RADIO DIRECTION FINDING AT 1.67-METER WAVES

THESIS BY

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ABSTRACT

Different antenna systems were tested for both horizontal and vertical directivity on this wavelength at distances of from 7 to 30 miles. The antennas used in these experiments included parabolic antenna, V-type, double V-type, Adcock antennas, etc.

Using an Adcock antenna the azimuth of the incoming electromagnetic wave can be defined within one half degree accuracy, and with a slight modification of the receiving elements to form a horizontal H antenna, the vertical angle of the incoming wave can also be obtained with the same degree of accuracy. The former antenna can be converted into the latter by mechanical means within a few seconds and thus both vertical and horizontal angles can be measured with the same antenna set-up.

With the antenna one and a half wavelengths above the ground and with the ground surface homogeneous in the immediate vicinity of the receiving antenna, the direction of the incoming electromagnetic wave coincides with that of the transmitter emitting the wave, within the same accuracy of one half degree.

Deviations from the true directions at different locations and at different times were observed.

A simple theory of reception of the horizontal H and the Adcock antennas were also given.

The receiver used for this experiment is a superheterodyne receiver specially designed for this purpose using a resistance-coupled I-F ampligier. It is very stable in operation and has ample sensitivity.

CONTENTS

INTRODUCTION

In the past few years different methods have been worked out for direction finding at various short wavelengths using different kinds of antenna systems. When speaking of direction finding, the defining of horizontal or azimuthal angles of the direction of the incoming electromagnetic waves emitted from a distant transmitter is generally referred to.

Most of the work done on direction finding has been on wavelengths of over ten meters. Due to reflections from Heavyside layers in the high atmospheres alone seriously erronous results often arise.

The modern radio direction finder undoubtedly owes its success very largely to the introduction of vacuum-tube amplifiers, enabling a moderately large reception range to be obtained, and its practical development therefore dates from about 1915. Previous to this, such systems of direction finding as were in existence were confined to short-distance working and the comparatively crude instruments then in use made accurate systematic observations difficult to obtain. As early as 1908, however, Pickard observed that large errors might be obtained in the reading of coil direction finders due to buildings, trees, and other obstacles in the neighborhood. In the diagrammatic representation of his results, the errors are shown to be approaching 90 degrees. It was found also by Fessenden in the years 1901-07, that errors in apparent direction

of as much as 20 degrees to 45 degrees might be obtained in the indication of these instruments when receiving over a range of 100 miles. These errors were attributed to a refraction effect resulting from the difference in conductivity of land and sea-water, or even to a varying local conductivity of the ground and of vegetation. In making continuous observations day and night for a week, Fessenden was apparently the first to observe that the errors were greatest during the night, a fact which he attributed to a refraction effect of large clouds of ionized air in the path of the waves.

A method of obtaining an absolute zero of signal strength on a small frame-coil direction finder was described by A. H. Taylor, in which the "antenna effect" of the coil is compensated for by a small emf from an auxiliary frame at right angles to the first. Using this system at Washington, it was found that while readings taken in the daytime were fairly accurate those taken near sunset and at night were very erratic. While it appeared that the variations observed on continuous waves of wavelength 13,600 meters were greater than on shorter waves, they were quite serious on damped waves of 1,500 meters wavelength. These variable results were briefly ascribed to reflection and refraction effects occurring during the propagation of the electromagnetic waves over the earth's surface.

The liability of the metalwork of a ship to produce a quadrantal error in the readings of a direction finder mounted thereon was mentioned by Blondel in 1919, while the corresponding effects

on an aeroplane were later described by Robinson. The complete theory of the effect of the metal hull of a ship on a direction finder was first given by Mesny in 1920. Calculations from this theory, confirmed by experimental results, showed that the quadrantal error obtained may be as great as 12 degrees. This error was shown to be independent of wavelength and to decrease with the height of the frame coil above the deck. Attention was also drawn in the above paper to the approximately analogous case of a direction finder erected upon a hill or an island, and the resulting quadrantal error which may be obtained in such a case is illustrated by a curve having a maximum value of 15 degrees.

The phenomenon of the refraction of electromagnetic waves in passing over a surface of suddenly changing conductivity was discussed by T. L. Eckersley in 1920. Experimental observations made in Cyprus and Egypt on wavelengths between 800 and 1,100 meters showed that wireless waves in crossing a coastal boundary between sea and land might suffer a deviation of as much as 4 degrees. This deviation falls to zero for normal incidence of the waves on the coast line, and it was also shown to be negligible for wavelengths exceeding 2,000 meters. In the paper there is quoted an interesting case of a bad day minimum being produced by the reception of two waves arriving by different paths and with a phase difference which resulted in a rotating field.

Somewhat similar refraction effects on wireless or radio waves passing from dry to wet ground and across a river were mentioned by

Kiebitz in connection with experiments on a directional transmitter. The deviations of the waves amounted to 8 degrees or 9 degrees for a wavelength of 550 meters.

Some results showing the errors to which a radio direction finder may be subject due to local conditions were given by Hollingworth and Hoyle. Masses of metalwork, tuned circuits, and overhead wires were found to produce appreciable errors in the readings.

In 1920, Round gave an account, chiefly from his personal experience, of the development and application of the direction finder during the war. The manner in which the instrument was perfected as a useful tool for both military and naval purposes was described together with the various types of errors encountered, both by day and by night, Reference was made to the work of Adcock, Eckersley, and Wright in connection with these errors, and a brief indication was given of the means by which they might be eliminated for practical direction finding purposes.

A large amount of experimental work on the intensity and directional properties of the electro-magnetic field radiated from an aeroplane transmitter was described by Baldus, Buchwald, and Hase in 1920, while a mathematical treatment of this case was given by Burstyn. The errors in the apparent bearings of an aeroplane at a ground direction finding station were discussed in detail in their relation to the plane of polarization of the emitted waves. The experiments of Baldus and Buchwald, in particular, showed that

a closed-coil direction finder on the ground could give errors of as much as 60 degrees in the bearings of aircraft. This fact is interesting in connection with the patent filed by Adcock in 1919, in which was described a means of eliminating the error of observation of the orientation of aeroplanes.

Some further observations on the variable night errors were published in 1920 by Kinsley and Soby. Variations in the apparent bearings ranging up to 50 degrees were recorded on wavelengths between 960 and 17,300 meters, and for ranges of transmission from 40 up to 7500 miles.

Towards the end of 1920, R. L. Smith-Rose made regular observations of the apparent radio bearings of various transmitting stations in order to obtain data on the nature, magnitude, and other characteristics of the variations of bearings which were previously known to take place. The range of wavelengths covered in these observations was from 300 to 20,000 meters. Experiments were carried out to ascertain the effect of local conditions such as metal work, overhead wires, trees, etc, on the readings of direction finders. These experiments showed that some quite large errors, ranging up to 22 degrees, can be produced by the proximity of such obstacles and emphasize the importance of exercising care in selecting a suitable site for a direction finding installation. The difficulty in finding any approach to an ideal site was illustrated by the results obtained from the stations selected. In very few cases was the error due to local

conditions less than 2 degrees. However, such a type of error remains constant in value for any particular direction, so that it could be treated as if it was a permanent deviation. In one case, the cause of permanent errors ranging up to 15 degrees was traced to a long iron plate beneath the ground and supporting a sewer duct, over which the direction finding installation was inadvertently erected.

In 1938, Smith-Rose and H. G. Hopkins obtained an accuracy of $\pm 2^{\circ}$ for wavelengths between 6 and 10 meters using loop and Adcock antennas. The sensitivity of their instruments was such that it was sufficient for observations on an experimental 50-watt transmitter at ranges up to twenty two miles over flat ground. Their experiments have shown that the site on which the direction finder was used must be clear of obstacles, particularly trees and vertical wires, for a radius of at least 50 to 100 yards; and there were indications that similar conditions are necessary for the site of the transmitter. When such conditions were satisfied, the bearings observed at distances up to twenty two miles from the transmitter may be in error by as much as 8 degrees, although in the majority of cases the error was less than 2 degrees. They also found that for a given set of conditions the changes in bearings observed from day to day do not exceed about 2 degrees for ranges of twenty miles, although in some long-distance observations made at a range of 3000 miles the variations in bearings was as much as 15 degrees in the course of few minutes'

observations.

Later, H. G. Hopkins using a loop antenna at the same wave range of from 6 to 10 meters reported an accuracy of 0.1 degree in defining the horizontal angle of a local transmitter at a distance of twenty five yards using modulated signals. However, he didnot mention anything about accuracies at long distances, only in which erronous results often arise. The loop he used to get resonance at 6-meter waves was a square one seven inches on each side. The receiver was superheterodyne type with a band width for the 2-megacycle intermediate frequency of 10 kilocycles for half amplitude, and has a poor selectivity. The loop was supported at a height of about six feet above ground. During observations the observer has to change position to keep on a line perpendicular to the plane of the loop in order that he might not affect the bearings. Even so, slight head movements affected the bearings by ± 0.2 degree.

So far, no effort has ever been made to accurately define the vertical angle of the direction of an incoming wave from a distant transmitter high above ground.

The object of the present experiment was to develop suitable antenna systems at 1.67 meters to define both the azimuthal and vertical angles of the waves emitted by a small radio-meteorograph transmitter sent aloft on a sounding balloon.

One of the main difficulties one encounters in getting down much below 6 meters for direction finding is the problem of building a suitable receiver at this short wavelength that has satis-

factory characteristics. Other difficulties involved in these ultra high frequencies include: Perfect shielding to prevent stray pick-up of signals from parts other than the antenna system itself, low loss insulation, perfect mechanical and hence electrical symmetry, possible reflections from nearby objects, high absorption, etc.

Since the transmitter has a power output of only a small fraction of a watt, a very sensitive receiver must be used in conjunction with the direction finding system.

In order to examine the directional properties on this wavelength of 1.67 meters, different antenna systems were thoroughly tested for both vertical and horizontal directivity at distances of from seven to thirty miles. The antenna tested in these experiments included parabolic, V-type, double V-type and Adcock types. The loop antenna was not used because of its small size at this wavelength that the sensitivity of the direction finder would be very low.

A constantly revolving parabolic antenna system for determining the azimuthal angle was tested. Different numbers of reflecting elements and various spacings were tried. A recording device operated by the signal output from a super-regenerative receiver was attached to the rotating antenna. For each complete revolution of the antenna an arc of from 40 degrees to 120 degrees facing the direction of the incoming wave was drawn on the table by the recording device, and the line which bisected this arc gave

the azimuth of the incoming wave. This method not only lacked consistant accuracy but also was unable to define the vertical angle. The Adcock type oriented for null readings was finally adopted for defining the horizontal angle. The V-types that were tried also lacked the desired instrumental accuracy.

Using an Adcock antenna the azimuth of the incoming electromagnetic wave can be defined within one-half degree accuracy, and with a slight modification of the receiving elements to form a horizontal H antenna, the vertical angle of the incoming wave can also be obtained with the same degree of accuracy. The conversion from the Adcock to the horizontal H type requires but a few seconds and will be described later. Thus both vertical and horizontal angles can be measured with the same antenna set-up.

APPARATUS

(a) Transmitter

The transmitter operates on a wavelength of 1.67 meters and a power output of a small fraction of a watt. A 955 acorn tube is used in a Colpitt's oscillator circuit which is shown in Fig.1b. The circuit is simple and readily tuned. The weight of this transmitter is less than two ounces. Fig. 1a shows the actual layout of the transmitter.

Fig. 1a

TRANSMITTER

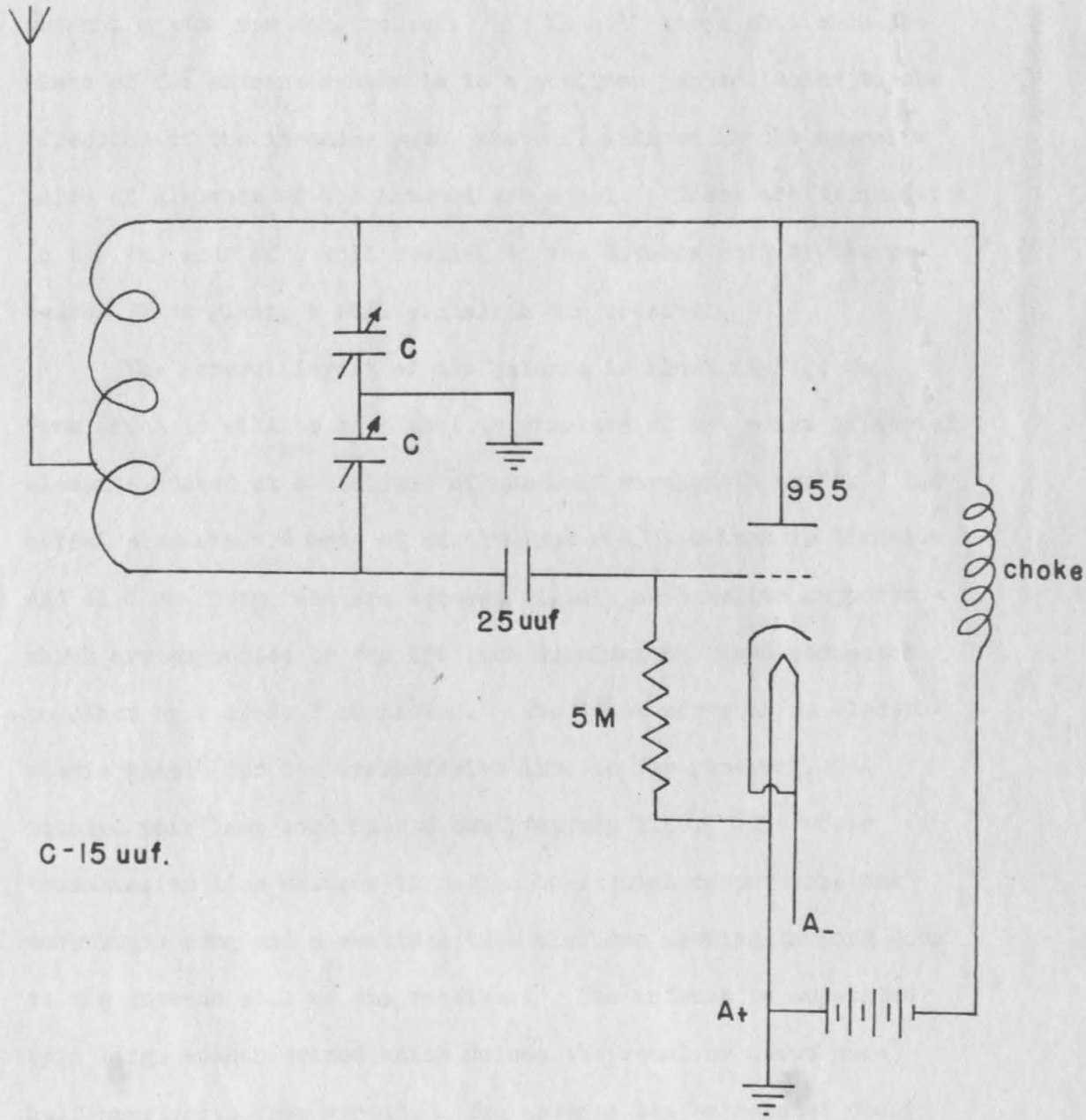


Fig. 1b

(b) Antenna System

For measuring the azimuthal angle a conventional Adcock antenna system was constructed. It is well known that when the plane of the antenna system is in a position perpendicular to the direction of the incoming wave, the emf. induced in the opposite pairs of elements of the antenna are equal. These are transmitted to the two ends of a coil coupled to the antenna coil of the receiver, thus giving a null signal in the receiver.

The general layout of the antenna is shown in Fig. 2a from which it will be seen that it consists of two pairs of aerial elements spaced at a distance of one-half wavelength apart. The aerial elements are made of duraluminum rod, 1/4 inch in diameter and 41.3 cm. long, and are screwed rigidly on bakelite supports which are supported by two 1/2 inch duraluminum tubes connected together by a brass T connector. The tubes serve as an electrostatic shield for the transmission line to the receiver. A twisted pair lamp cord made a satisfactory line. The whole transmission line extends through a horizontal copper tube one wavelength long and a vertical tube also one wavelength long down to the antenna coil of the receiver. The antenna is supported by a large wooden tripod which raises the receiver about one-half wavelength from ground. The antenna can be rotated about the vertical component of the transmission line as the vertical axis. The reason that the antenna is displaced one wavelength

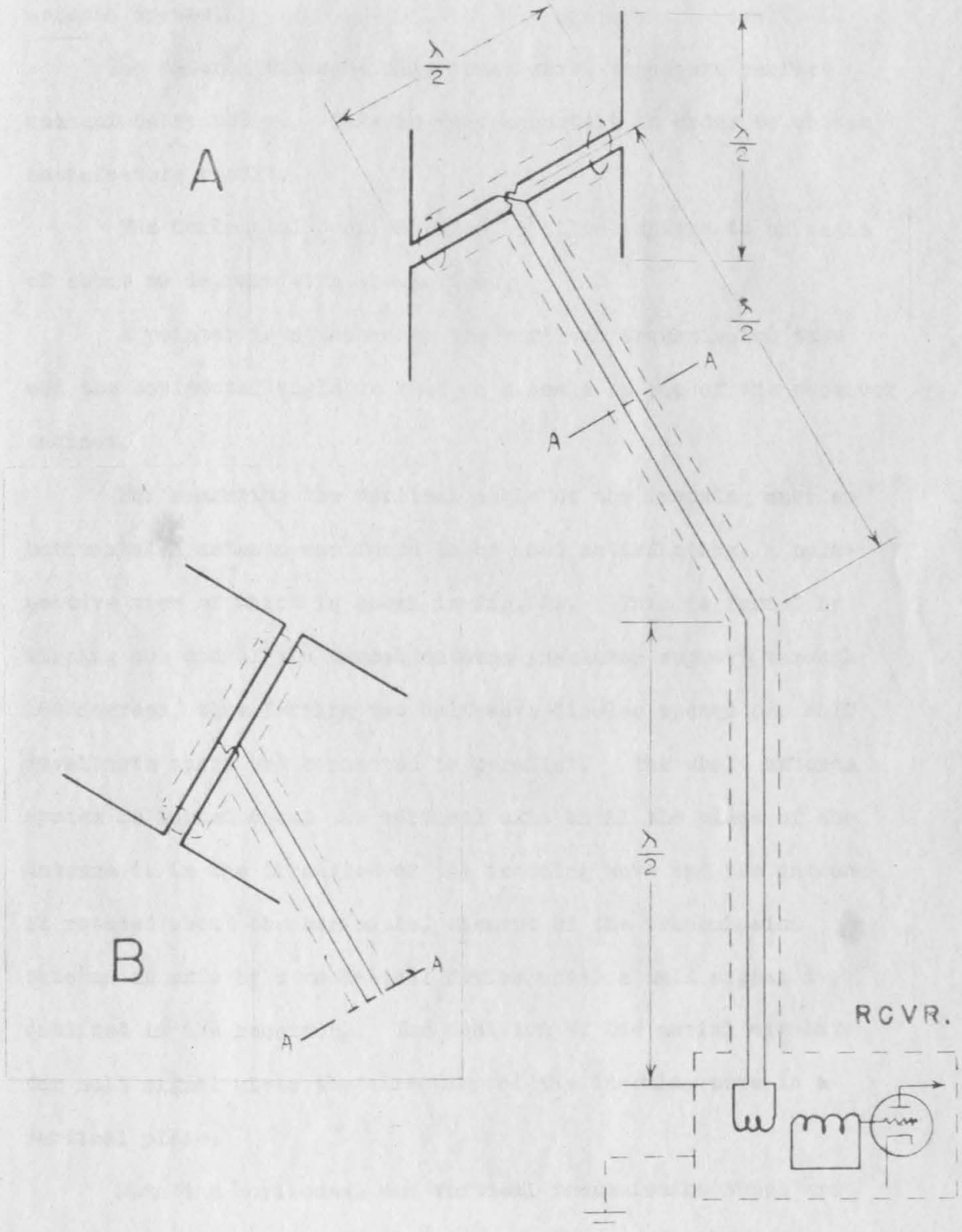


Fig. 2

away from the vertical axis is to avoid any unsymmetry in the antenna system.

The antenna was carefully constructed to secure perfect mechanical symmetry. This is very important in order to obtain satisfactory results.

The horizontal beam can also be tilted upward to an angle of about 60 degrees with the horizon.

A pointer is attached to the vertical transmission tube and the horizontal angle is read on a scale on top of the receiver cabinet.

For measuring the vertical angle of the incoming wave an horizontal H antenna was found to be most satisfactory, a perspective view of which is shown in Fig. 2b. This is formed by turning one end of the Adcock antenna insulator support through 180 degrees, thus forming two half-wave dipoles spaced one half wavelength apart and connected in parallel. The whole antenna system is turned about the vertical axis until the plane of the antenna is in the direction of the incoming wave and the antenna is rotated about the horizontal element of the transmission tube as an axis by a mechanical device until a null signal is obtained in the receiver. The position of the aerial elements for null signal gives the direction of the incoming wave in a vertical plane.

Both the horizontal and vertical transmission tubes are attached to the wooden tripod and the complete assembly can be easily folded together to be transported.

Fig. 3a is the picture of the antenna in the set-up and Fig. 3b is the complete assembly of the apparatus in the field set up for making observations.

