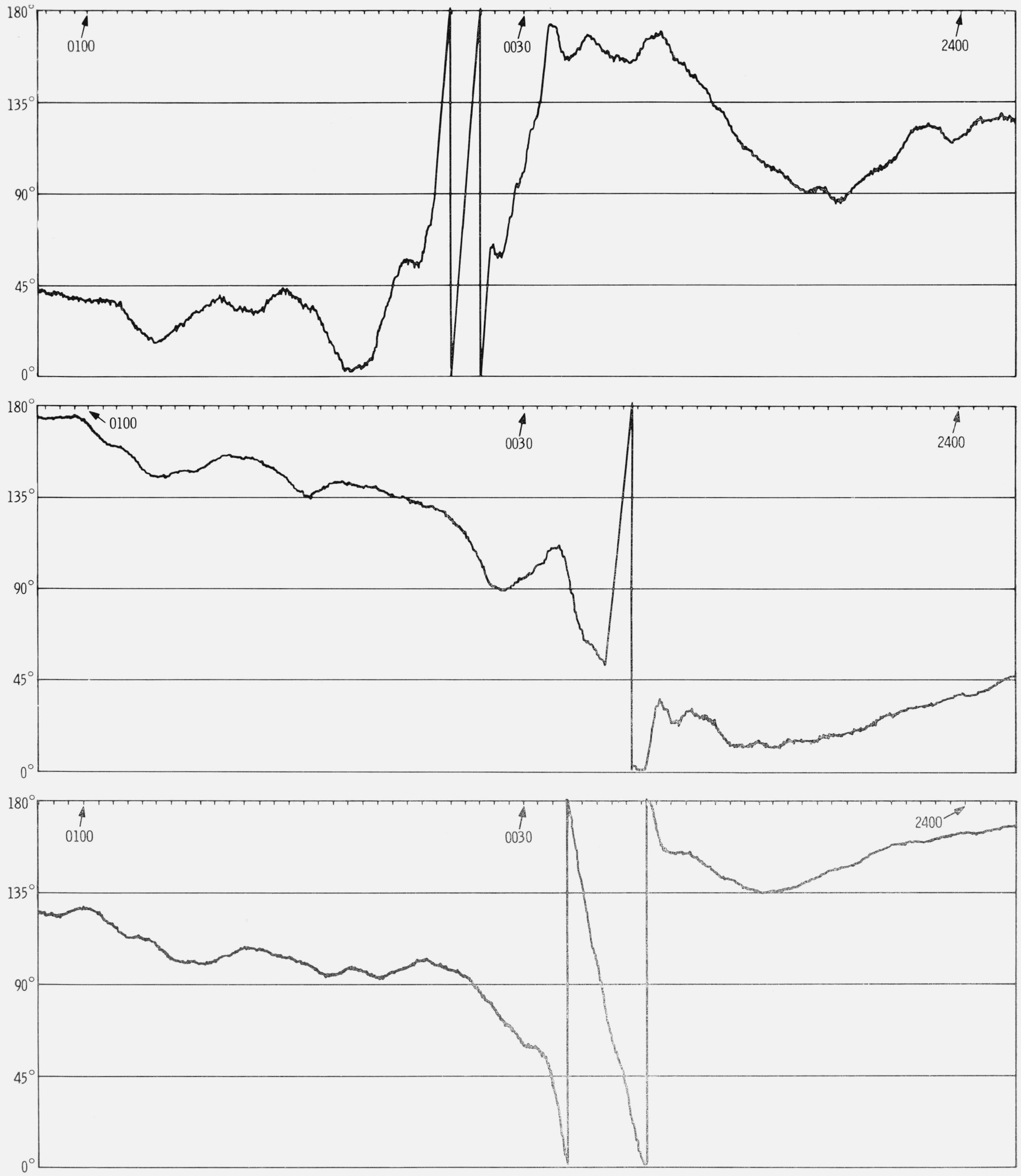

FIGURE 14. *Phase records at MW (top) CD (middle) and YT(2) (bottom) showing large rapid phase changes.*
Radiofrequency is 17 kc/s.

