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Electrical ~~ATMOSPHERIC~~ PATH FLUCTUATIONS IN THE ATMOSPHERE: A PRELIMINARY REPORT ON THE MEASUREMENT OF DIFFERENTIAL OVERGROUND PATH FLUCTUATIONS AT 5.6 KMc

Nigel J. Keen

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I. Abstract

Two 10-foot dishes transmit CW signals horizontally in opposite directions from a central location. A plane reflector reflects each signal back to its respective dish, whereupon the phase of each returning signal is compared with the phase of the (common) outgoing signal. The phase fluctuations over each path are recorded digitally, while an analog record gives the single path fluctuations and the difference between these fluctuations. Typical records are shown in Figures I through VII.

If the reflectors are each 300 meters from the dishes, rapid peak-to-peak differential fluctuations ($\sim$1 minute) have magnitudes as great as 15° in warm, humid weather, and these fluctuations are uncorrelated: this is equivalent to a path fluctuation of 2.3 mm in 600 m. Slow differential fluctuations (>15 minutes) of twice this magnitude have been observed under similar atmospheric conditions, although really slow differential fluctuations (> 1 hour) appear to be absent in most cases. Single path fluctuations > 60° are observed with periods over several hours, suggesting that the large scale atmospheric fluctuations are usually well correlated. Rain appears to give short-term differential fluctuations larger than those without precipitation, even during the night (when path conditions are usually most stable).

No attempt has been made at this stage statistically to analyze the digital data, nor have quantitative meteorological measurements been taken. However, we consider experimental results by other workers insofar as they are relevant to radio astronomical problems.

II. Basic Considerations

Microwave signals passing through the atmosphere suffer random variations of path-length, mainly due to the variation of water-vapor in the wave-path.* These

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* The variation of path length depends on the distribution of the precipitable water, as well as on the quantity, although we will not attempt to separate the causes here.

variations may affect radio astronomical interferometer observations in two ways. In the first place, source signals arriving at the two antennas of an interferometer may suffer uncorrelated delays prior to arrival at each dish. Also, local oscillator signals may experience random phase fluctuations if transmitted by a radio link. Both phenomena will produce a random movement of the interferometer fringes, and our experiment allows us to make some quantitative judgments about overground path fluctuations. Furthermore, Tatarski [1] has performed experiments on intensity (rather than phase) fluctuations of a beam of light transmitted overground, and has obtained the spectral distribution of these fluctuations. We will discuss these results briefly later in this report.

The spectrum of phase fluctuations will be obtained at NRAO when sufficient data is available to permit a statistical analysis of the phase fluctuation spectrum.

III. Theoretical and Experimental Considerations

We wish to study the nature of the fluctuations in electrical path through the atmosphere. These fluctuations depend on the variations in temperature and absolute humidity of the atmosphere, although there are two mathematical processes occurring simultaneously to produce these fluctuations:

(a) Turbulence which may be considered on a statistical model; and

(b) Non-statistical (quasi-systematic) atmospheric processes, such as radiation losses and frontal movements.

Tatarski has studied the path fluctuations in a turbulent medium and finds that the structure function

$$D_f(\vec{r}_1, \vec{r}_2) = [f(\vec{r}_1) - f(\vec{r}_2)]^2$$

is given by

$$D_f(r) \sim r^{2/3}$$

where $\vec{r}_2 = \vec{r} + \vec{r}_1$. Hence the rms path fluctuations are given by

$$R \sim r^{1/3}$$

This is in agreement with the experimental results of Gossard [2], where temperature, humidity and refractive index measurements were made from aircraft and balloons.

The use of the structure function, rather than the correlation function

$$\rho(r) = [f(r_1) - \overline{f(r_1)}]\,[f^*(r_2) - \overline{f^*(r_2)}]$$

permits the idea of locally homogeneous and isotropic random fields, without regard to $\overline{f(r)}$. This concept is also employed by Booker [3] although that author uses a Gaussian model of turbulence (in the ionosphere).

We have to consider the upper scale of turbulence — where a gross, quasi-systematic process causes turbulence to commence — and the lower scale of turbulence — where sufficient energy is lost to permit laminar flow to commence. Since the lower scale of turbulence does not exceed a few millimeters in the atmosphere [1, p. 210], we only concern ourselves with the upper scale, L_o. The variation of structure function with r is shown in Figure VIII and the rms variation of path difference is shown (on logarithmic scale) in Figure IX. The transition from turbulence to quasi-systematic flow is not sudden, but extends over a considerable range of r (shown by the full line). The system employed by the National Bureau of Standards, Boulder, Colorado [4] is shown in Figure X. Here the transition is even longer, and is qualitatively predicted by von Hoerner [5] as shown dotted in Figure IX. This appears to be in agreement with the experimental results of NBS [4, p. 69].