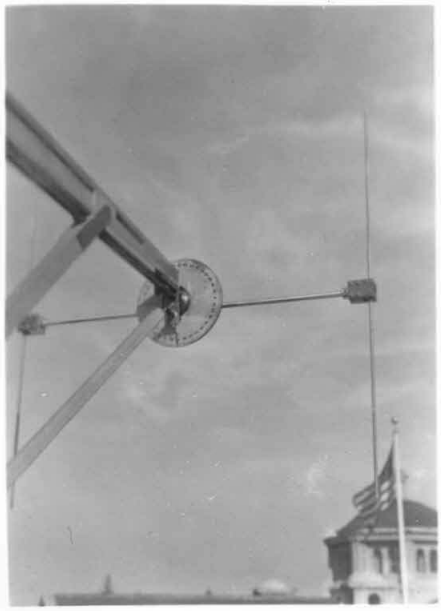


Fig. 3a

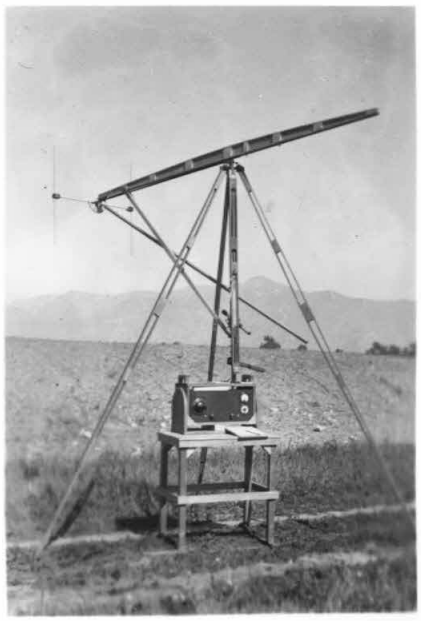


Fig. 3b

(c) Superheterodyne Receiver

This receiver was especially designed and built to operate at 1.67 meters for the reception of weak signals emitted from a small radiometeorograph transmitter sent sloft by sounding balloons. Since it was to be used primarily for direction finding at this wave length, stability in operation and sensitivity were essential characteristics.

The super-regenerative type receiver is very sensitive and satisfactory for most ultra high frequency purposes, but it is not suitable for direction finding due to its automatic volume control action. A superheterodyne receiver using a conventional tuned intermediate frequency amplifier is also unsatisfactory due to the narrow band width of the intermediate frequency amplifier. The inconstancy of the intermediate frequency due to slight frequency variations in the ultra high frequency heterodyne oscillator or the signal causes the output to fluctuate considerably. Thus it is essential to have an intermediate frequency amplifier with a flat overall gain over a wide band of frequencies. While this characteristic could be obtained in a band-pass amplifier, the same can be achieved with a resistance-coupled amplifier, the latter, however, is much simpler in design and construction. In addition, it is more compact and is free from misalignment due to the rough handling incidental to field observations.

The receiver consists of two units, a converter unit and a high gain resistance coupled intermediate frequency amplifier together with diode detectors and a vacuum tube voltmeter. The resistance coupled intermediate frequency amplifier has a very flat frequency response

over a frequency range of 110 kilocycles thus allowing for any slight variations etc. without affecting the output of the receiver.

The Converter Unit

The converter unit consists of a 956 radio frequency amplifier, a 954 mixer and a 955 oscillator. The radio frequency amplifier gives an amplification of approximately two and a half for the stage. The tuning condensers, C_3, are National UM-50 cut down to two rotor plates and one stator plate. One of the stator supports was removed and all excess shaft was cut off to reduce the minimum capacity. The rotor brushes were carefully cleaned and the spring tension increased to give smoother contact. Relatively large trimmer condensers, C_T, are used to give a band spread effect to the tuning. All coils are one and half turns of #20 phospher bronze wire 1/4 inch in diameter. The length of each coil is about 1/4 inch; however, in order to match their inductances slight variations in the lengths are necessary. A grounded Faraday screen electrostatically shields the inductively coupled antenna coil from the radio frequency coil (Fig. 4). The plate of the radio frequency tube is capacitively coupled to the grid coil of the mixer stage at the point one-half turn down from the grid end.

The suppressor grid of the mixer tube is connected directly to the grid of a conventional triode oscillator. The tap onthe oscillator.coil is about one-half turn up from ground.

The different stages are assembled in shielded compartments as

shown by dotted lines in Fig. 5a, with the pentode tubes mounted through the shields. The three tuning condensers are ganged together with Pyrex rods passing through the shields thus reducing the back lash, high frequency losses, and particularly the interstage coupling to a minimum. While all three rotors of the tuning are grounded, interstage coupling results if a common shaft is used. Mechanical considerations require universal couplings between these condensers. Even though isolantite universals are employed thus isolating the rotors electrically, if metal shafts are used for ganging, at these ultra high frequencies enough energy is transmitted through the shields by them to produce instability.

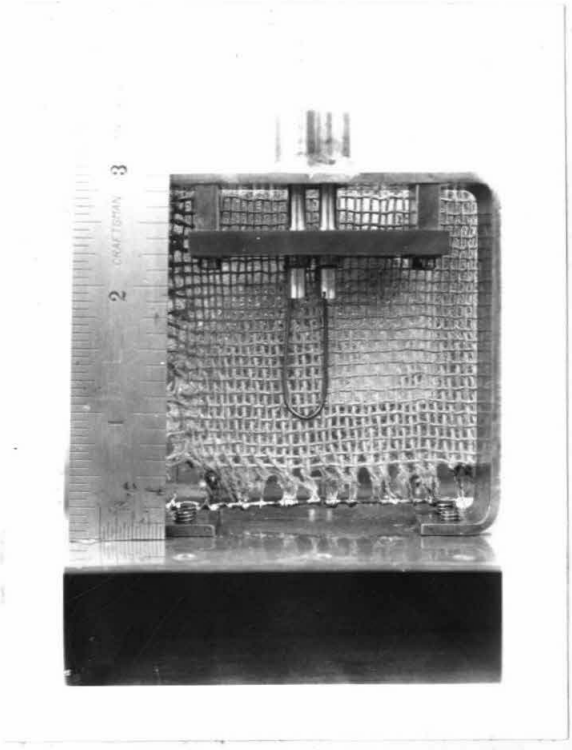


Fig. 4

All filaments, plates and screen grids of the three tubes are isolated from the external circuits by chokes and by-pass condensers. Small mica condensers were built into the tube sockets for each element where radio frequencies must be bypassed to ground. These are

supplemented by large condensers connected in parallel for maximum bypassing efficiency. Chokes in the high voltage circuits are designed to be resonant at this particular frequency. Small chokes

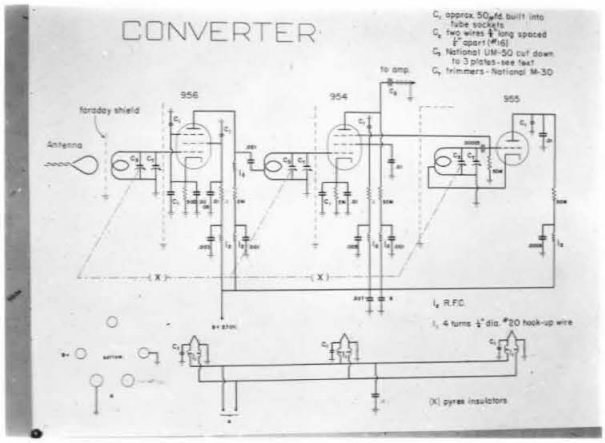
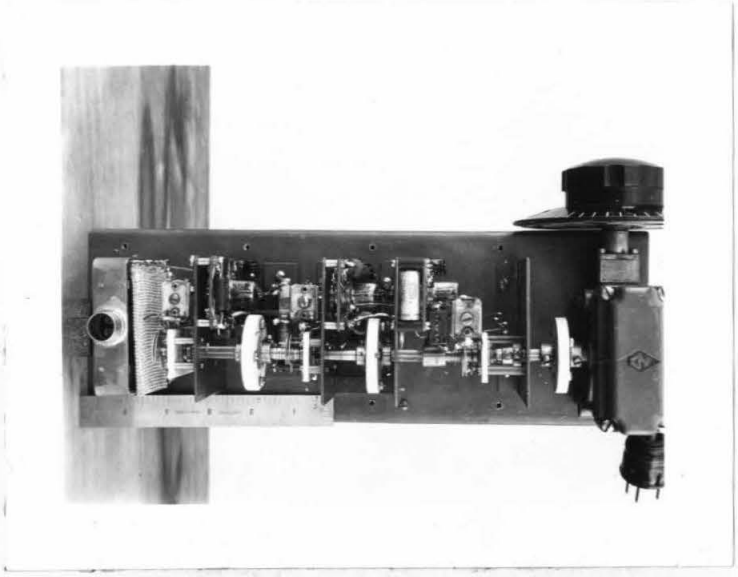


Fig. 5a

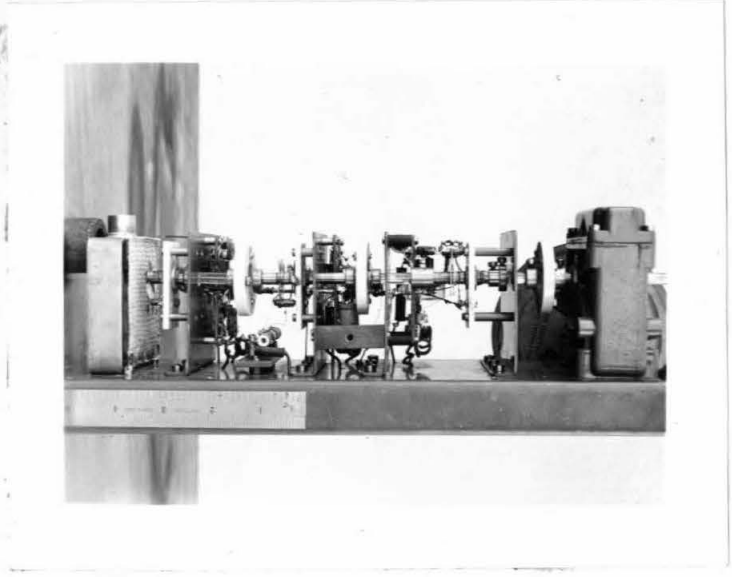
and the by-pass condensers at the heater terminals of the tube sockets confine any stray radio frequencies to the respective tube circuits.

In order to reduce the noise level due to microphonic and tube noises down to a desired minimum, the coupling condenser, C_2, to the intermediate frequency amplifier must be very small. C_2 consists of two wires 5/8 inch long and 1/2 inch apart (#16 wire) which is sufficient to give the desired coupling. The whole converter unit is shown in Fig. 5b and 5c , while Fig. 5d shows the bottom view of the chassis of the converter.



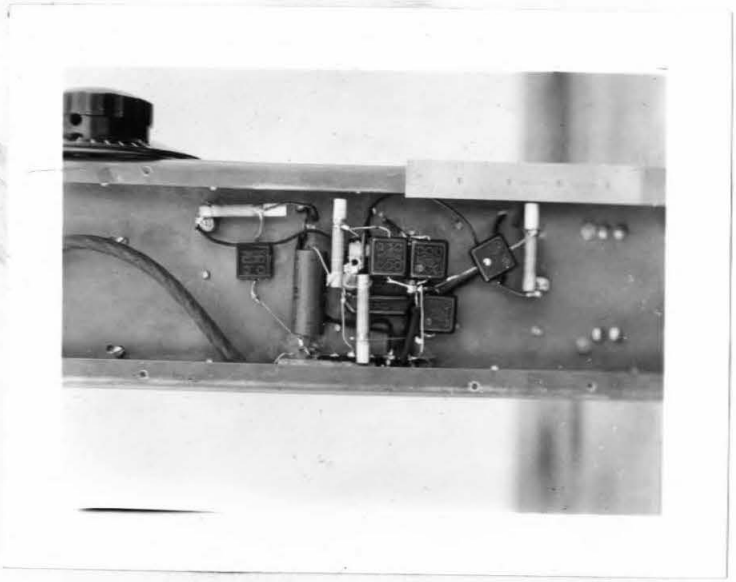
Top view of converter unit.

Fig. 5b



Side view of converter unit.

Fig. 5c



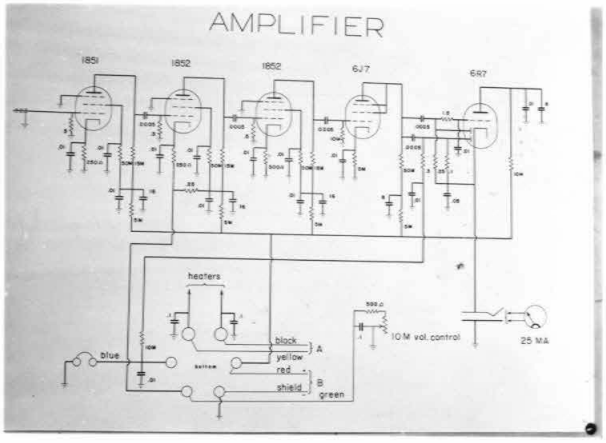
Bottom view of chassis of converter

Fig. 5d

Intermediate Frequency Amplifier

The intermediate frequency amplifier consists of four resistance coupled stages. An 1851 and two 1852 high u television amplifier tubesdrive a 6J7 in triode connection (Fig. 6). This amplifier is capable of delivering seven intermediate frequency volts to the diode before overloading.

The overall amplification of this amplifier unit is approximately 110,000 at 220 kilocycles. The response curve of the unit is flat from 150 to 260 kilocycles as shown in Fig. 7 , which is plotted with the volume control so set that the amplifier is at the threshold of noise.



Schematic circuit diagram of the I-F amplifier and the detector unit.

Fig. 6

Frequency Characteristics of I-F Amplifier

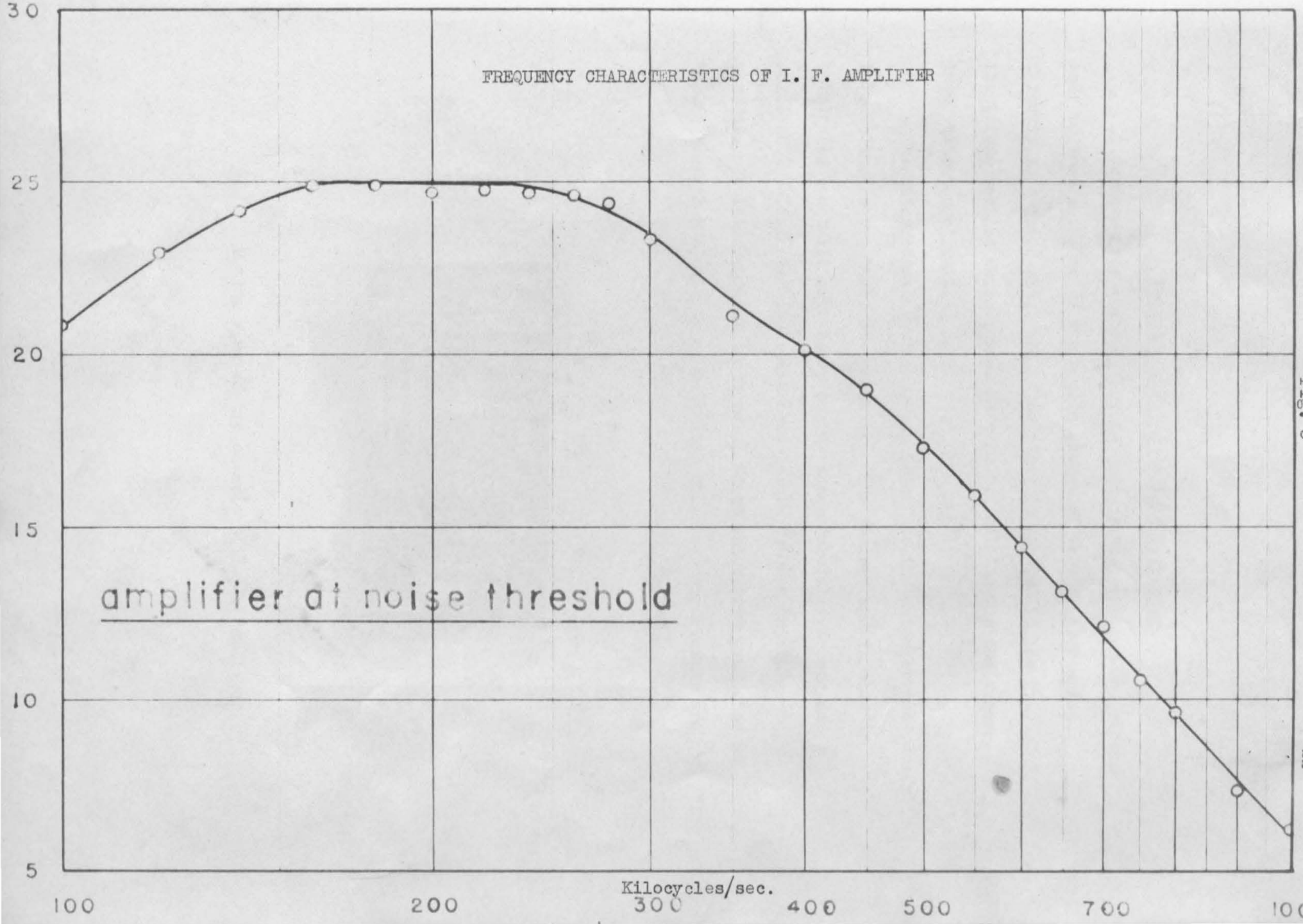
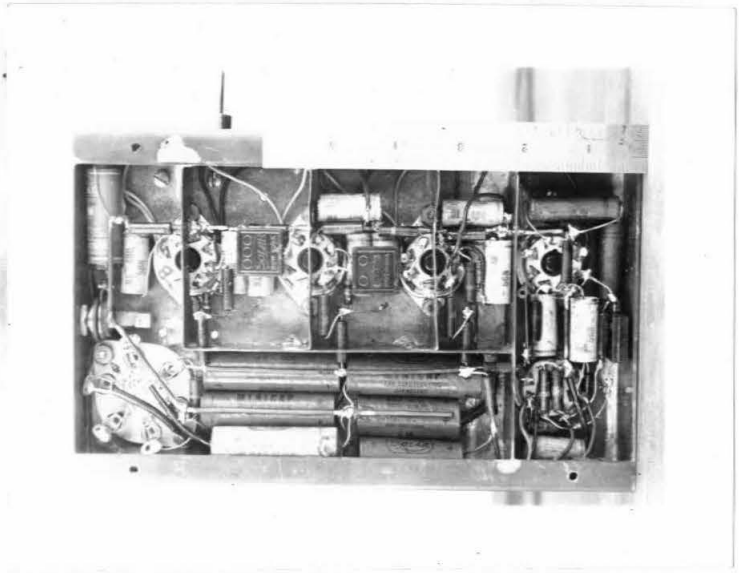


Fig. 3

Detector and Vacuum Tube Voltmeter

A duplex-diode triode, 6R7, is used as the combined and vacuum tube voltmeter. One of the double diodes of the 6R7 is coupled directly to a phone plug, while the other is coupled to the grid of the triode section which serves as a D. C. amplifier in the vacuum tube voltmeter circuit.

The intermediate frequency amplifier and the detector and vacuum tube voltmeter are built as one unit. The chasses and shields of both units are built with heavy copper sheet carefully formed and soldered to eliminate high resistance joints between shields and chassis. Shields enclose those metal tubes which have grid caps on top. Beneath the chassis of this unit shielded compartments are

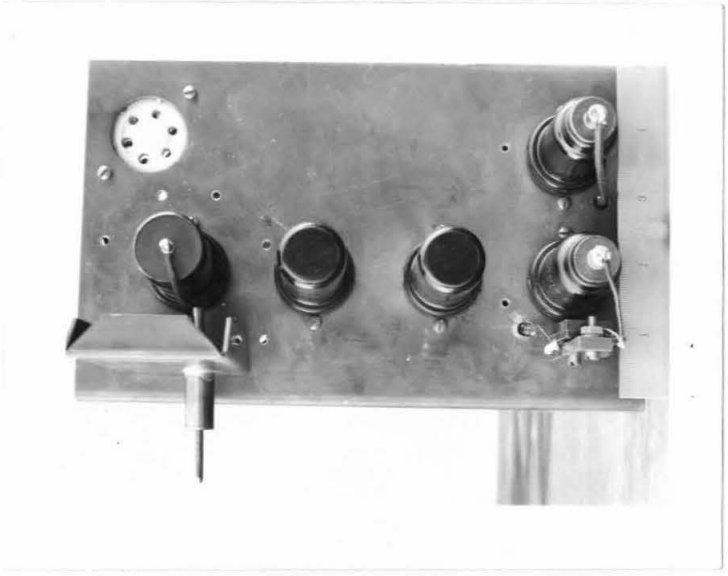


Bottom view of the chassis of I. F. amplifier.

Fig. 8a

made according to the individual circuits rather than to the individual tubes thus giving the stability required in an amplifier of such high amplification (Fig. 8a). This unit is coupled to the converter unit by a shielded single-prong plug. External connections are made through a six-prong plug and jack. Fig. 8b shows the top view of this unit.

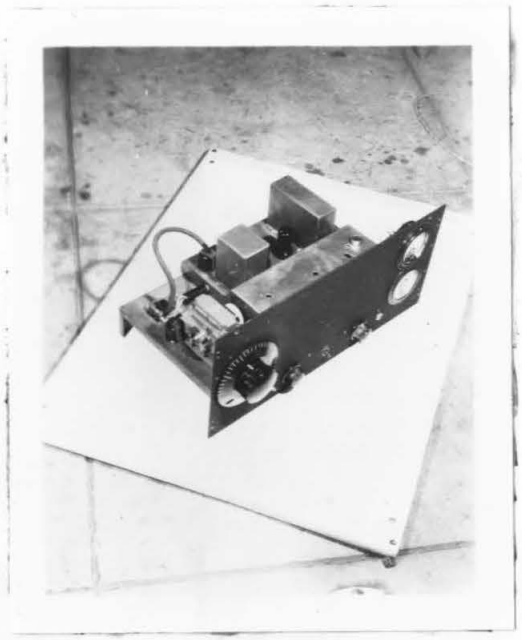
The whole assembly of the superheterodyne receiver is shown in Fig. 9. The receiver has a high sensitivity. Using a single 955



Top view of I. F. amplifier unit.

Fig. 8b

tube transmitter with a plate input of one watt over a thirty-mile optical path, the signal is strong enough to develop an intermediate frequency voltage of sixteen volts on the plate of 6J7, i.e. to operate the receiver to its full capacity.



Superheterodyne receiver

Fig. 9

The frequency range of the receiver covers from 1.64 meter to about 1.98-meter and spreads the band over the 500 divisions of the National PWO dial, whereon each division represents a frequency change of about sixty three kilocycles.