4. Spaced Receiver Observations

Spaced receiver experiments show that horizontally propagating disturbances of the kind required by the above model do in fact occur. For these tests three receivers were placed in a triangle as shown in figure 12. Abrupt phase changes of about 180° or 360° were often observed at all three receiver sites with different arrival times at the different sites. Some examples of such disturbances are shown in figures 13 and 14. As would be expected, the resultant vector does not always encircle the origin and there are many cases when a sharp spike is noted in the phase record where the phase changes almost 180° in one direction and then returns to its previous value. Sometimes the resultant encircles the origin at one site but not at another so that the same disturbance can produce a 360° change at one station, a 180° change at another, and simply a perturbation at the third. The horizontal velocities of propagation may be high [Paulson et al., 1962] and are often observed to exceed 100 mph.

5. Summary of Results

In summary, the model requiring the fewest assumptions to explain the June–July data appears to be one in which the base of the nighttime *E*-region occurs at approximately 100 km. Below this height a ledge of electron density of approximately 180 electrons per cm^3 extends downward to a height of about 90 to 95 km. Perturbations of one of the boundaries having amplitudes of 2 or 3 km, and moving horizontally, then cause large phase and amplitude fluctuations and lead to approximately 180° or 360° phase changes when the spacing of the layers and the electron density are near the critical values for the radiofrequency being used.

6. Appendix

The potential importance of the groundwave to the interpretation of the experimental evidence presented in this paper makes it desirable to discuss the relative magnitudes of the measured fields in terms of a maximum possible groundwave component.

Figure 15 shows the amplitude record corresponding to the phase record in the middle of figure 14. It is seen that the interfering component which caused the fade from 0014 to 0039 and reduced the signal to almost zero with a corresponding rapid phase change, must have had a magnitude of about 0.5 μa-turns per meter. It is therefore of interest to examine the possible magnitude of the groundwave.

As stated earlier the method used to examine the groundwave makes use of the time variation of the skywave to separate it from the constant groundwave component. The simplest way to do this is to plot phase and amplitude on polar coordinate paper. As reflection height and absorption vary through the day the received field vector will rotate in phase and change in magnitude. If there is no groundwave, it should approximate a spiral centered on the origin. If a groundwave is present, the spiral should be centered on some point off the origin and the displacement represents the magnitude of the groundwave vector. At night the signal is too erratic for this

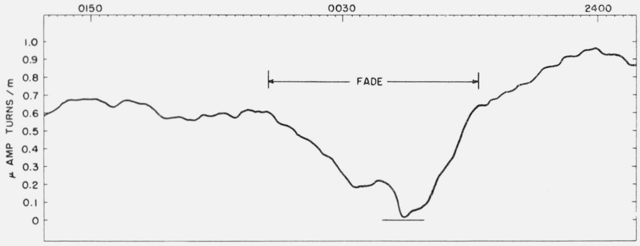

FIGURE 15. *Amplitude record in microampere-turns per meter at Castle Dome corresponding to the phase record shown at the top of figure 14.*

Time is MST.

technique to be of much value, but following sunrise the signal generally becomes quite stable and very meaningful plots can often be obtained. The polar plot made for the same day and receiver as figure 15 is shown in figure 16. Unfortunately, the plot on this occasion is not as well behaved as can generally be anticipated so a "best fit" spiral (dashed curve) has been drawn through the data in order to clarify its interpretation. It is clear that it is impossible to obtain a groundwave of much more than 0.03 μa-turns per meter (arrow) from this data. This is obviously insufficient to interfere effectively with the large nighttime skywave.