Considering the uncorrelated path fluctuations for a signal arriving at the two dishes of an interferometer, the rms apparent angular movement of a source is $\frac{r^{1/3}}{r}$ radians, which means that larger angular position fluctuations ($\sim r^{-2/3}$) should occur at shorter spacings due to turbulence alone. Tatarski predicts [1, p. 227] that the "quivering" of optical source images decreases slowly as the (filled) aperture diameter is increased, although, as he points out, most of the experimental work has been performed on amplitude fluctuations of sources, rather than on phase (direction) fluctuations. An interesting aspect of Tatarski's experimental intensity fluctuation spectra [1, pp. 248-9] is the considerably reduced amplitude of fluctuations < 20 c/s in winter (compared with summer), suggesting less large scale turbulons. Unfortunately, Tatarski did not observe below 2 c/s. Caution should be used in comparing optical and microwave results, however, since it is suggested [6] that optical fluctuations are primarily a high altitude temperature effect. Megaw [7] [11] studied direction- and intensity-fluctuations at both radio and optical wavelengths.

It is important to determine the upper scale of turbulence, L_o. Tatarski and Gossard independently found $L_o \approx 100$ m [1, p. 266]*. In high resolution radio astronomy we are concerned with fluctuations in paths separated by distances $> L_o$. Hence we must now consider quasi-systematic atmospheric fluctuations, which means that path fluctuations to the two (or more) dishes of a high resolution instrument must be considered empirically. Site meteorological conditions (especially the total atmospheric water content) will tend to dictate an approximate resolution limit for a high-resolution instrument. Furthermore, as with turbulence, we are especially interested in the lower layers of the atmosphere. Barton [8] has evaluated the NBS data, and computes atmospheric path fluctuations for a 2200-meter baseline (10 arc second fringes at $\lambda = 11$ cm) which produce out-and-return rms position errors between 1.5 and 4 arc seconds over 1000 seconds. This gives one-way fringe fluctuations < 2 arc seconds, and greater for shorter integration times. For a 1100-meter baseline the fluctuations are a little more (< 2.5 arc seconds) than for 2200-meters. This appears to indicate that random fringe fluctuations approach an asymptotic limit not much smaller than 2 arc seconds, and hence percentage fringe fluctuations will increase rapidly below 10 arc seconds.

Drake [9] determined the positions of various radio sources using the NRAO 85-foot telescope at $\lambda = 3.75$ cm. He claims an overall rms error of about 3 arc seconds, including a maximum position-reading accuracy of < 2 arc seconds. Results for Cygnus A are shown in Figure XI, and the resultant errors will certainly be < 5 arc seconds. Drake [10] states that the receiver accounts for at least 3 arc seconds of this error, so rms single-beam errors due to atmospheric fluctuation appear to be

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* According to Tatarski, we are unable to determine the "upper scale of turbulence". What we find is the order of the maximum correlation distance.

$\sim$ 1 arc second. However, there has been some difficulty in assessing the experimental errors of the system.

IV. The Differential Phase Measuring System

The system is shown in the block schematic diagram (Figure XII). A klystron is monitored by a crystal oscillator at 5.6 kMc, and transmits a signal from two 10-foot antennas facing in opposite directions. The signals are reflected back to the antennas by two plane reflectors, 8-foot square. The arrangement is shown in Figure XIII, together with possible reflector locations. Three out-and-return path distances are available: 200 m, 600 m, and 1000 m. The geographical situation is shown in Figure XIV. A 1000 c/s sawtooth waveform is generated (in a special oscillator developed at NRAO) and applied to the helix of a traveling wave tube amplifier. Since a TWT is phase modulated by varying the helix voltage, correct choice of sawtooth amplitude permits 360° of phase change for each sawtooth cycle. If the sawtooth fly-back time is very short, the microwave signal experiences a uniform frequency change equal to the sawtooth frequency.

Part of the oscillator signal is passed through the sawtooth-modulated TWT and the output of the TWT is mixed with the returned microwave signal from each path. The output from each mixer is passed through a 1000 c/s filter so that the filter outputs are 1000 c/s sine waves containing the information on the phase fluctuations. Since the sawtooth waveform is the 1000 c/s reference, it is filtered until only a 1000 c/s sine wave remains. The sine wave from each path is then compared with the reference (filtered sawtooth). The returned signal is isolated from the outgoing signal by a 50 db isolator, specially selected for the purpose.