The tuning is sharp and smooth and no more critical than average broadcast receivers. The calibration and overall performance remain very constant through the variations in temperature and humidity, and rough handling encountered in field measurements over an extended period of time. The maximum variation observed due to the combined changes in the transmitter and receiver is not over one-half division of the dial which represents 0.017% of the frequency used.

SIGNAL RESPONSE OF RECEIVER

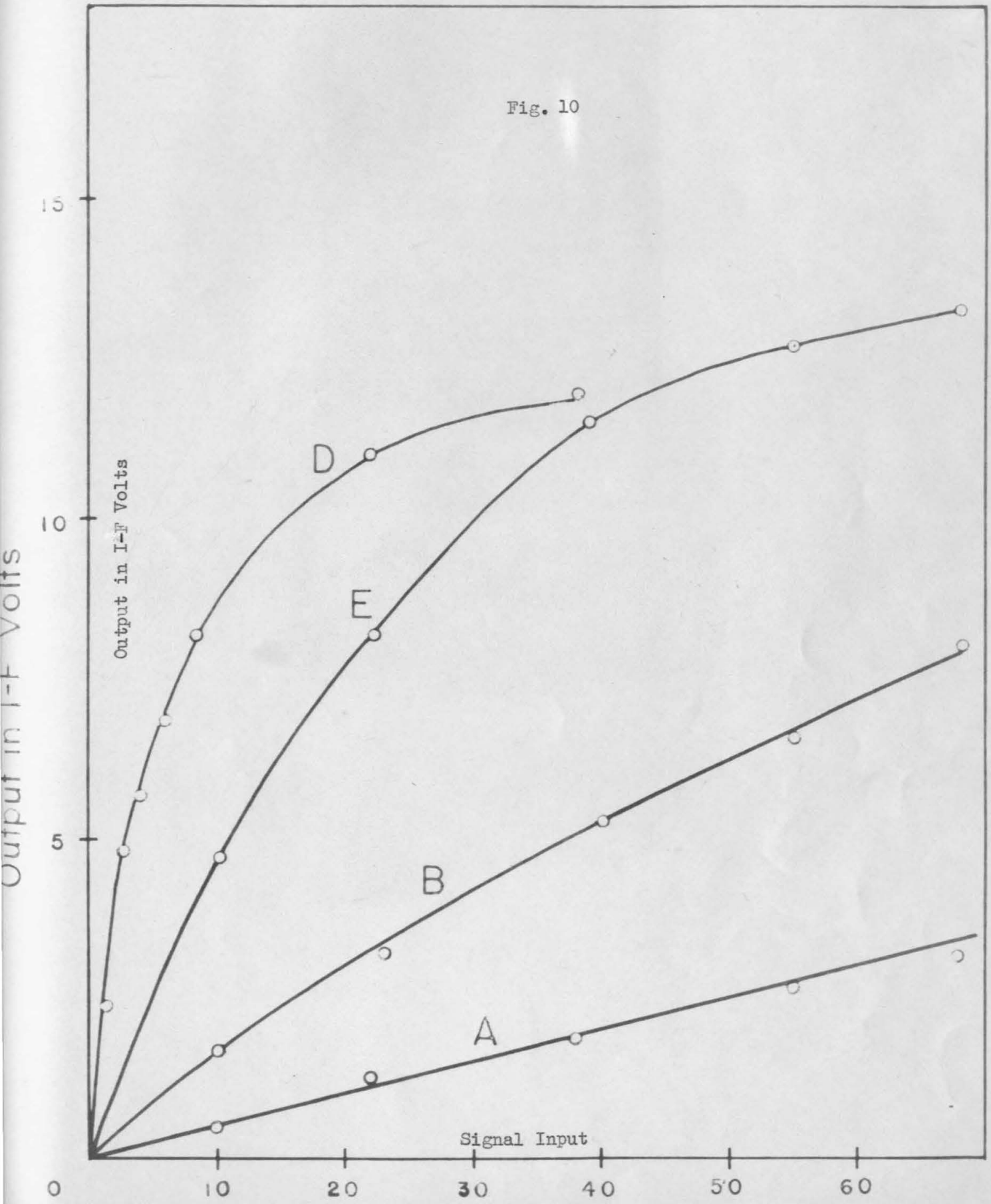


Fig10 shows the signal response with the output in intermediate frequency volts plotted as a function of signal input, for different settings of the gain control. The input was measured by observing the antenna current of the transmitter used as the signal source, the transmitter and receiver remaining at fixed positions during the observations. Curve A shows the linear characteristics of the converter and amplifier at a low gain setting. At higher gain settings, curves B and E show the increasing effects of overloading in the latter stages of the intermediate frequency amplifier at higher output levels. In curve E the gain was set for the threshold of noise. Curve D is for maximum gain and shows a very steep slope at the region of low signal input, so that a slight variation in the neighborhood of zero signal produces a great change in the output signal voltage. Since the receiver is primarily for direction finding by a null point method, it is highly desirable to have a steep response curve as shown in D.

THEORY OF ANTENNA

(a) Horizontal H antenna.

Consider the H antenna as placed in an electromagnetic field, E, of a half wave radiator. The electric field strength in volts per meter at a distance r and at an angle ψ from the center of the radiator is given by the expression

$$E = 60\frac{i_o}{r}\frac{\cos(\frac{\pi}{2}\cos\psi)}{\sin\psi}\sin\omega(t-\frac{r}{c}) \qquad (1.a)$$

where i_o is the current in amperes at the center of the radiating antenna. This is the magnitude of the electric vector in the plane of the radiating antenna and in the direction perpendicular to that of the radial vector r. Writing in exponential form we have

$$E = 60\frac{i_o}{r}\frac{\cos(\frac{\pi}{2}\cos\psi)}{\sin\psi}e^{j\omega(t-\frac{r}{c})} \qquad \text{(imag. part)} \qquad (1.b)$$

Let the H antenna be in the plane containing r and E and be tilted at an angle θ from E, as shown in Fig.A. Since the middle parts AB, and CD of the antenna are well shielded, any pick up due to these parts can be ignored.

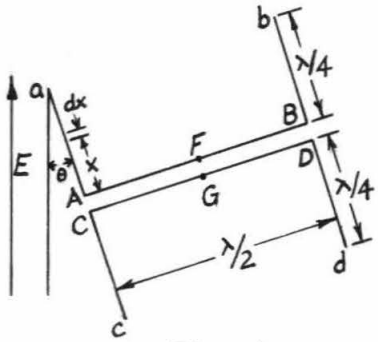


Fig. A

The emf. generated in a length dx of the wire Aa at a point x from A is $E_x dx \cos\theta$, where E_x is the field strength at the point x. Since Aa is one quarter wavelength long, it is necessary to take into account the variation in the phase of E in calculating E_x. It is seen that the phase factor a distance x from A is given by $e^{j\frac{2\pi}{\lambda}x\sin\theta}$. There is an additional phase lag before this impulse reaches A alone the wire given by $e^{-j\frac{2\pi}{\lambda}x}$. Since the reflections from the upper end of the wires depends upon the impedance of the antenna circuit which is a constant in this case,

their effects can be ignored. The interactions between the elements are also neglected. Hence the integral of the product of these terms along the wire gives the total effective emf. Thus the potential at A is given by

$$\mathcal{E}_A = \int_0^{\frac{\lambda}{4}} 60 \frac{i_0}{r} \frac{\cos(\frac{\pi}{2}\cos\psi)}{\sin\psi} e^{j\omega(t-\frac{r_0}{c})} \cos\theta \, e^{j\frac{2\pi}{\lambda}(\sin\theta - 1)x} dx \qquad (2.a)$$

where r_0 is the distance from the center of radiating antenna to A.

Since $\lambda/4 \ll r_0$, therefore we can write

$$60 \frac{i_0}{r} \frac{\cos(\frac{\pi}{2}\cos\psi)}{\sin\psi} \simeq 60 \frac{i_0}{r_0} \frac{\cos(\frac{\pi}{2}\cos\psi)}{\sin\psi} \equiv K \qquad (2.b)$$

Thus

$$\mathcal{E}_A = K e^{j\omega(t-\frac{r_0}{c})} \cos\theta \int_0^{\lambda/4} e^{j\frac{2\pi}{\lambda}(\sin\theta - 1)x} dx$$

$$= -j \frac{\lambda}{2\pi(1-\sin\theta)} K e^{j\omega(t-\frac{r_0}{c})} \cos\theta \left[1 - e^{j\frac{\pi}{2}(\sin\theta - 1)}\right] \qquad (2.c)$$

Similarly the potential at B is given by

$$\mathcal{E}_B = -j \frac{\lambda}{2\pi(1-\sin\theta)} K e^{j[\omega(t-\frac{r_0}{c}) - \frac{2\pi}{\lambda}\cdot\frac{\lambda}{2}\cos\theta]} \cos\theta \left[1 - e^{j\frac{\pi}{2}(\sin\theta - 1)}\right] \qquad (3.a)$$

since E_x at B differs from it at A by a phase factor $e^{-j\frac{2\pi}{\lambda}\overline{AB}\cos\theta}$ or $e^{-j\frac{2\pi}{\lambda}\frac{\lambda}{2}\cos\theta}$, and Bb is parallel to Aa.

The potential at C due to the induced emf. in Cc can be obtained just by finding the potential at a for the element Aa in the above case only with an additional phase factor in the expression of E_x of amount $e^{j\frac{2\pi}{\lambda}\cdot\frac{\lambda}{4}\sin\theta}$ or $e^{j\frac{\pi}{2}\sin\theta}$. The phase factor at a distance $(\lambda/4 - x)$ from a is biven by $e^{-j\frac{2\pi}{\lambda}(\frac{\lambda}{4} - x)\sin\theta}$, and the additional phase lag before the impulse reaches a along the wire given by $e^{j\frac{2\pi}{\lambda}(\frac{\lambda}{4} - x)}$. Thus the potential at C is given by

$$\mathcal{E}_c = K e^{j\omega(t-\frac{r_0}{c})} e^{j\frac{\pi}{2}\sin\theta} \cos\theta \int_0^{\lambda/4} e^{j\frac{2\pi}{\lambda}[(\frac{\lambda}{4} - x)(1-\sin\theta)]} dx$$

$$= -j \frac{\lambda}{2\pi(1-\sin\theta)} K e^{j\omega(t-\frac{r_0}{c})} e^{j\frac{\pi}{2}\sin\theta} \cos\theta \, e^{j\frac{\pi}{2}(1-\sin\theta)} \left[1 - e^{j\frac{\pi}{2}(\sin\theta - 1)}\right]$$

$$= -j \frac{\lambda}{2\pi(1-\sin\theta)} K e^{j\omega(t-\frac{r_0}{c})} \cos\theta \, e^{j\frac{\pi}{2}} \left[1 - e^{j\frac{\pi}{2}(\sin\theta - 1)}\right] \qquad (4.a)$$

Similarly the potential at d

$$\mathcal{E}_D = -j \frac{\lambda}{2\pi(1-\sin\theta)} K e^{j[\omega(t-\frac{r_0}{c}) - \pi\cos\theta]} e^{j\frac{\pi}{2}} \cos\theta \left[1 - e^{j\frac{\pi}{2}(\sin\theta - 1)}\right] \qquad (5.a)$$

Now since the antenna system is symmetrical with respect to F and G, the resultant potential difference across EF can be represented by

$$\mathcal{E}_{FG} = \mathcal{E}_A + \mathcal{E}_B - (\mathcal{E}_C + \mathcal{E}_D)$$

$$= -j\frac{\lambda}{2\pi(1-\sin\theta)} K e^{j\omega(t-\frac{r_0}{c})} \cos\theta \left[1+e^{-j\pi\cos\theta}\right]\left[1-e^{j\frac{\pi}{2}(\sin\theta-1)}\right]$$

$$+j\frac{\lambda}{2\pi(1-\sin\theta)} K e^{j[\omega(t-\frac{r_0}{c})+\frac{\pi}{2}]} \cos\theta \left[1+e^{-j\pi\cos\theta}\right]\left[1-e^{j\frac{\pi}{2}(\sin\theta-1)}\right]$$

$$= -j\frac{\lambda}{2\pi(1-\sin\theta)} K e^{j\omega(t-\frac{r_0}{c})} \cos\theta \left[1-e^{j\frac{\pi}{2}}\right]\left[1+e^{-j\pi\cos\theta}\right]\left[1-e^{j\frac{\pi}{2}(\sin\theta-1)}\right] \qquad (6.a)$$

The position of antenna at $\theta = \frac{\pi}{2}$ gives a null signal in the receiver since $\mathcal{E}_{FG}=0$ at this position.

The converted values of $\mathcal{E}_{FG}$ corresponding to the readings in the output meter is plotted against θ as shown in Fig. 11A.

(b) Adcock Antenna

In this case the electric vector, E, of the incoming electromagnetic wave is parallel to the antenna elements Aa etc. Let the plane of the Adcock antenna make an angle ϕ with the wave front as shown in Fig. B.

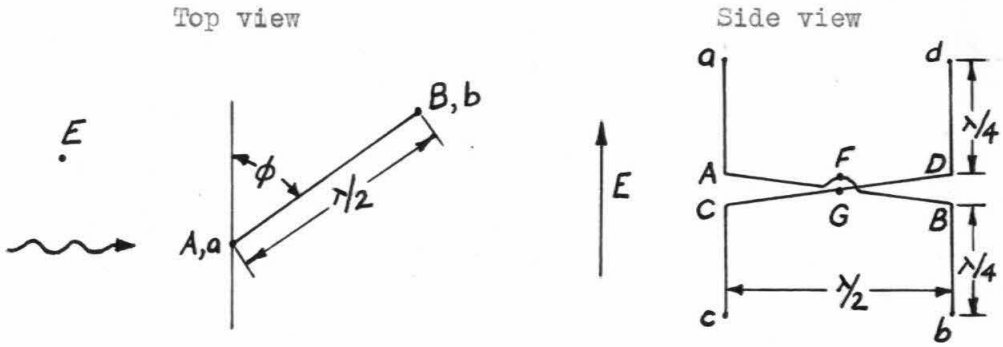


Fig. B

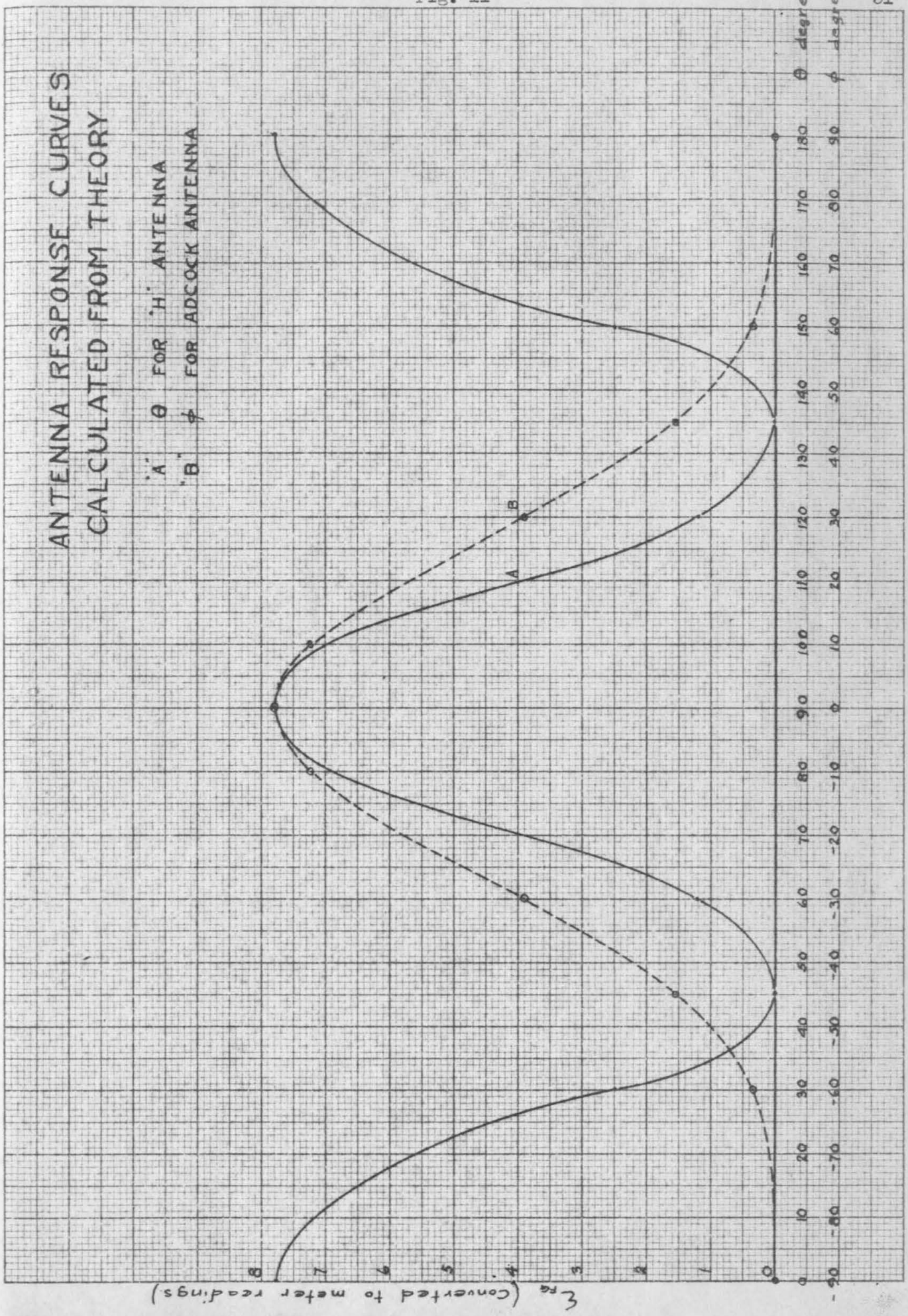
The potentials at A, B, C and D can be easily got from (2.a), (3.a), (4.a) and (5.a) by putting $\theta = 0$, hence

$$\mathcal{E}_A = -j\frac{\lambda}{2\pi} K e^{j\omega(t-\frac{r_0}{c})}\left[1-e^{-j\frac{\pi}{2}}\right] \qquad (7.a)$$

$$\mathcal{E}_D = -j\frac{\lambda}{2\pi} K e^{j[\omega(t-\frac{r_0}{c})-\frac{2\pi}{\lambda}\cdot\frac{\lambda}{2}\sin\phi]}\left[1-e^{-j\frac{\pi}{2}}\right] \qquad (7.b)$$

$$\mathcal{E}_C = -j\frac{\lambda}{2\pi} K e^{j\omega(t-\frac{r_0}{c})} e^{j\frac{\pi}{2}}\left[1-e^{-j\frac{\pi}{2}}\right] \qquad (7.c)$$

$$\mathcal{E}_B = -j\frac{\lambda}{2\pi} K e^{j[\omega(t-\frac{r_0}{c})-\frac{2\pi}{\lambda}\cdot\frac{\lambda}{2}\sin\phi]} e^{j\frac{\pi}{2}}\left[1-e^{-j\frac{\pi}{2}}\right] \qquad (7.d)$$


ANTENNA RESPONSE CURVES
CALCULATED FROM THEORY
"A" θ FOR "H" ANTENNA
"B" φ FOR ADCOCK ANTENNA
A
B
θ degrees
φ degrees
E_{RS} (Converted to meter readings)

where ϕ is the angle which the plane of the Adcock antenna made with the wave front, and $e^{-j\frac{2\pi}{\lambda}\cdot\frac{\lambda}{2}\sin\phi}$ is the phase lag of E at B from A.

By similar arguments as in (a), the resultant potential difference across FG can be written as

$$\begin{aligned}
\mathcal{E}_{FG} &= \mathcal{E}_A + \mathcal{E}_B - (\mathcal{E}_C + \mathcal{E}_D) \\
&= -j\frac{\lambda}{2\pi}K e^{j\omega(t-\frac{r_0}{c})}\left[1 + e^{-j(\pi\sin\phi+\frac{\pi}{2})}\right]\left[1 - e^{-j\frac{\pi}{2}}\right] \\
&\quad + j\frac{\lambda}{2\pi}K e^{j\omega(t-\frac{r_0}{c})}\left[e^{j\frac{\pi}{2}} + e^{-j\pi\sin\phi}\right]\left[1 - e^{-j\frac{\pi}{2}}\right] \\
&= -j\frac{\lambda}{2\pi}K e^{j\omega(t-\frac{r_0}{c})}\left[1 + e^{-j(\pi\sin\phi+\frac{\pi}{2})} - e^{j\frac{\pi}{2}} - e^{-j\pi\sin\phi}\right]\left[1 - e^{-j\frac{\pi}{2}}\right] \\
&= -j\frac{\lambda}{2\pi}K e^{j\omega(t-\frac{r_0}{c})}\cdot 2\left(1 - e^{-j\pi\sin\phi}\right)
\end{aligned} \tag{8.a}$$

We see that $\mathcal{E}_{FG} = 0$ at $\phi = 0$, which is a null point, and $\mathcal{E}_{FG}$ is a maximum at $\phi = \frac{\pi}{2}$. The converted values of $\mathcal{E}_{FG}$ corresponding to the readings in the output meter of the receiver is plotted against ϕ as shown in Fig. 11B.

RESULTS

The directional response curve of the Adcock antenna for horizontal angles is shown in Fig. 12 where the output meter reading, i. e. ten minus the signal output in the receiver is plotted against the azimuthal angles. It can be seen that the directional response of the antenna is very sharp at null signal. Fig. 12A shows the directional response of the Adcock antenna lying horizontally for vertical angle measurement. Fig. 12B shows the directional response of the horizontal H antenna used for vertical angle determination. The latter has a very much sharper response curve, as can be seen by comparson of the two curves. The characteristic curves were made with the transmitter at a distance of seven miles from the direction finder.

With a small transmitter on top of Mt. Wilson and with the direction finder in open fields at distances varying from seven to thirty miles optical path, both the azimuthal and the vertical angles of the incoming wave can be determined well within 1/2 degree and possibly 1/4 degree accuracy.