7. References

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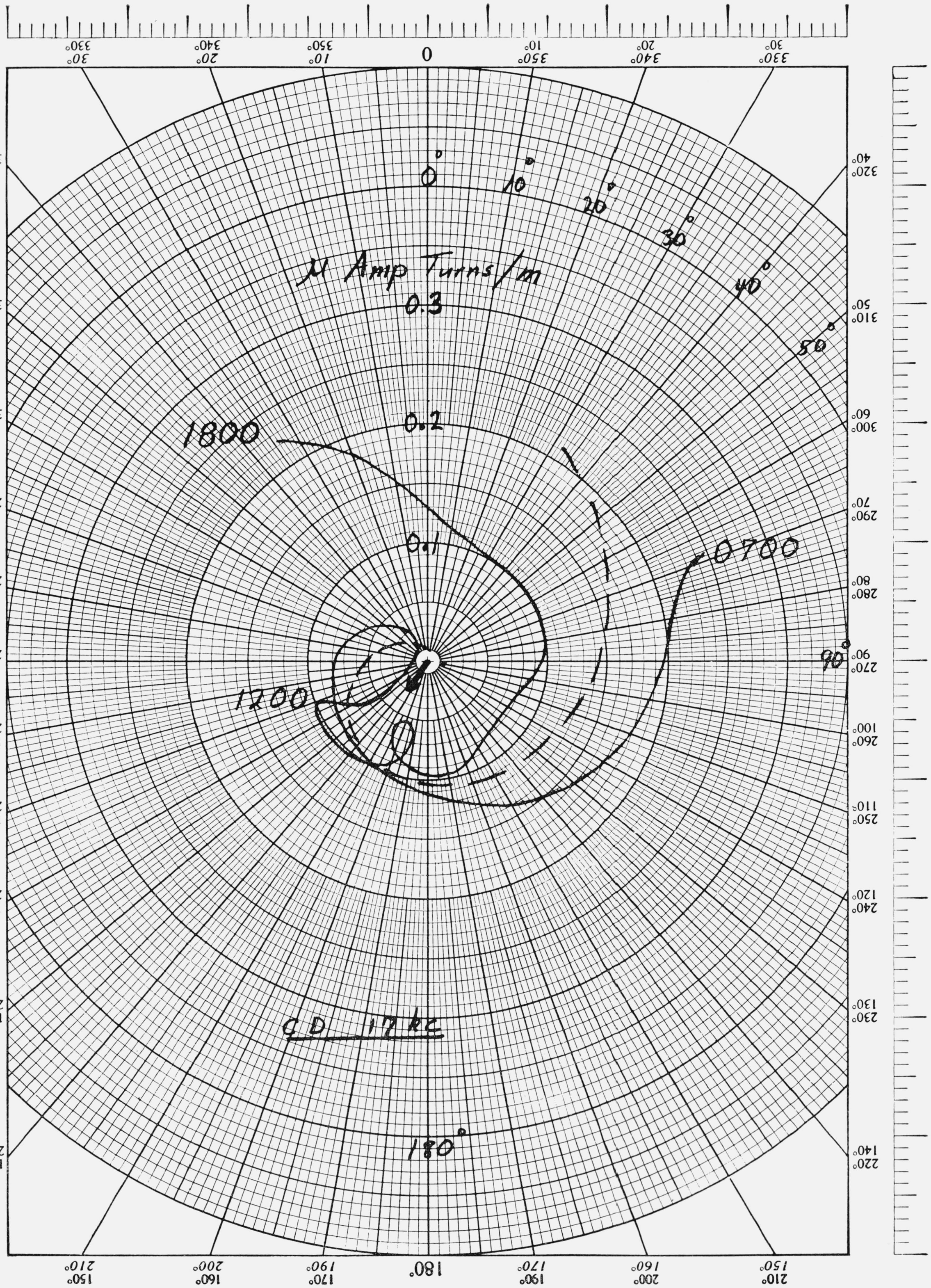

FIGURE 16. *Polar plot of phase and amplitude from 0700–1800 MST at Castle Dome for 24 October 1962.*

The receiving loop is normal to the plane of propagation. The dashed spiral is a smoothed average of the data plot (solid curve). The arrow represents the estimated maximum groundwave component.

(Paper 68D3–341)