In the original apparatus, designed by M. Vinokur for determining phase fluctuations along a single path, the comparison of the phases of received and transmitted signals was obtained in an Ad-Yu meter. The output of this meter was a voltage proportional to phase difference. In the two path equipment described here, the sine waves are converted to square waves in "zero-crossover" detectors built at NRAO. The leading edges of these square waves are coincident with the zero crossover of the sine waves to within 0.3° for sine wave amplitudes between 2 volts and 15 volts. The leading edge of the reference is used to open a gate, and allows a train of 1 Mc pulses to pass to a counter until the leading edge of one of the returned-signal square waves (we call them "East" and "West") closes the gate. Hence direct counting of the pulses would give one thousand pulses for a 360° phase difference. Trains of East and West pulses are summed alternately in the counter and sum-times of either half a second or eight seconds, may be pre-selected. Phase shifters permit convenient phase reference levels to be selected. In order to simplify digital logic the output of the counter is divided down so that 1000 pulses represent 180° of phase change. Hence only three decimal digits are required for each observation of phase.

Since East and West phases are recorded alternately, a digital marker is generated for each reading, which indicates whether the path being considered is East or West. Hence, together with the end-of-line marker, five characters are punched out every half second or every 8 seconds. This is well within the capability of the NRAO scanner and the Friden punch.

One further feature of the system is the analog record. The output of the counter is alternately passed to the "East buffer" and the "West buffer" where digital-to-analog converters turn the pulses into a DC voltage proportional to the count stored in either buffer. The voltage from each d-to-a unit is recorded on a Sanborn 4-channel recorder, together with the difference between the voltages. Hence we have a digital record of East and West phases, relative to some arbitrary reference phase, and an analog record of East, West and Difference phases. Typical analog records are shown in Figures I through VII.

Interesting aspects of the equipment described are:

(1) The reliability of the Computer Control Company logic cards, used for all digital circuits;

(2) The use of the phase modulated TWT, and its considerable temperature dependence;

(3) The necessity for constant VSWR checks and a very stable oscillator frequency; and

(4) The extreme care required in aligning antennas and reflectors.

V. Experimental Results

Results to date have been for path distances of 600 meters, although 200 meters were initially used to calibrate the equipment. Digital records have been obtained, although sufficient data is not yet available to make a spectral analysis of phase fluctuations. For the time being we can only make quantitative judgments from the analog records (Figures I-VII). From these records we see:

(1) Since difference fluctuations will give the uncorrelated fluctuations in each path, short-term (turbulent) fluctuations are the main feature of the difference record; long-term (quasi-systematic) fluctuations appear fairly well correlated.

(2) Short-term ($\sim$ 1 minute) peak-to-peak fluctuations as great as 15° are observed in warm, humid weather. This is equivalent to a maximum path fluctuation of 2.3 mm in 600 m.

(3) Short-term fluctuations appear to be uncorrelated, although fluctuations > 15 minutes are sometimes uncorrelated also.

(4) The only large slow fluctuation of the difference record ($\sim$several hours) occured at the end of a spell of low humidity weather (Figure VI). This does not appear to be an instrumental effect. There was little or no wind during the night, although the West side is more protected than the East side. The large rapid East fluctuations during the night are also extraordinary.

(5) Extremely large correlated and uncorrelated phase fluctuations ($\sim 40^\circ$) occur with the advent of rain.

(6) Long- and short-term phase fluctuations are very much smaller during the night than during the day (with the exception of the East record on Figure VI).

VI. Conclusions

Since insufficient information is available at the moment a detailed spectral analysis is not yet possible. However, indicative results may contribute something to an understanding of atmospheric behavior at microwave frequencies.

References

[1] "Wave Propagation in a Turbulent Medium", Tatraski. McGraw-Hill (1961).

[2] "Power Spectra of Temperature, Humidity and Refractive Index from Aircraft and Tethered Balloon Measurements", E. E. Gossard. Trans. IRE, Ap. 8 (1960), 186.

[3] "The Use of Radio Stars to Study Irregular Refraction of Radio Waves in the Ionosphere", H. G. Booker. Proc., IRE 46 (1958), 298.

[4] "An Experimental Study of Phase Variations in Line-of-Sight Microwave Transmissions", K. A. Norton, et al., NBS Monograph 33 (1961).

[5] S. von Hoerner, private communication.

[6] "Die Szintillation der Sterne", H. Elsässer. Die Naturwissenschaften, 47 (1960), 6.

[7] "Scattering of Electromagnetic Waves by Atmospheric Turbulence", Megaw. Nature, 166 (1950), 1100.