With the antenna one and a half wavelengths above the ground and with the ground surface homogeneous in the immediate vicinity of the receiving antenna, the indicated direction of the incoming electromagnetic wave coincides with that of the transmitter emitting the wave, within the same one half degree accuracy (Table I).

In order to determine the effect of possible reflections

TABLE I

Asimuth of incoming wave as determined by direction finder at repeated times in degrees.	Average in degrees	Azimuth of transmitter as determined visually in degrees
0		
0		
+1/4	+1/7	0
+1/4		
+1/4		

(Observations made at a different date but at approximately the same location)

0		
0		
-1/8	-1/8	0
-1/4		
-1/4		

Vertical angle of incoming wave as determined by direction finder at repeated times in degrees	Average in degrees	Vertical angle of transmitter as determined visually in degrees
+8 1/4		
+8		
+8 1/4		
+8 1/2	+8 1/4	+7 3/4
+8 1/4		
+8 1/4		

(Observations made at a different date but at approximately the same location)

+7 1/4		
+7 1/2		
+7 1/4		
+8	+7 5/7	+7 3/4
+8		
+8		
+8		

from nearby hills or buildings that might interfere with the direct wave, a rotable parabolic reflector was set up at the transmitting antenna on top of Mt. Wilson. It was found that change in directions of the incoming wave appreciably (Table II).

Experiments were also made by tilting the transmitting antenna 45 degrees from the vertical. When tilted in eight different directions, both the horizontal and the vertical directions of the incoming wave remained unchanged. Although the tilt produced a slight decrease in the received signal strength, the sharpness in determining the directions is unaffected. Thus for a considerable swing in the transmitting antenna through an angle as large as 90 degrees both the direction of the incoming wave and the sharpness in defining the direction are not affected (Table III).

Apparent horizontal deviations of the incoming wave from the true direction of the transmitter were observed at different tilts which the plane of the Adcock antenna made with the vertical. Horizontal deviations at different dates and at different times of the day were also recorded. The results obtained in a field at Lombardy Road are shown in Figs. 13-16. In Fig. 13 it is seen that at zero tilt the variation in the horizontal deviation for each run is mostly less than one degree, although in one case it reached one and half degree.

The site on which these observations were made was covered with vegetation and a big tree located at about thirty wavelengths

TABLE II

Position of transmitting antenna (reflector position)	Azimuth of incoming wave (in degrees)	Vertical angle of incoming wave (in degrees)
	-(1/8)	5
	-(1/8)	$4\frac{3}{4}$
	-(1/8)	$4\frac{3}{4}$
	-(1/8)	$4\frac{3}{4}$
	-(1/8)	$4\frac{1}{2}$
	-(1/8)	$5\frac{1}{2}$

To receiving antenna

TABLE III *

Position of transmitting antenna	Azimuth of incoming wave (in degrees)	Vertical angle of incoming wave (in degrees)
(1) Straight vertical.	$3\frac{3}{8}$	$3\frac{1}{4}$
(2) Antenna tilted 45° from vertical pointing in the direction of receiving antenna.	$3\frac{1}{4}$	$3\frac{7}{8}$
(3) Antenna pointing 45° from direction of receiving antenna. (anticlockwise)	3	$3\frac{7}{8}$
(4) Same as (3) but 90°.	3	$3\frac{3}{4}$
(5) Same as (3) but 180°.	$2\frac{7}{8}$	$3\frac{3}{4}$
(6) Same as (3) but 270°.	$3\frac{1}{8}$	4
(7) Same as (3) but 315°.	3	$3\frac{7}{8}$
True bearing.	0	7

* This series of readings was taken following a rain while the ground was still in a wet condition.

north-west of the direction finder. Evidently the tree some effect to the horizontal direction of the incoming wave as can be seen from Fig. 17. When the direction finder was moved twenty wavelengths west, and the tree was almost in the direct path of the incoming wave, much smaller deviations were observed, and the deviations thus obtained were of opposite sign as in the four other cases.

In Figs. 14-16 it is seen that the horizontal deviation is at a maximum at about thirty-five-degree tilt.

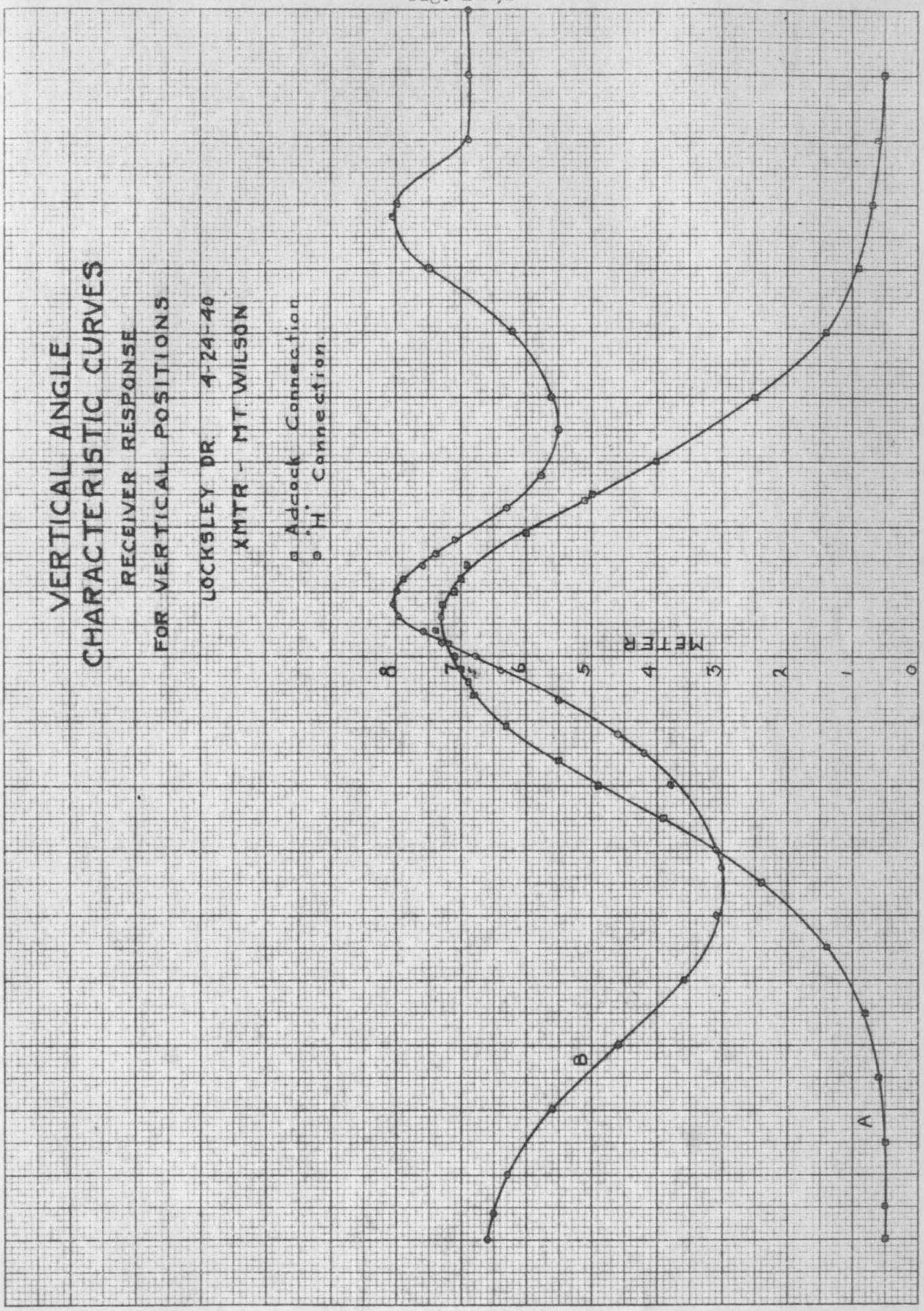
Fig. 18-29 show similar observations of horizontal deviations at different vertical tilts made on the roof of East Bridge Laboratory. This site is surrounded by many other buildings from which reflections of incoming waves were expected thus the horizontal deviations observed were much larger than those observed in the field.

Similar observations made with antenna at different heights above ground are shown in Fig. 30. It seems that the height of antenna at a distance not higher than two wavelengths from ground does not affect the shape of the deviation curve. Due to practical difficulties antenna higher than two wavelengths from ground has not yet been tried.

Observations with antenna elements tilted five degrees from vertical to form a double-V both in forward and backward direction were also made as shown in Fig. 31.

Both vertical and horizontal deviations from true direc-

tions at different dates and different times of the day were made on the roof of East Bridge Laboratory (Figs. 32-34).


VERTICAL ANGLE
CHARACTERISTIC CURVES
RECEIVER RESPONSE
FOR VERTICAL POSITIONS
LOCKSLEY DR. 4-24-40
XMTR - MT. WILSON
a Adcock Connection
b 'H' Connection
METER
8
7
6
5
4
3
2
1
0
A
B
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
90
100
'V.' TILT degrees.

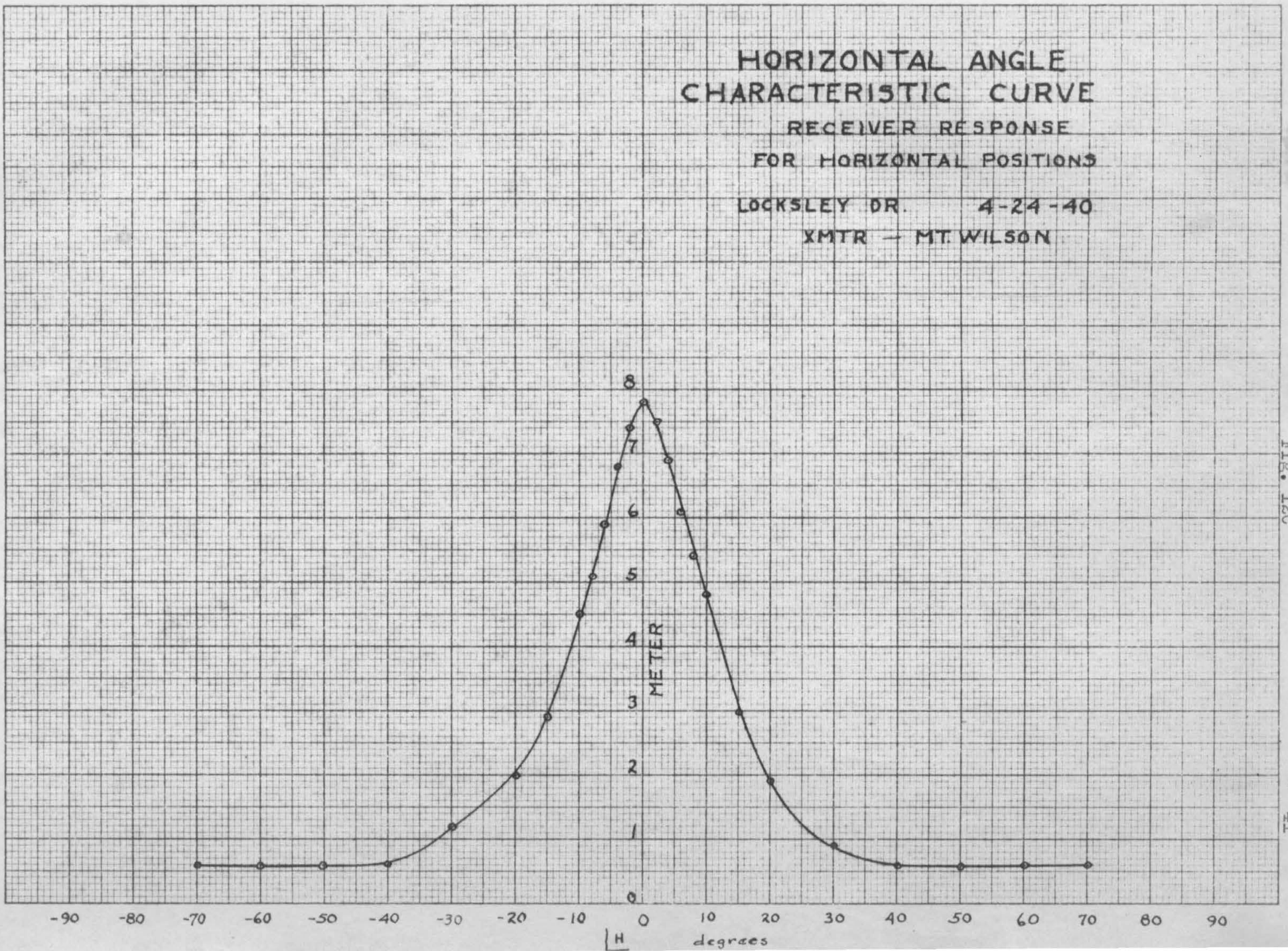
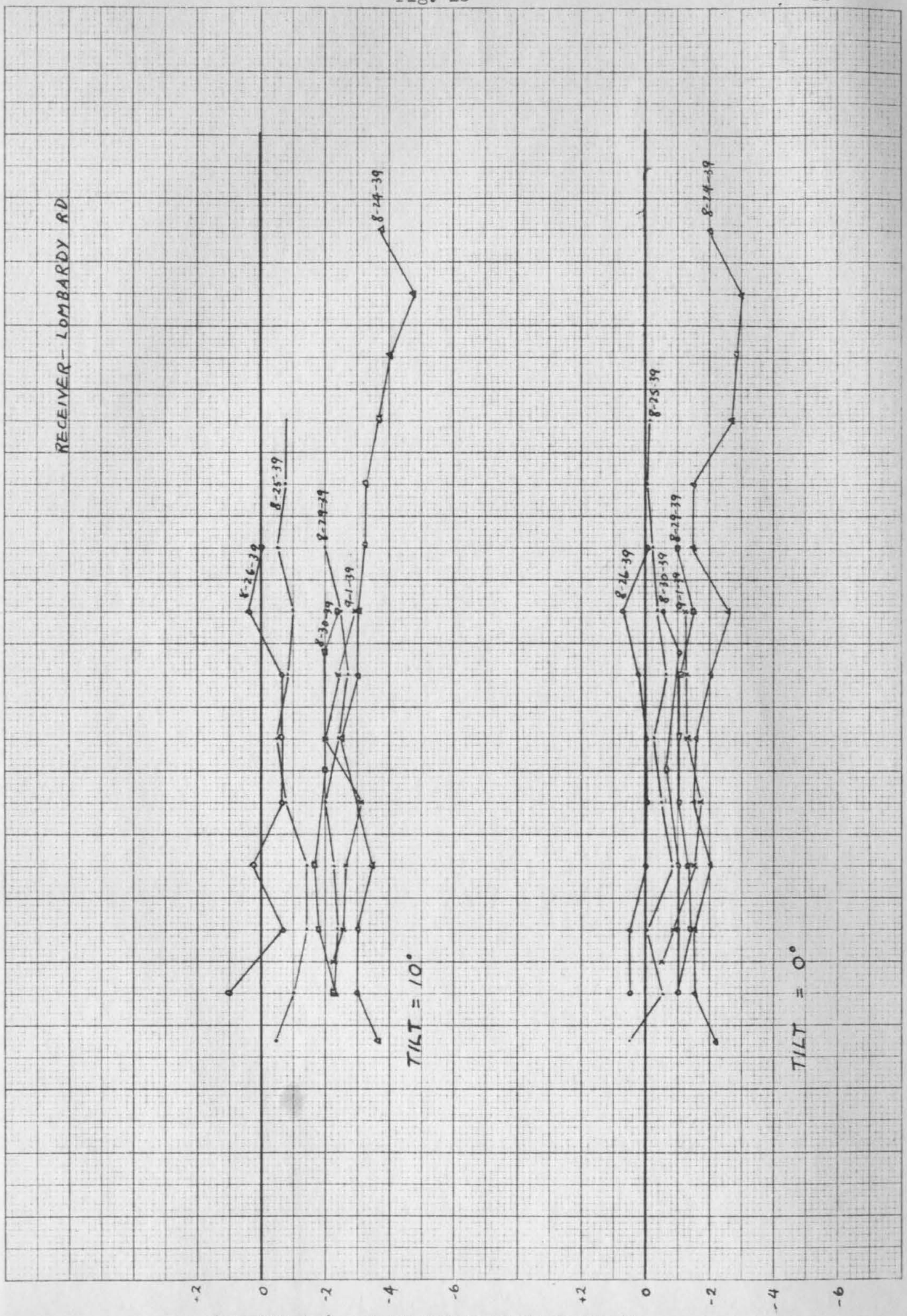
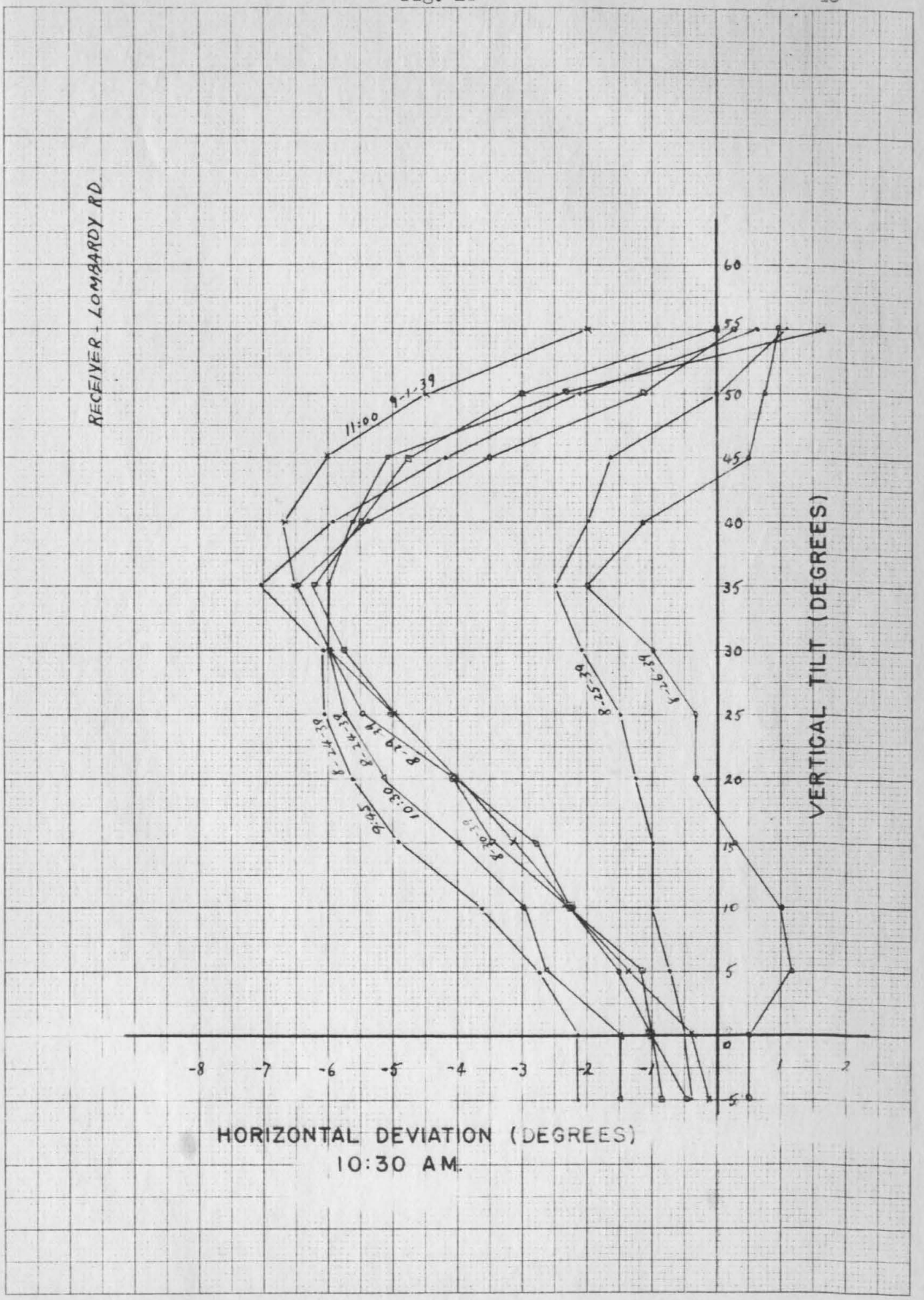
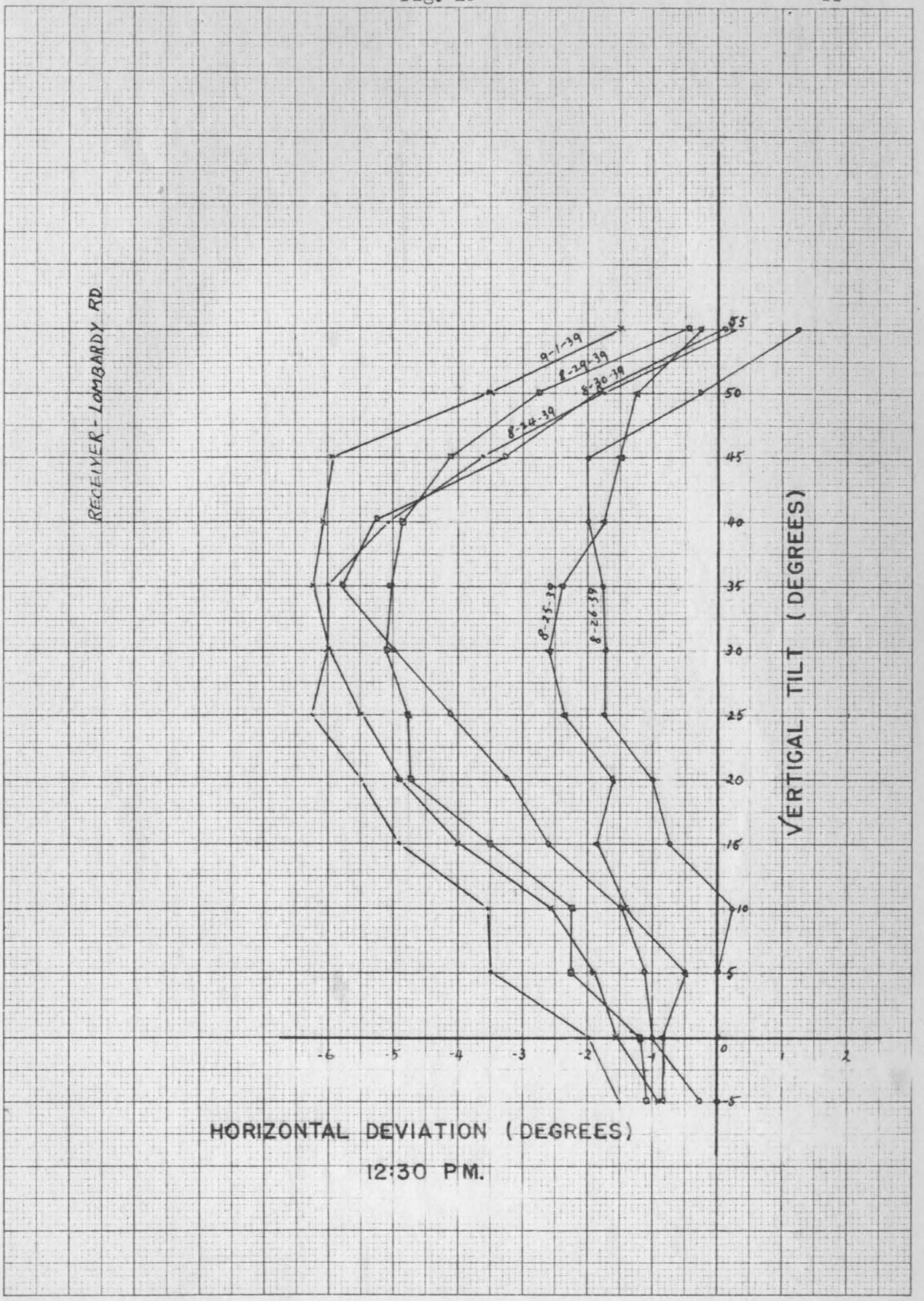
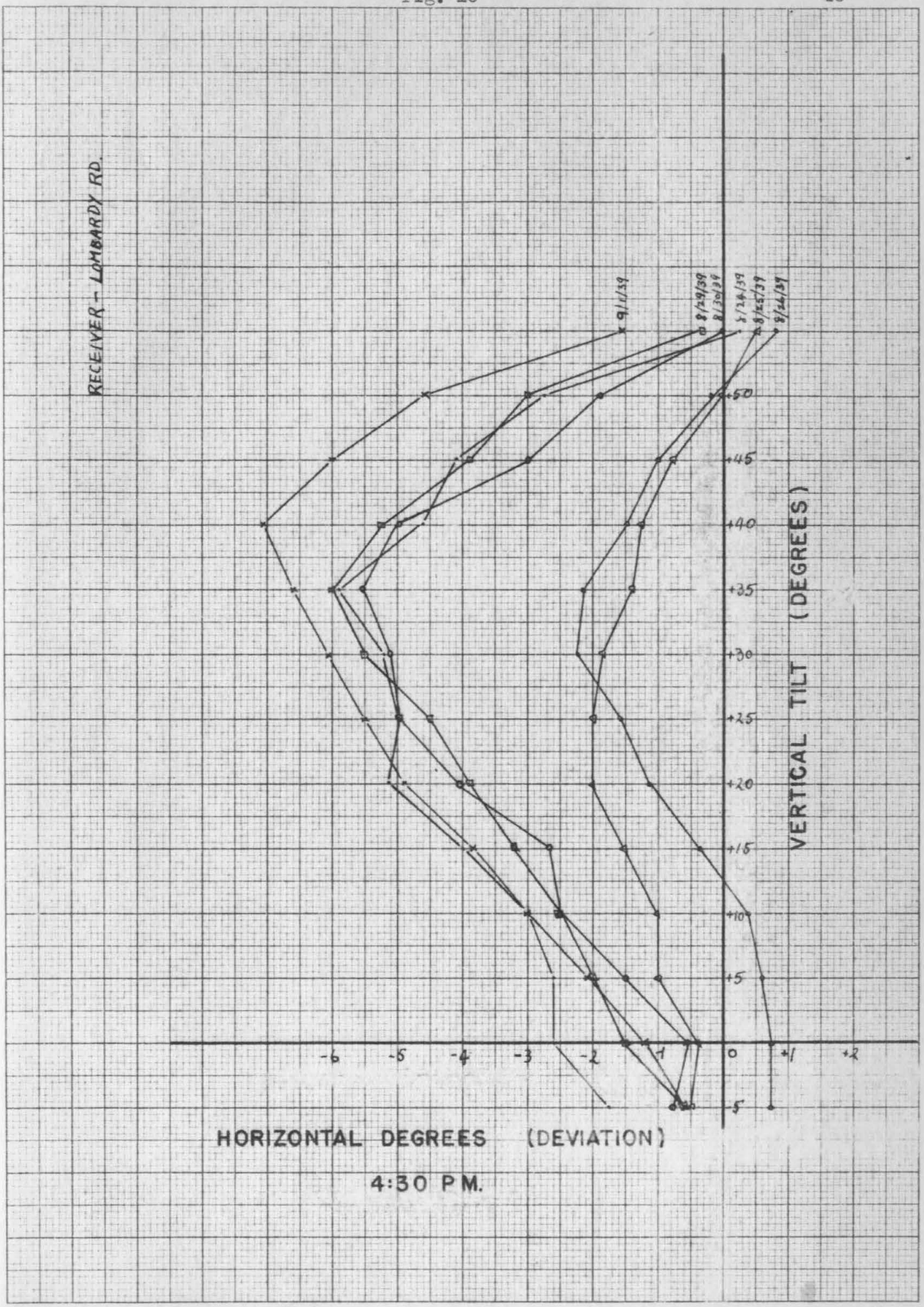

HORIZONTAL ANGLE
CHARACTERISTIC CURVE
RECEIVER RESPONSE
FOR HORIZONTAL POSITIONS
LOCKSLEY DR. 4-24-40
XMTR — MT. WILSON
METER
0
1
2
3
4
5
6
7
8
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
90
H
degrees

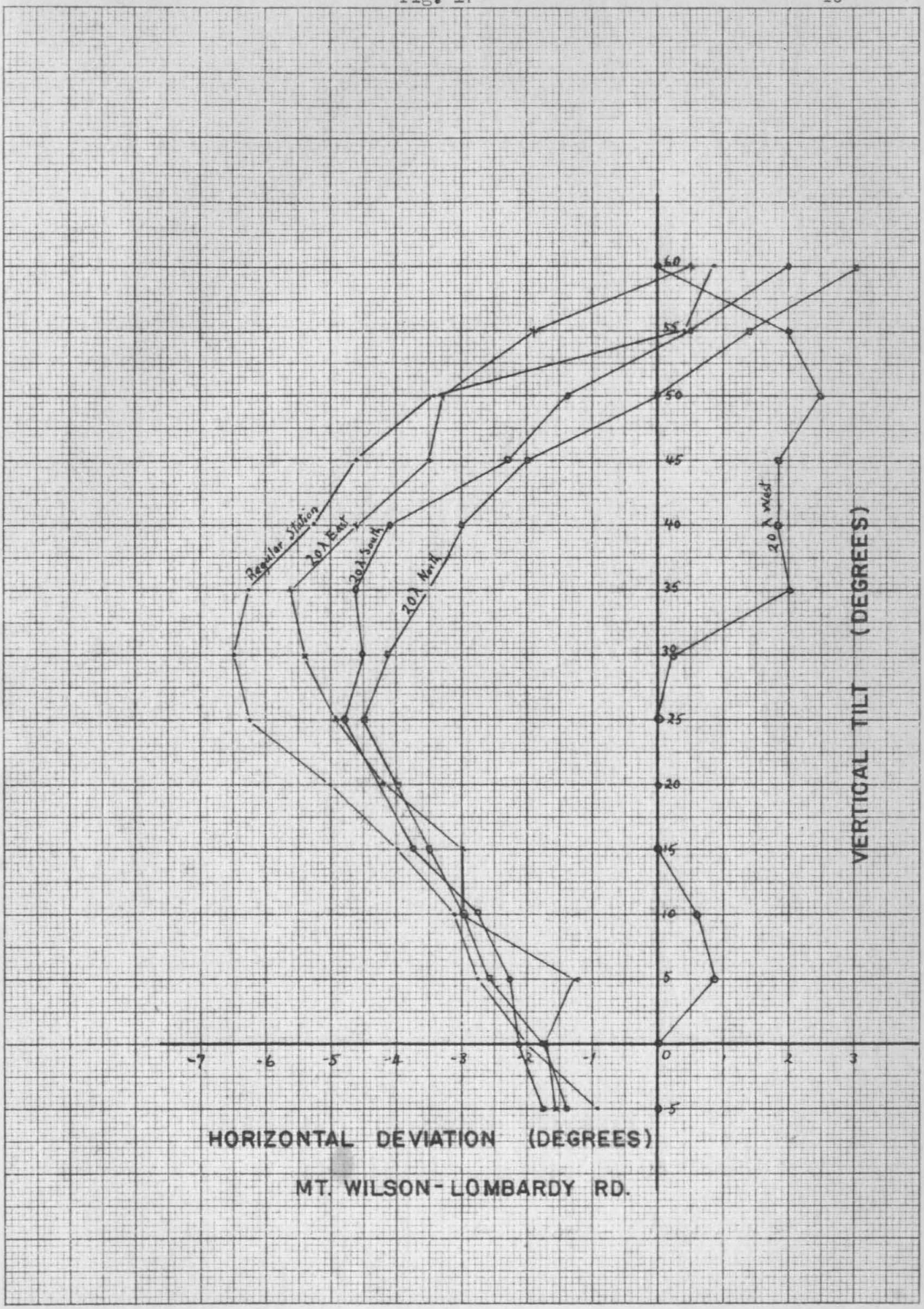
Fig. 12C


RECEIVER - LOMBARDY RD
8-24-39
8-25-39
8-26-39
8-27-39
8-30-39
9-1-39
TILT = 10°
8-24-39
8-25-39
8-26-39
8-29-39
8-30-39
9-1-39
TILT = 0°
HORIZONTAL DEVIATION (DEGREES)
+2
0
-2
-4
-6
TIME
A.M.
P.M.
6
7
8
9
10
11
12
1
2
3
4
5
6
7
8
9
10
11
12


RECEIVER - LOMBARDY RD.
11:00
9-1-39
10:30
9:45
8-20-39
8-14-39
8-25-39
8-26-39
VERTICAL TILT (DEGREES)
HORIZONTAL DEVIATION (DEGREES)
10:30 AM.


RECEIVER - LOMBARDY RD.
9-1-39
8-29-39
8-30-39
8-24-39
8-25-39
8-26-39
VERTICAL TILT (DEGREES)
55
50
45
40
35
30
25
20
15
10
5
0
-5
-6
-5
-4
-3
-2
-1
0
1
2
HORIZONTAL DEVIATION (DEGREES)
12:30 P.M.


RECEIVER - LOMBARDY RD.
9/1/39
8/29/39
8/30/39
8/24/39
8/25/39
8/26/39
+50
+45
+40
+35
+30
+25
+20
+15
+10
+5
0
-5
-6
-5
-4
-3
-2
-1
0
+1
+2
VERTICAL TILT (DEGREES)
HORIZONTAL DEGREES (DEVIATION)
4:30 P.M.


Regular Station
20λ East
20λ South
20λ North
20λ West
VERTICAL TILT (DEGREES)
HORIZONTAL DEVIATION (DEGREES)
MT. WILSON-LOMBARDY RD.

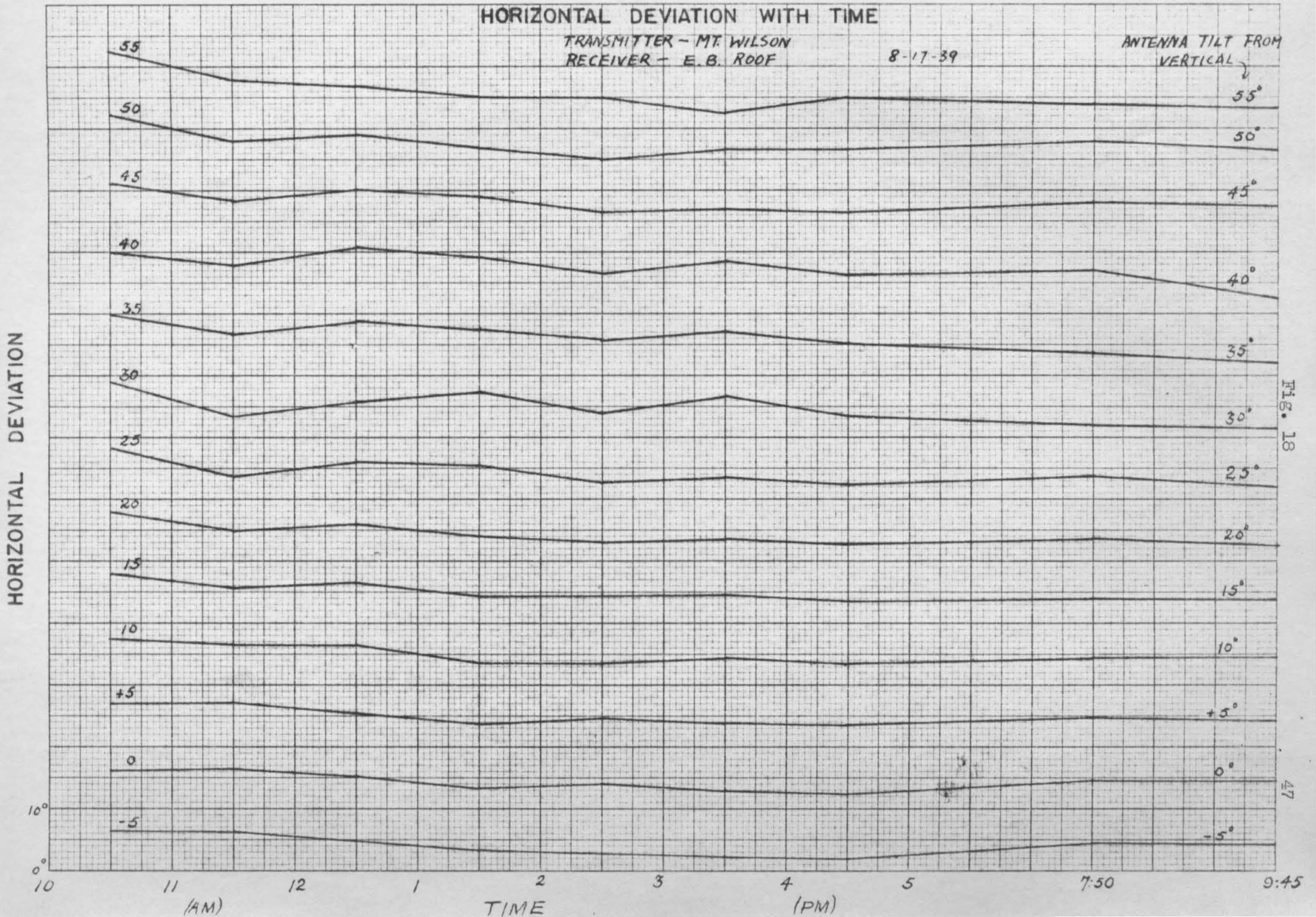
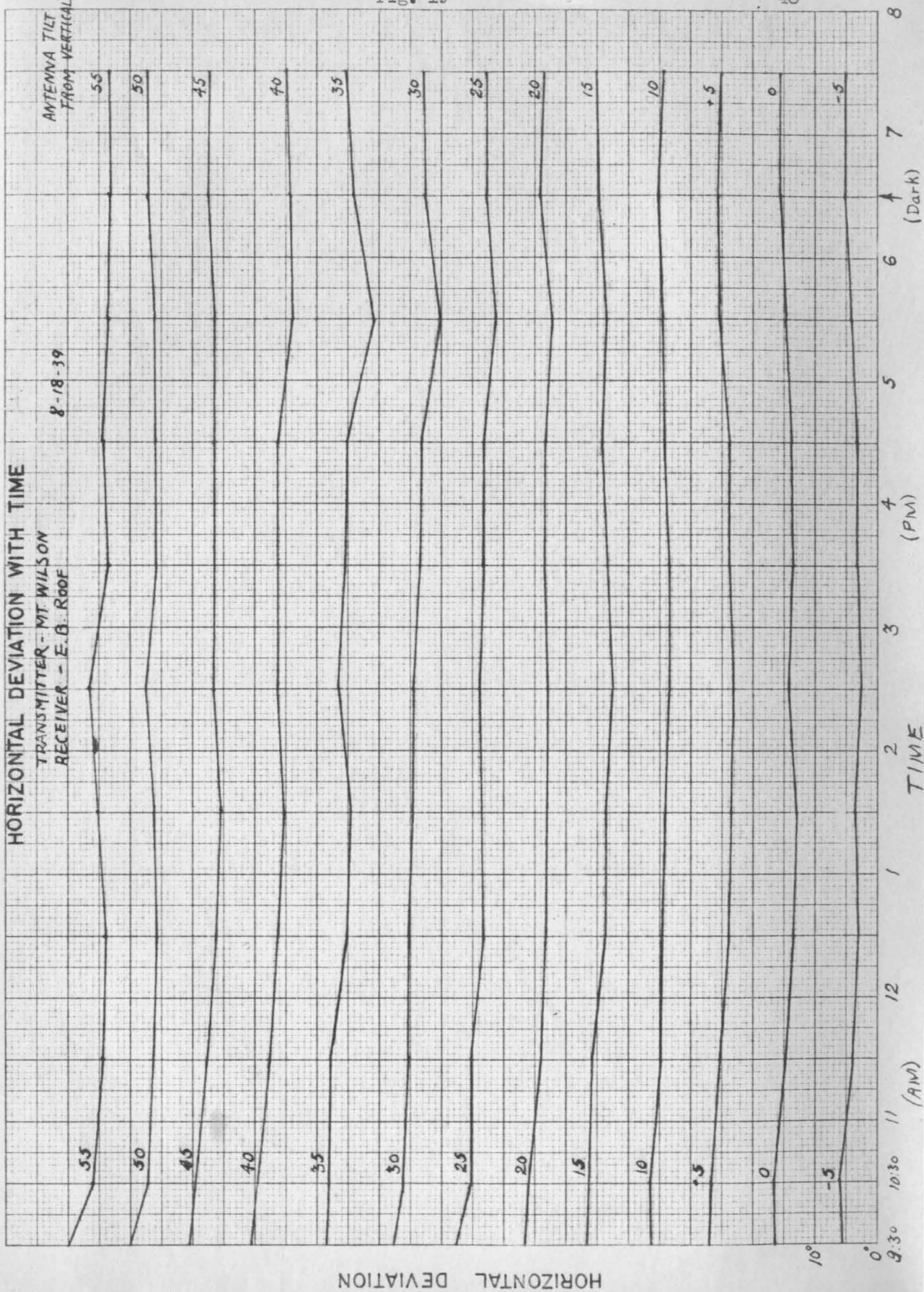
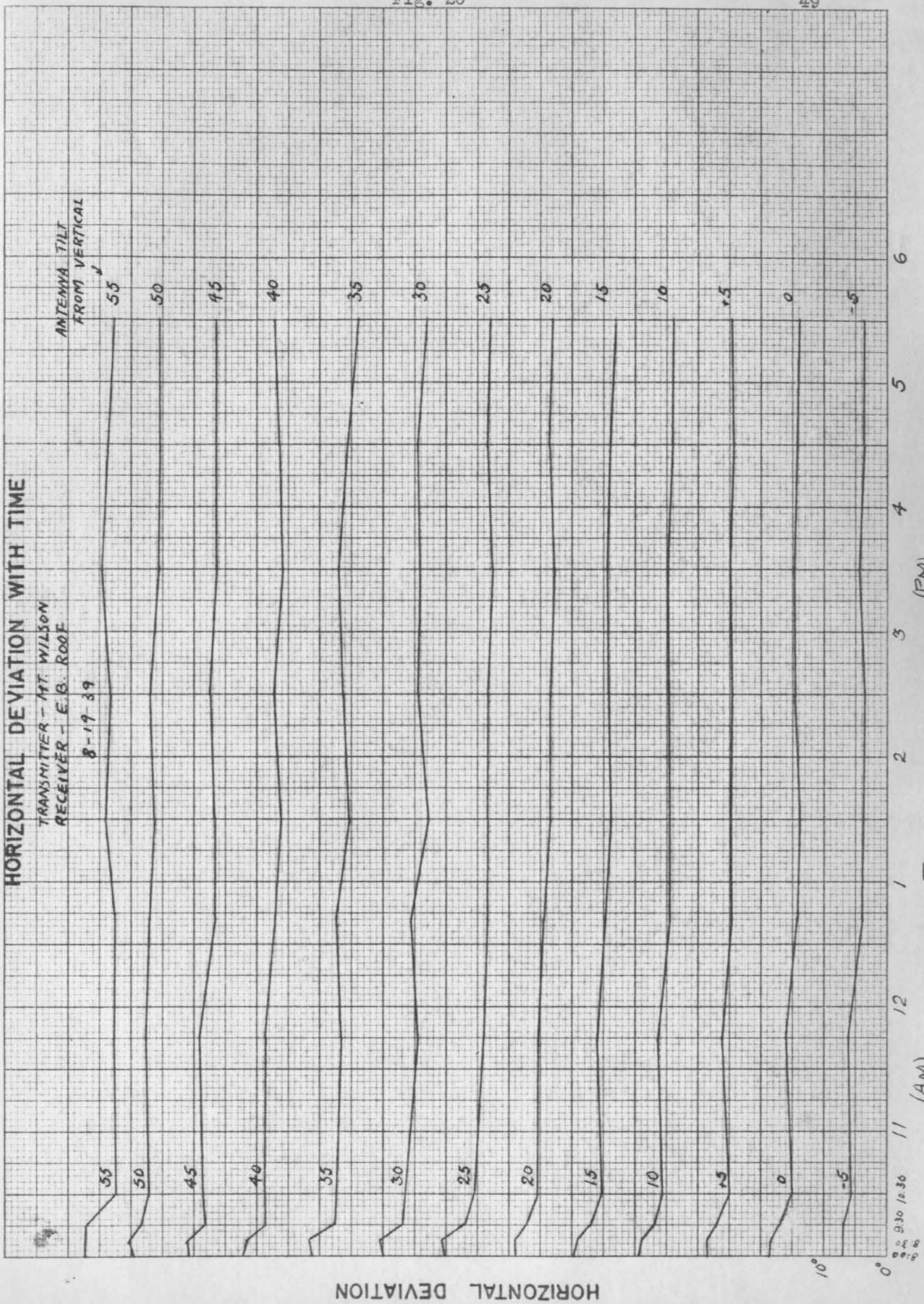
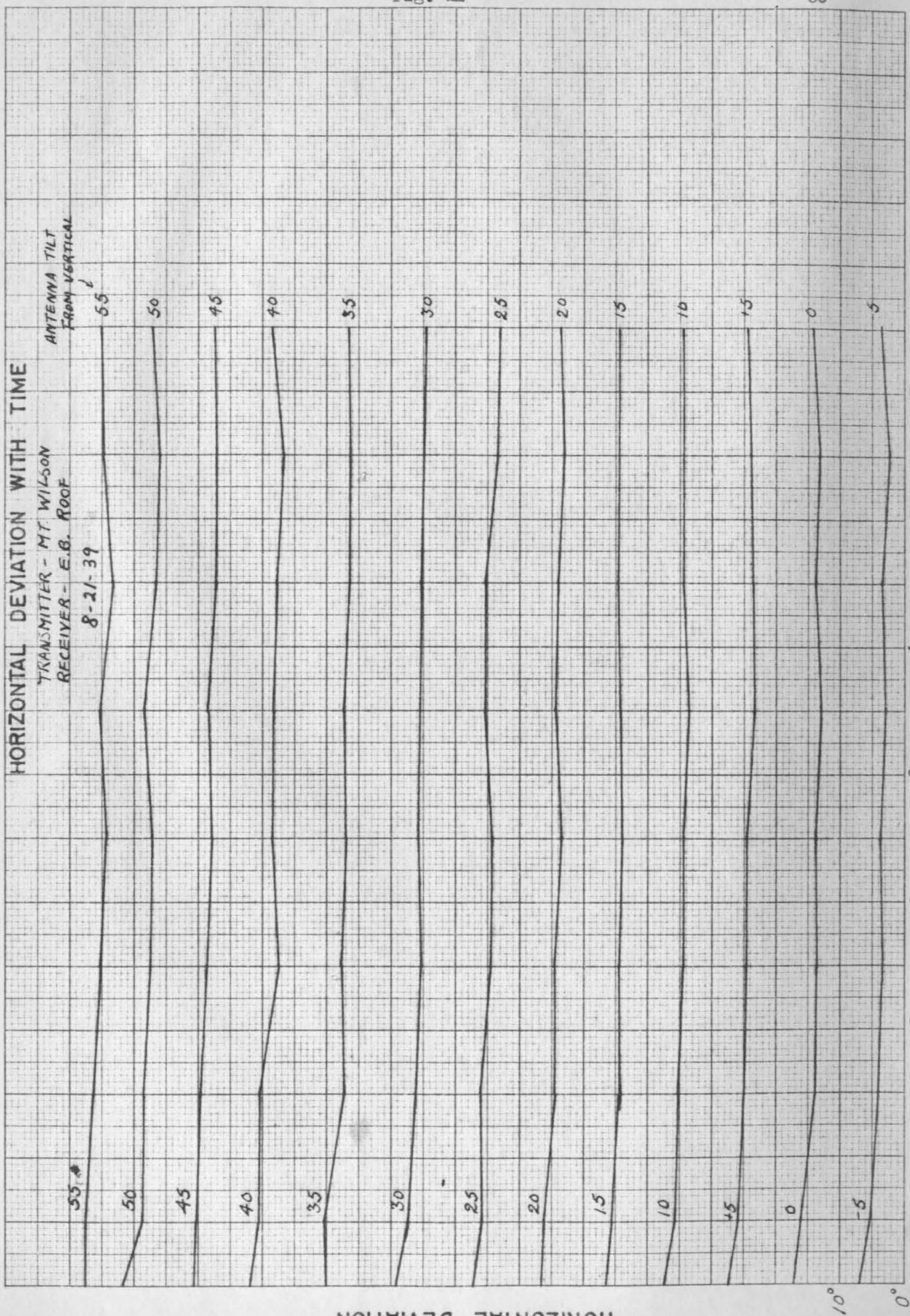
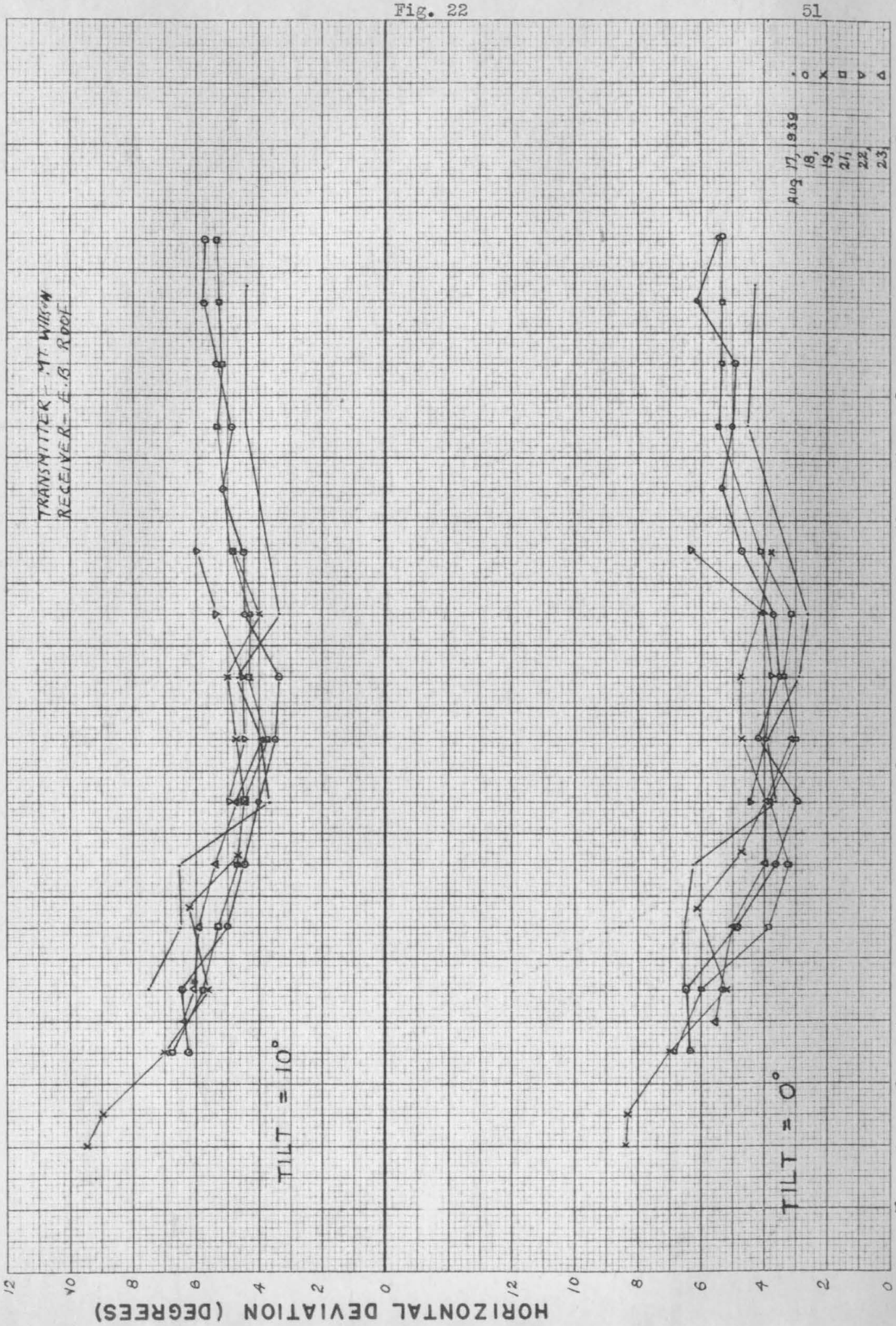

HORIZONTAL DEVIATION WITH TIME
TRANSMITTER - MT. WILSON
RECEIVER - E.B. ROOF
8-17-39
ANTENNA TILT FROM VERTICAL
55°
50°
45°
40°
35°
30°
25°
20°
15°
10°
+5°
0°
-5°
55
50
45
40
35
30
25
20
15
10
+5
0
-5
10°
0°
HORIZONTAL DEVIATION
10
11
12
1
2
3
4
5
7:50
9:45
(AM)
TIME
(PM)

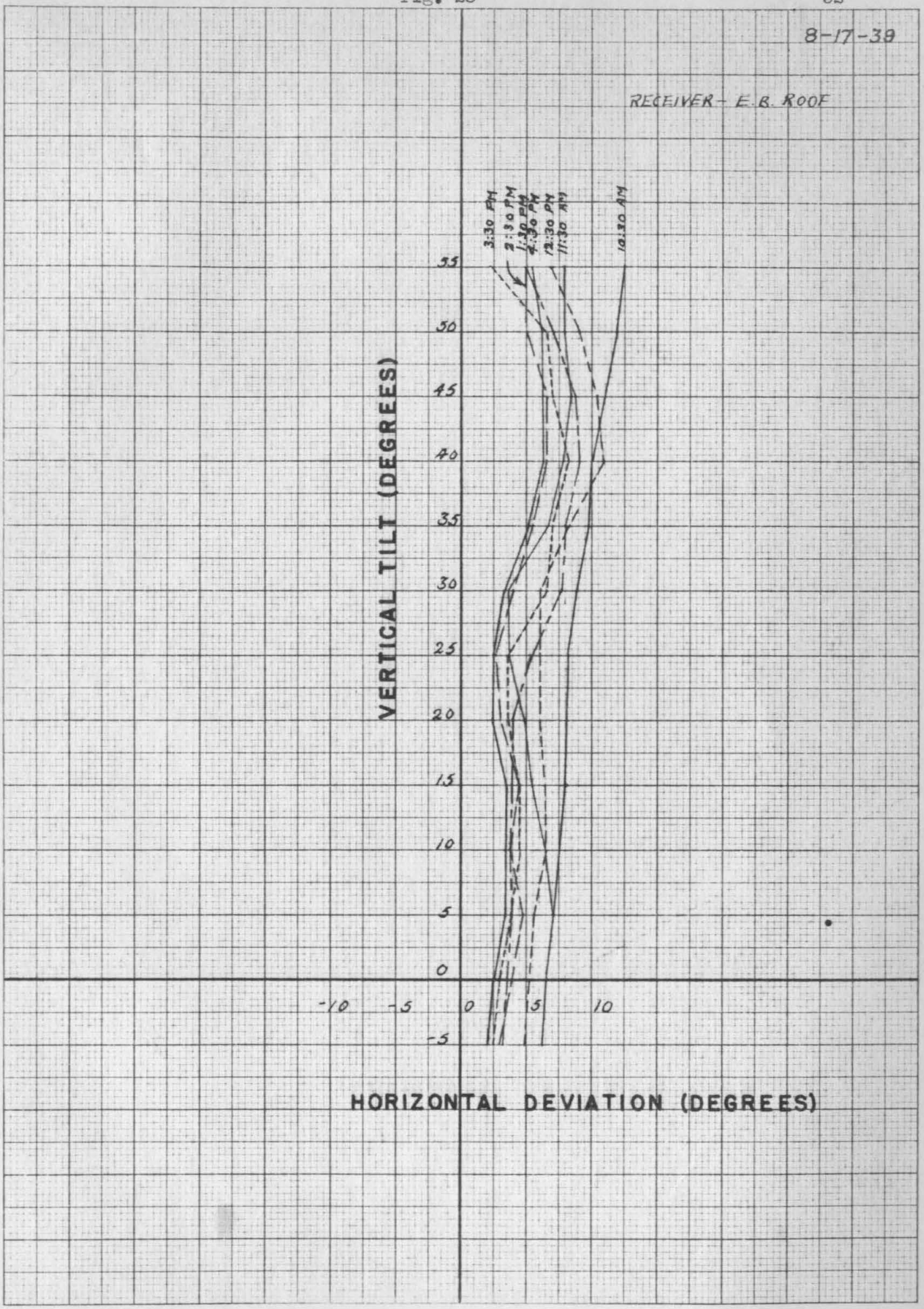
Fig. 18

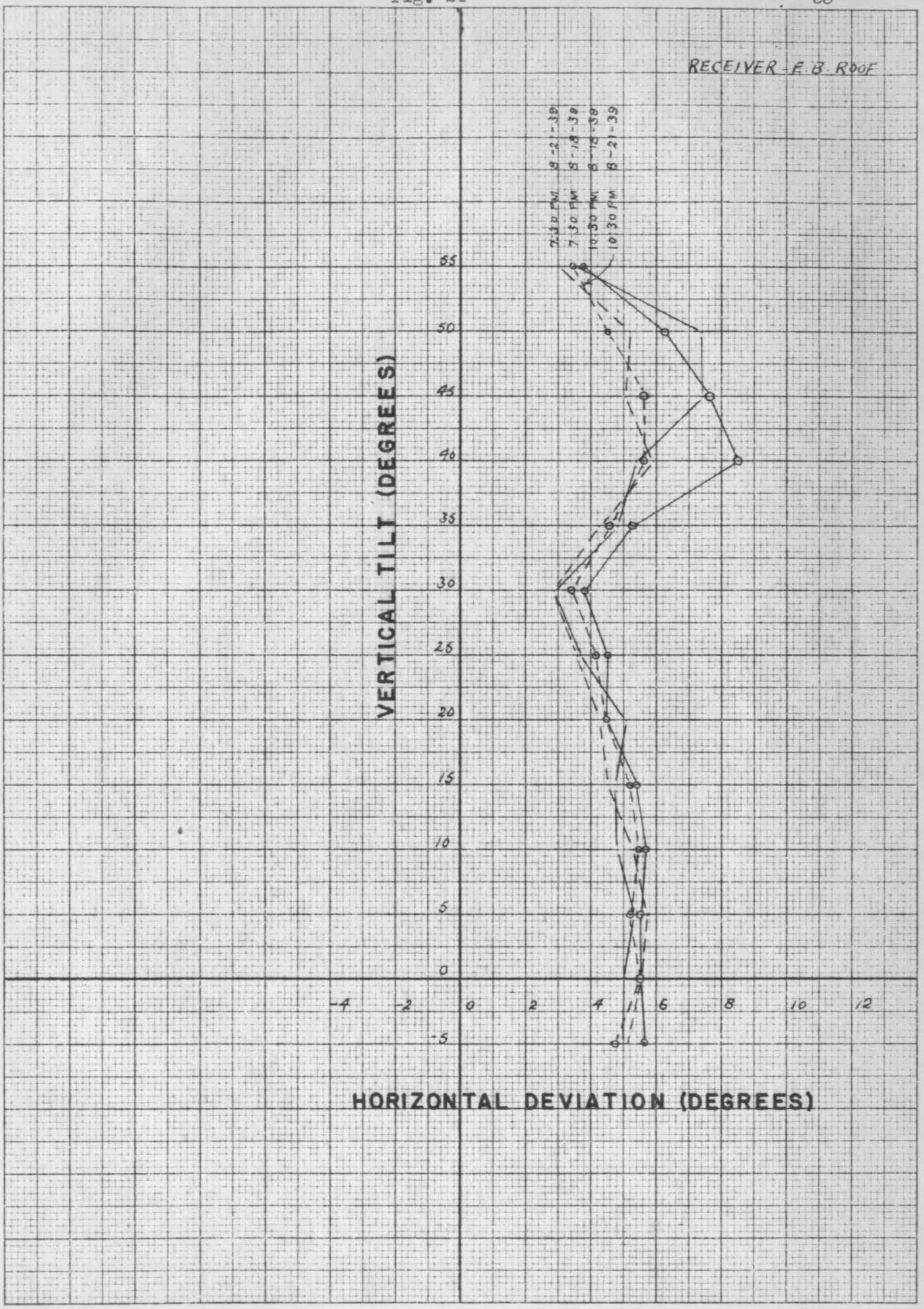

HORIZONTAL DEVIATION WITH TIME
TRANSMITTER - MT. WILSON
RECEIVER - E.B. ROOF
8-18-39
ANTENNA TILT FROM VERTICAL
55
50
45
40
35
30
25
20
15
10
+5
0
-5
9:30
10:30
11
(AM)
12
1
2
3
4
(PM)
5
6
7
8
(Dark)
TIME
10°
0°
HORIZONTAL DEVIATION

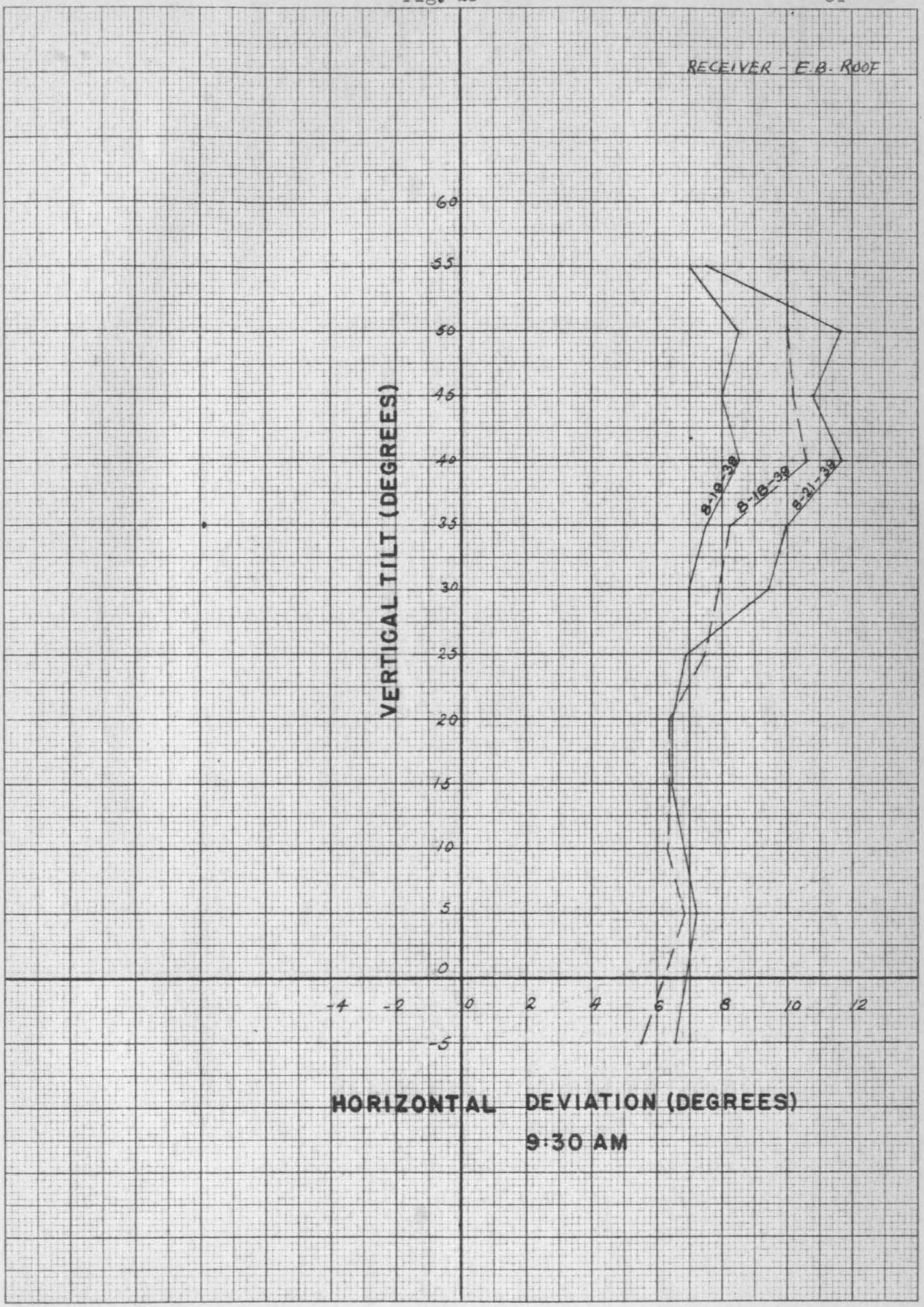

HORIZONTAL DEVIATION WITH TIME
TRANSMITTER - MT. WILSON
RECEIVER - E.B. ROOF
8-19-39
ANTENNA TILT FROM VERTICAL
55
50
45
40
35
30
25
20
15
10
5
0
-5
HORIZONTAL DEVIATION
0°
10°
9:30 10:30
11
12
1
2
3
4
5
6
(AM)
(PM)
TIME

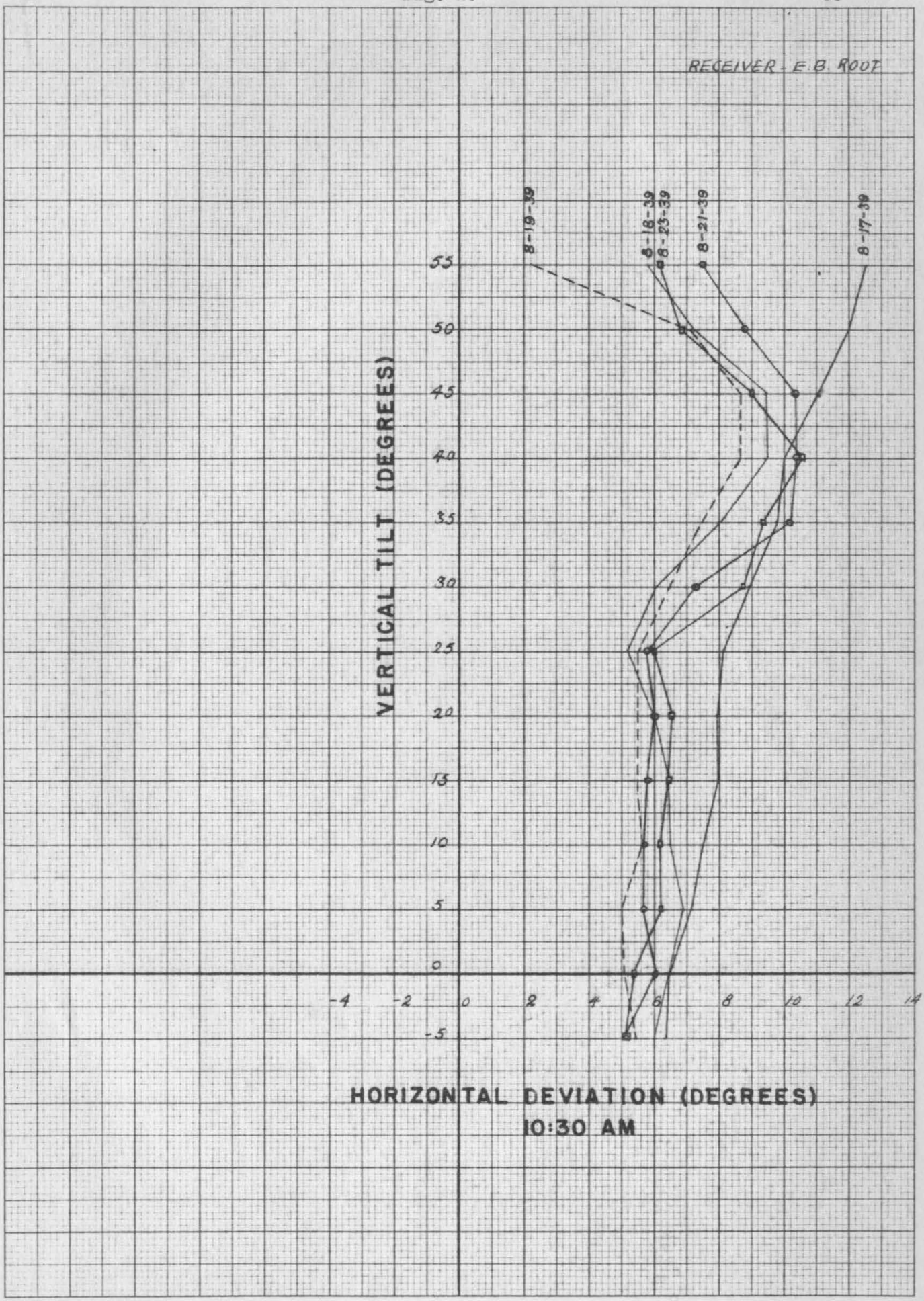

HORIZONTAL DEVIATION WITH TIME
TRANSMITTER - MT. WILSON
RECEIVER - E.B. ROOF
8-21-39
ANTENNA TILT FROM VERTICAL
55
50
45
40
35
30
25
20
15
10
5
0
-5
10°
0°
9:30
10:30
11
12 (AM)
1
2
3
4
5 (PM)
TIME
HORIZONTAL DEVIATION

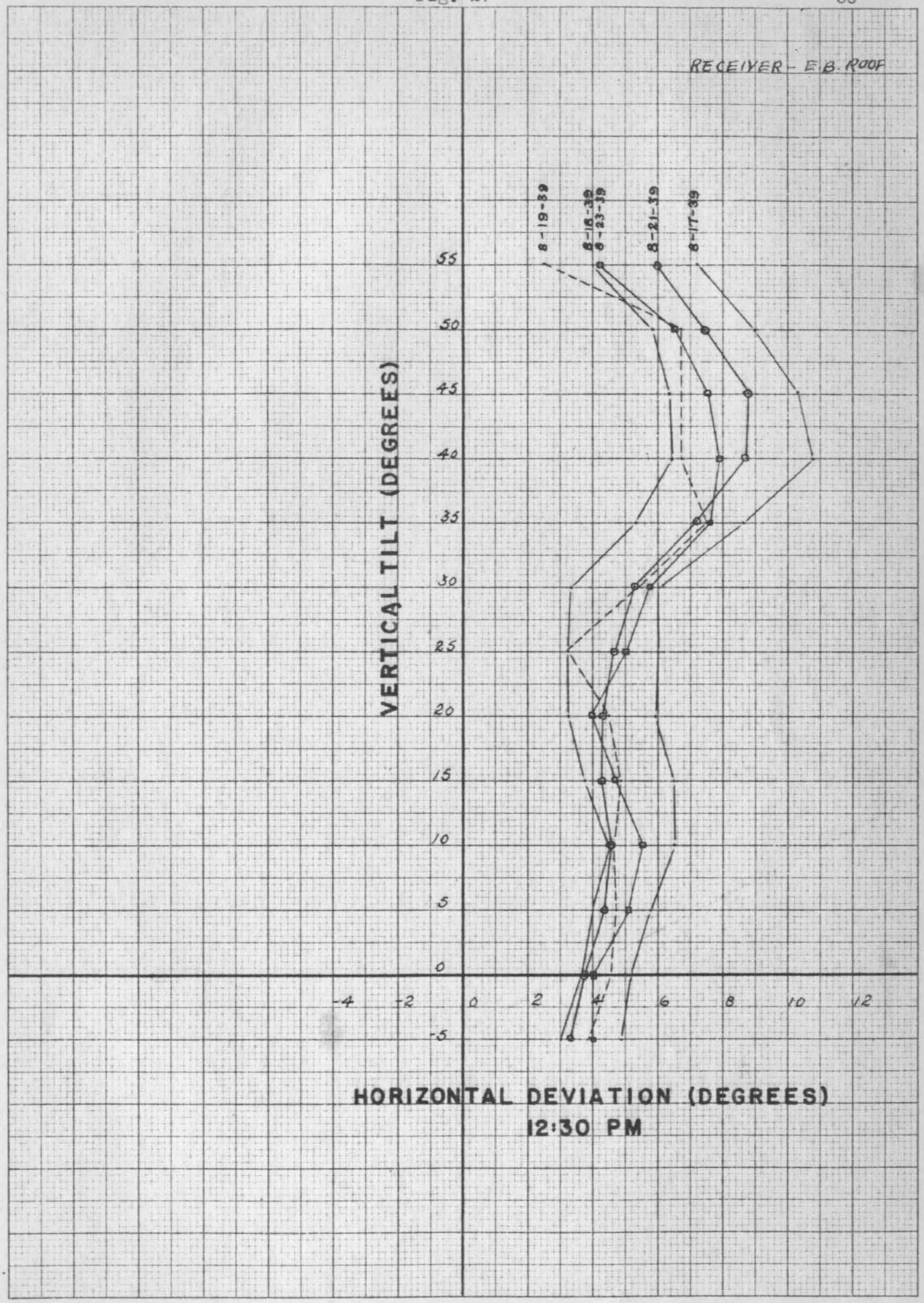

TRANSMITTER - MT. WILSON
RECEIVER - E.B. ROOF
TILT = 10°
TILT = 0°
Aug 17, 1939
18,
19,
21,
22,
23,
HORIZONTAL DEVIATION (DEGREES)
TIME
(A.M.)
(P.M.)

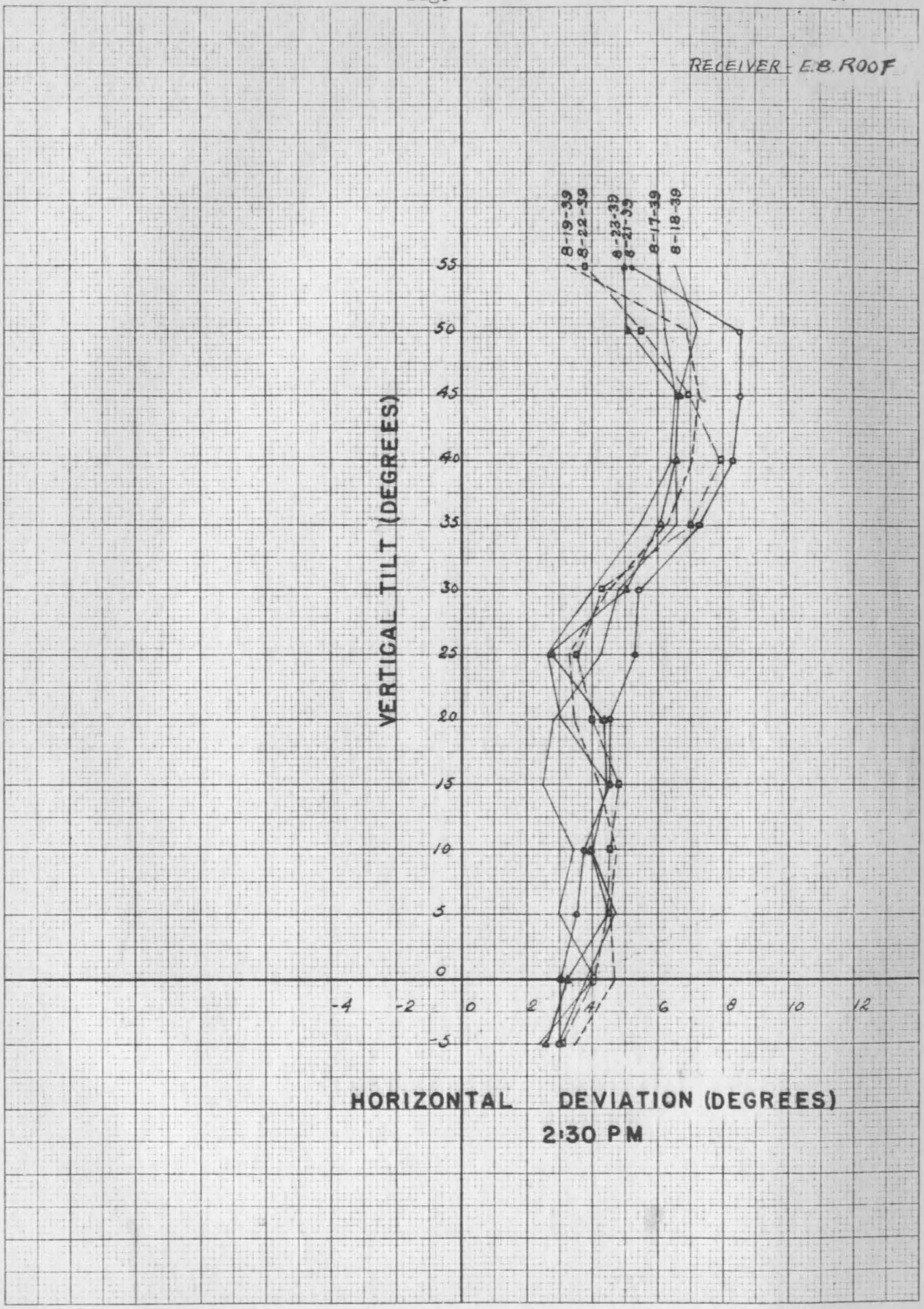

8-17-39
RECEIVER - E.B. ROOF
3:30 PM
2:30 PM
1:30 PM
12:30 PM
11:30 AM
10:30 AM
VERTICAL TILT (DEGREES)
55
50
45
40
35
30
25
20
15
10
5
0
-5
-10
-5
0
5
10
HORIZONTAL DEVIATION (DEGREES)


RECEIVER - E B ROOF
7:30 PM 8-21-39
7:30 PM 8-18-39
10:30 PM 8-18-39
10:30 PM 8-21-39
VERTICAL TILT (DEGREES)
55
50
45
40
35
30
25
20
15
10
5
0
-5
-4
-2
0
2
4
6
8
10
12
HORIZONTAL DEVIATION (DEGREES)


RECEIVER - E.B. ROOF
VERTICAL TILT (DEGREES)
60
55
50
45
40
35
30
25
20
15
10
5
0
-5
-4
-2
0
2
4
6
8
10
12
8-19-38
8-18-38
8-21-38
HORIZONTAL DEVIATION (DEGREES)
9:30 AM


RECEIVER - E.B. ROOT
8-19-39
8-18-39
8-23-39
8-21-39
8-17-39
VERTICAL TILT (DEGREES)
55
50
45
40
35
30
25
20
15
10
5
0
-5
-4
-2
0
2
4
6
8
10
12
14
HORIZONTAL DEVIATION (DEGREES)
10:30 AM


RECEIVER - E.B. ROOF
8-19-39
8-16-39
8-23-39
8-21-39
8-17-39
VERTICAL TILT (DEGREES)
55
50
45
40
35
30
25
20
15
10
5
0
-5
-4
-2
0
2
4
6
8
10
12
HORIZONTAL DEVIATION (DEGREES)
12:30 PM


RECEIVER - E.B. ROOF
8-19-39
8-22-39
8-23-39
8-21-39
8-17-39
8-18-39
VERTICAL TILT (DEGREES)
55
50
45
40
35
30
25
20
15
10
5
0
-5
-4
-2
0
2
4
6
8
10
12
HORIZONTAL DEVIATION (DEGREES)
2:30 PM

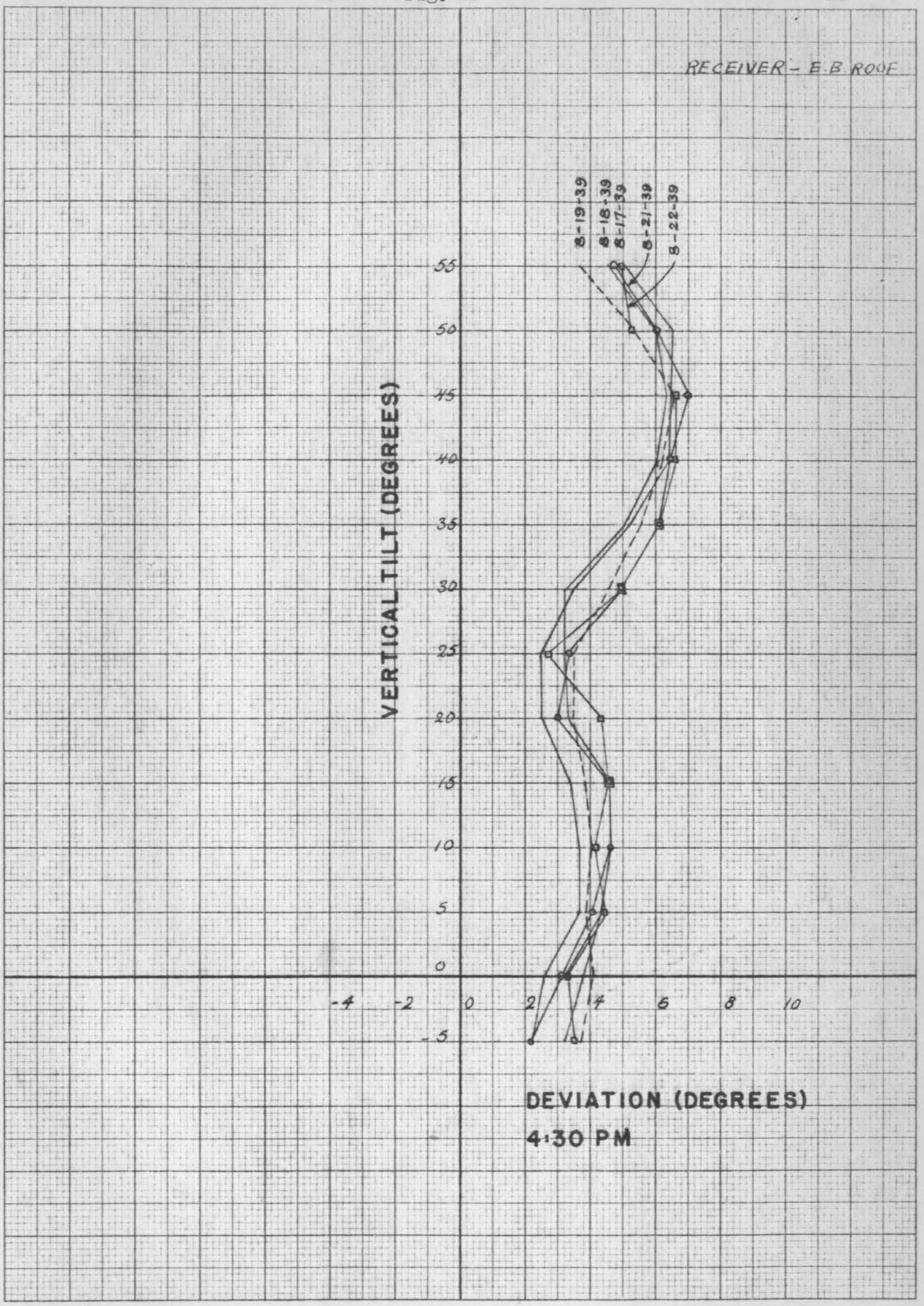
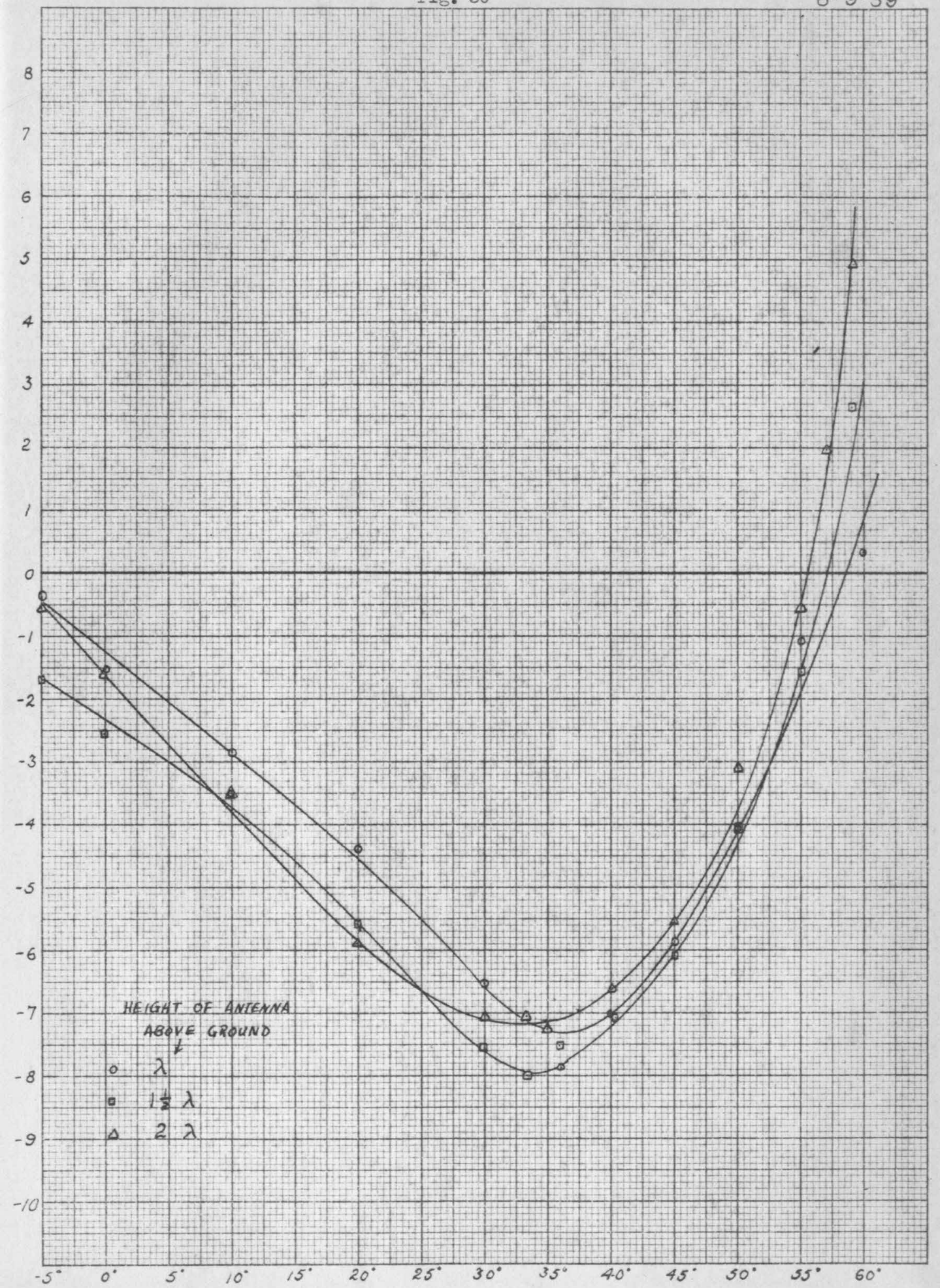
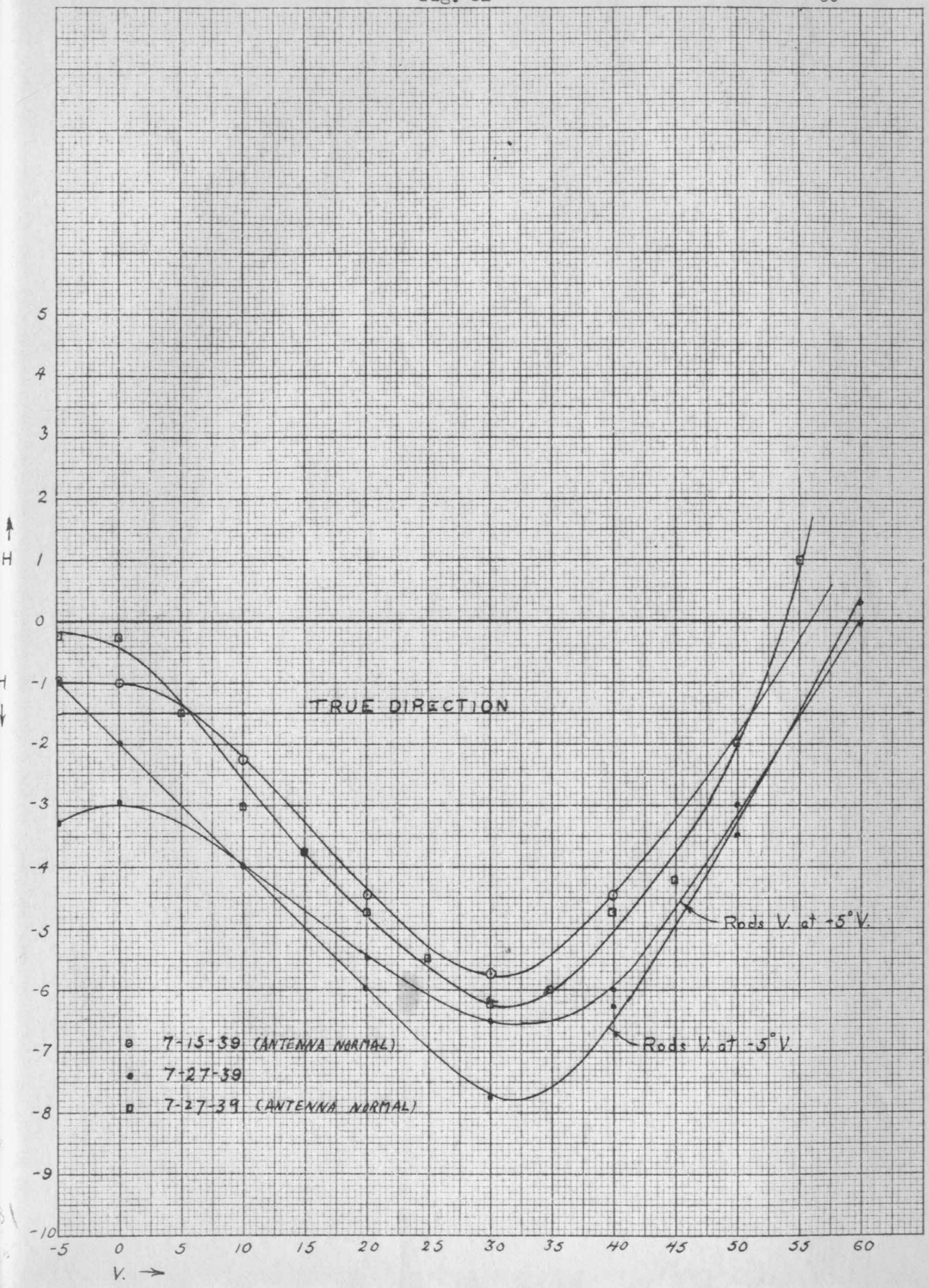
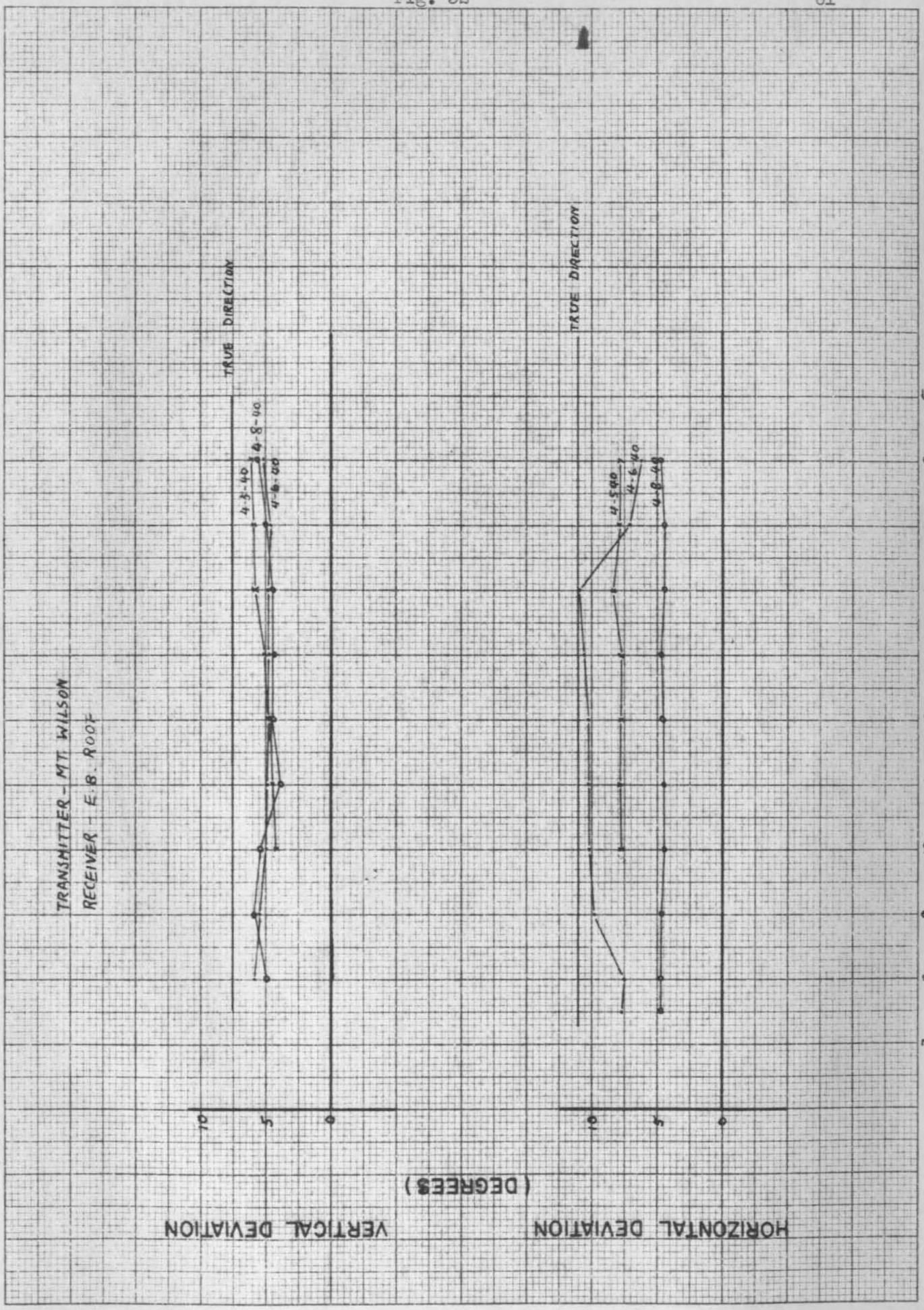
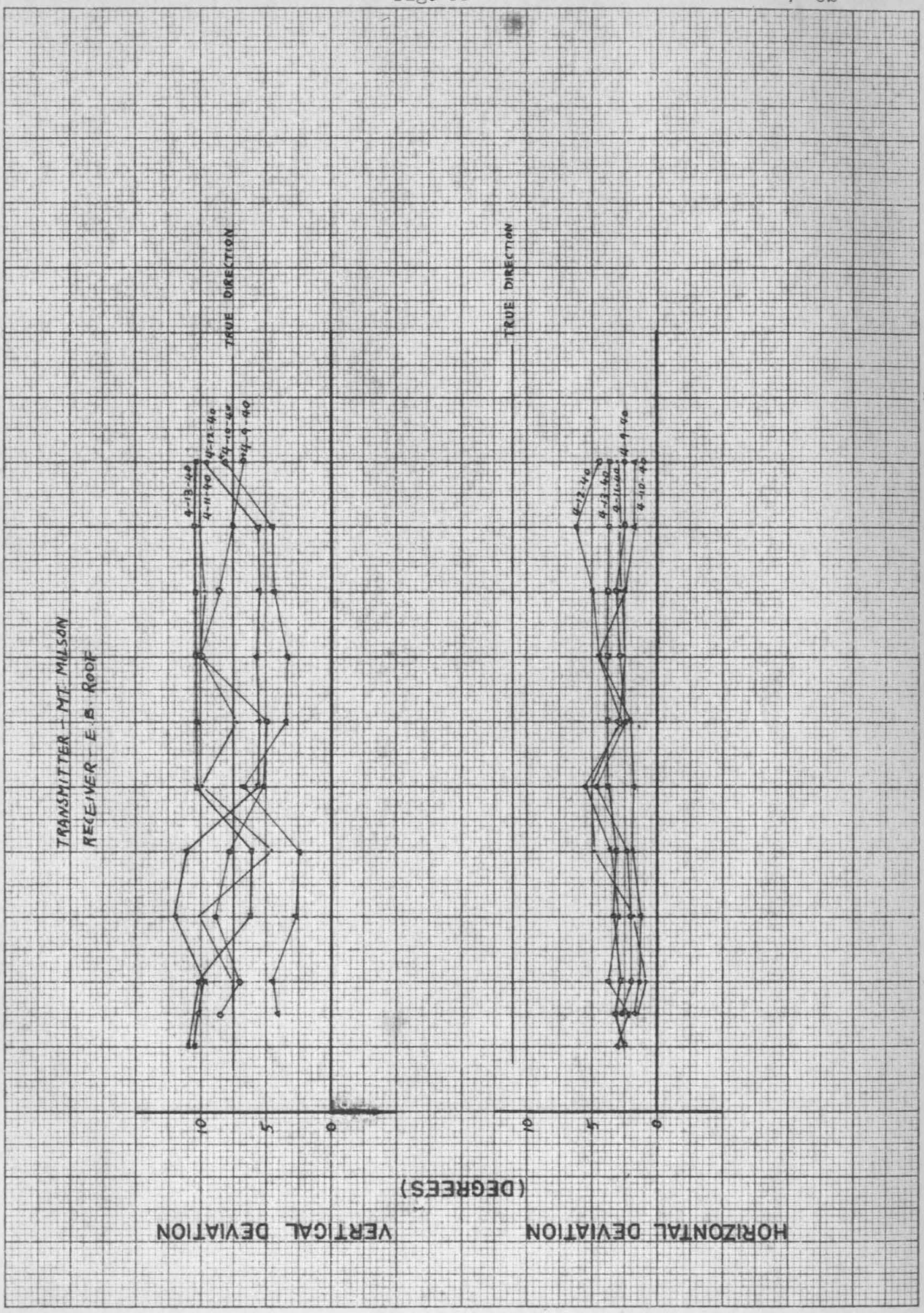

RECEIVER - E.B. ROOF
8-19-39
8-18-39
8-17-39
8-21-39
8-22-39
VERTICAL TILT (DEGREES)
55
50
45
40
35
30
25
20
15
10
5
0
-5
-4
-2
0
2
4
6
8
10
DEVIATION (DEGREES)
4:30 PM

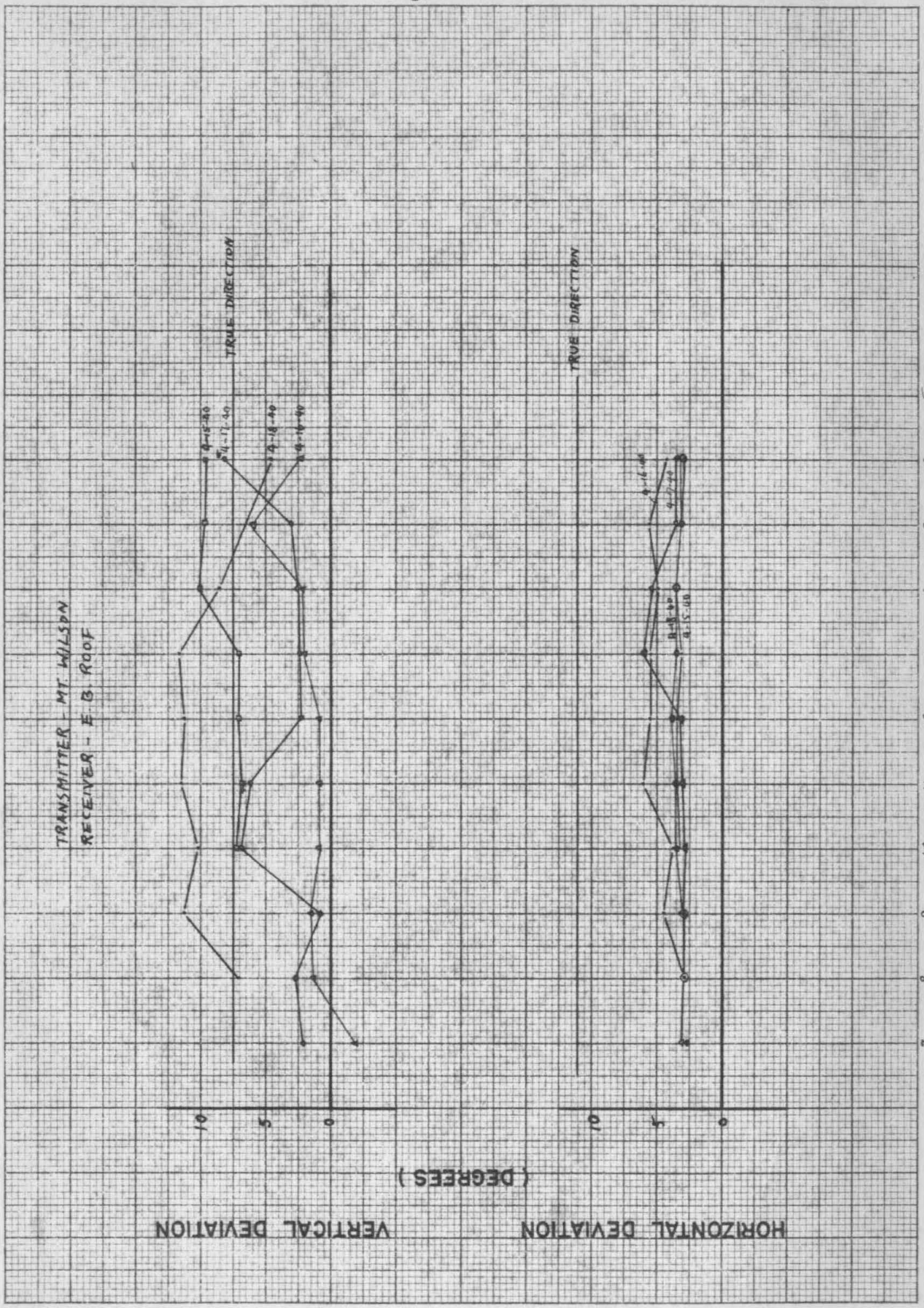
Fig. 30 8-9-39


8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-5°
0°
5°
10°
15°
20°
25°
30°
35°
40°
45°
50°
55°
60°
HEIGHT OF ANTENNA
ABOVE GROUND
λ
1½ λ
2 λ


5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
H
-5
0
5
10
15
20
25
30
35
40
45
50
55
60
V.
TRUE DIRECTION
Rods V. at +5° V.
Rods V. at -5° V.
7-15-39 (ANTENNA NORMAL)
7-27-39
7-27-39 (ANTENNA NORMAL)


TRANSMITTER - MT. WILSON
RECEIVER - E.B. ROOF
TRUE DIRECTION
4-3-40
4-8-40
4-6-40
TRUE DIRECTION
4-5-40
4-6-40
4-8-40
VERTICAL DEVIATION
HORIZONTAL DEVIATION
(DEGREES)
10
5
0
10
5
0
7
8
9
10
11
12
1
2
3
4
5
A.M.
TIME
P.M.


TRANSMITTER - MT. MILSON
RECEIVER - E.B. ROOF
TRUE DIRECTION
4-13-40
4-11-40
4-12-40
4-10-40
4-9-40
TRUE DIRECTION
4-12-40
4-13-40
4-11-40
4-9-40
4-10-40
10
5
0
10
5
0
(DEGREES)
VERTICAL DEVIATION
HORIZONTAL DEVIATION
7
8
9
10
11
12
1
2
3
4
5
A.M.
TIME
P.M.


TRANSMITTER - MT. WILSON
RECEIVER - E. B. ROOF
TRUE DIRECTION
4-5-80
4-17-80
4-18-80
4-16-80
TRUE DIRECTION
4-16-80
4-17-80
4-18-80
4-5-80
VERTICAL DEVIATION
HORIZONTAL DEVIATION
10
5
0
(DEGREES)
7
8
9
10
11
12
1
2
3
4
5
A.M.
TIME
P.M.

DISCUSSION AND CONCLUSION

Since the experiments were carried out mostly in the field, the apparatus has to be made light and easily transportable. Thus the slight bending of the legs of the tripod when swinging the antenna during observations and slight torsion in the vertical transmission tube greatly limit the accuracy of this instrument. In a permanent set up a more rigid support could be made for the antenna and greater accuracy in the observations could be expected.

The main difficulty that has been encountered seems to lie in the surface conditions of the ground in the vicinity of the receiving antenna. When the ground is wet, and expecially when the moisture is not uniformly distributed, deviation of the incoming wave from the true direction of the transmitter results. This is probably due chiefly to the difference in the velocity of propagation of the electromagnetic waves in the conducting earth's surface layer from that in the air immediately above the earth's surface thus resulting a tilt in the electric vector of the wave.

It was found that an automobile placed unsymmetrically on one side of the receiving antenna at a distance of over 25 feet does not effect the observations noticeably. But when it is placed closer to the antenna it greatly affects the readings to as much as three degrees.

Since the antenna height of one and half wavelength above ground is much greater than in the experiments of Smigh-Rose and Hopkins, the position of the observer is not as critical as in

their case. Provided he is not too close to the antenna, his influence can be ignored.

The following conclusions can be drawn from the results obtained:

(1) With the antenna one and a half wavelengths above the ground and with the ground surface homogeneous in the immediate vicinity of the receiving antenna, both the azimuthal and vertical angles of a transmitter emitting electromagnetic waves can be defined with an accuracy of one half degree and possibly one quarter degree as shown in Table I. This, however, is based on observations in which the transmitter was in one position only.

(2) Swinging of the transmitter antenna through angles up to 90 degrees does not affect either the direction of the transmitter as defined by the direction finder or the accuracy of the instrument in determining the directions (Table III).

(3) With the transmitter about seven degrees above the horizontal, different tilts of the plane of the Adcock antenna from the vertical show the horizontal deviation is a maximum at a tilt of about thirty five degrees from vertical and is minimum at about zero degree tilt and also at about fifty five degrees, but at the latter tilt the accuracy decreased tremendously. This holds true for different dates and at different times of the day (Figs. 14 to 16). At zero tilt the variation in the horizontal deviation for each day's setting is mostly less than one degree, with the average variation less than one half degree (Fig. 13). These were taken under conditions which were not ideal.

(4) Cars too close to the receiving antenna affect the readings by as much as three degrees; but at distances of over twenty five feet their effect is not appreciable.

(5) Big trees at distances of thirty wavelengths aways still have appreciable effects on the observations as shown in Fig. 17.

(6) Observations made on the roof of the East Bridge Building were very erratic and varied from day to day as can be seen from Figs. 18 to 21; but the horizontal deviations were all in the same direction. At zero vertical tilt of the Adcock antenna, an average horizontal deviation of about four degrees with a maximum deviation of eight and a quarter degrees was observed. While at ten-degree vertical tilt, the average deviation is about five degrees and a maximum deviation of nine and a quarter degrees (Fig. 22). However, observations made at different times of the day (Fig. 23) and at the same time of different dates show that the horizontal deviation is a maximum at a vertical tilt of about forty degrees and that the horizontal deviation is more or less independent of the vertical tilt at tilt angles of less than twenty five degrees (Figs. 24 to 29).

The vertical deviations from the true direction vary from three degrees on some of the dates (Fig. 32) to five degrees (Fig. 33), and as much as ten degrees on some other dates (Fig. 34). No conclusion can be drawn as to possible relations between the vertical deviation and the corresponding horizontal deviations at the same time (Figs. 32 to 34), because of the complicated reflections made at the surrounding buildings.

(7) Variation in the height of receiving antenna from one wavelength to one and half wavelengths above ground increases the horizontal deviation to about one degree at vertical tilts from -5 to 35 degrees. When antenna raised to two wavelengths above ground, the horizontal deviation decreases and coincides with that obtained at a height one wavelength above ground at zero degree tilt.

(8) The antenna must be made mechanically perfect. Unsymmetry of the Adcock antenna elements or rods affects the readings in the horizontal direction to as much as three degrees (Fig. 31).

(10) From reasons given in (3) zero tilt was chosen for defining horizontal directions.

Since the lower half of the Adcock antenna is closer to ground than the upper half, there is an assymmetry in the antenna system. Barfield showed that the error due to this assymmetry of the Adcock antenna causes a deviation from the true direction which decreases linearly as ℓ/d where ℓ is the length of each antenna element (in this case 1/4 wavelength) and d is the height of antenna above ground measured from the lower tip of the lower antenna elements. According to him a deviation of nine degrees was observed when $\ell/d = 8$, and the deviation decreases to two degrees when $\ell/d = 1$. Thus it may be expected that when the antenna is high enough, say a few wavelengths above ground, the error due to this assymmetry and possibly that caused by the tilting of electric vector travelling on inhomogenious ground might be eliminated.

Comparing the directional characteristic curves of the horizontal H and Adcock antennae calculated from the simple theory (Fig. 11A,B) against the experimental curves (Fig. 12B,C), we sdd that the theoretical curve for the H antenna has a similar form and the same number of minima as the experimental one. It is probably due to reflected waves from the ground that causes the unsymmetry of the experimental curve (Fig. 12B). Also we notice that the theoretical curve for the Adcock antenna, though agreeing in general shape with the experimental curve, is not as sharp as the latter. This is probably due to the effect of the interactions between the antenna elements which is neglected in the simple theory.

As mentioned before, since the frequency used is so high that there is no reflection from the Heavyside layer, the erroneous directions experienced with longer wavelengths are eliminated.

ACKNOWLEDGEMENT

These experiments were made under the direction of Professor Robert A. Millikan, to whom the writer is deeply indebted for his continued interest and encouragement. The writer wishes also to thank Professors S. S. Mackeown, G. Potapenko and William V. Houston for many helpful discussions, and Mr. Charles E. Miller for his help in the construction of the apparatus and the experimental work. Grateful acknowledgement is made to the Julien P. Friez & Sons without whose fund these experiments would not have been possible.

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No. 1, 1923

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