[8] "Reasons for the Failture of Radio Interferometers to Achieve Their Expected Accuracy", D. K. Barton, Proc., IEEE, 51 (1963), 626.

[9] "The Position-Determination Program of the NRAO", F. D. Drake. P.A.S. Pacific, 72 (1960), 494.

[10] F. D. Drake, private communication.

[11] "Fundamental Radio Scatter Propagation Theory", Megaw. P.I.E.E. (Brit.), 104C (1957), 441.

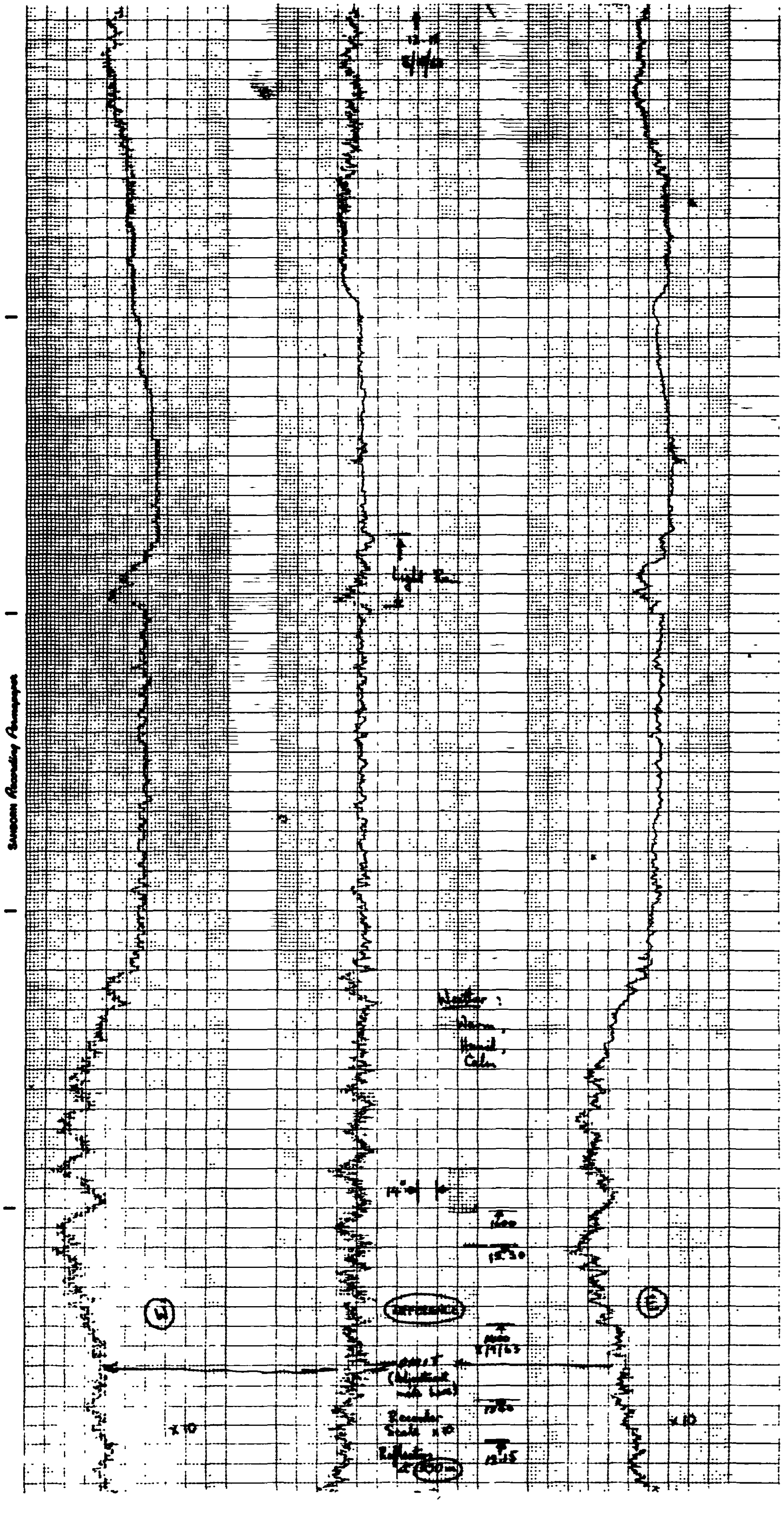

SANBORN Recording Permapaper
Light Rain
Weather: Warm, Humid, Calm
12:30
Ⓦ
DIFFERENCE
Ⓔ
x 10
Recorder Scale x 10
Reflector at 300 m
13:15
x 10

FIG. I

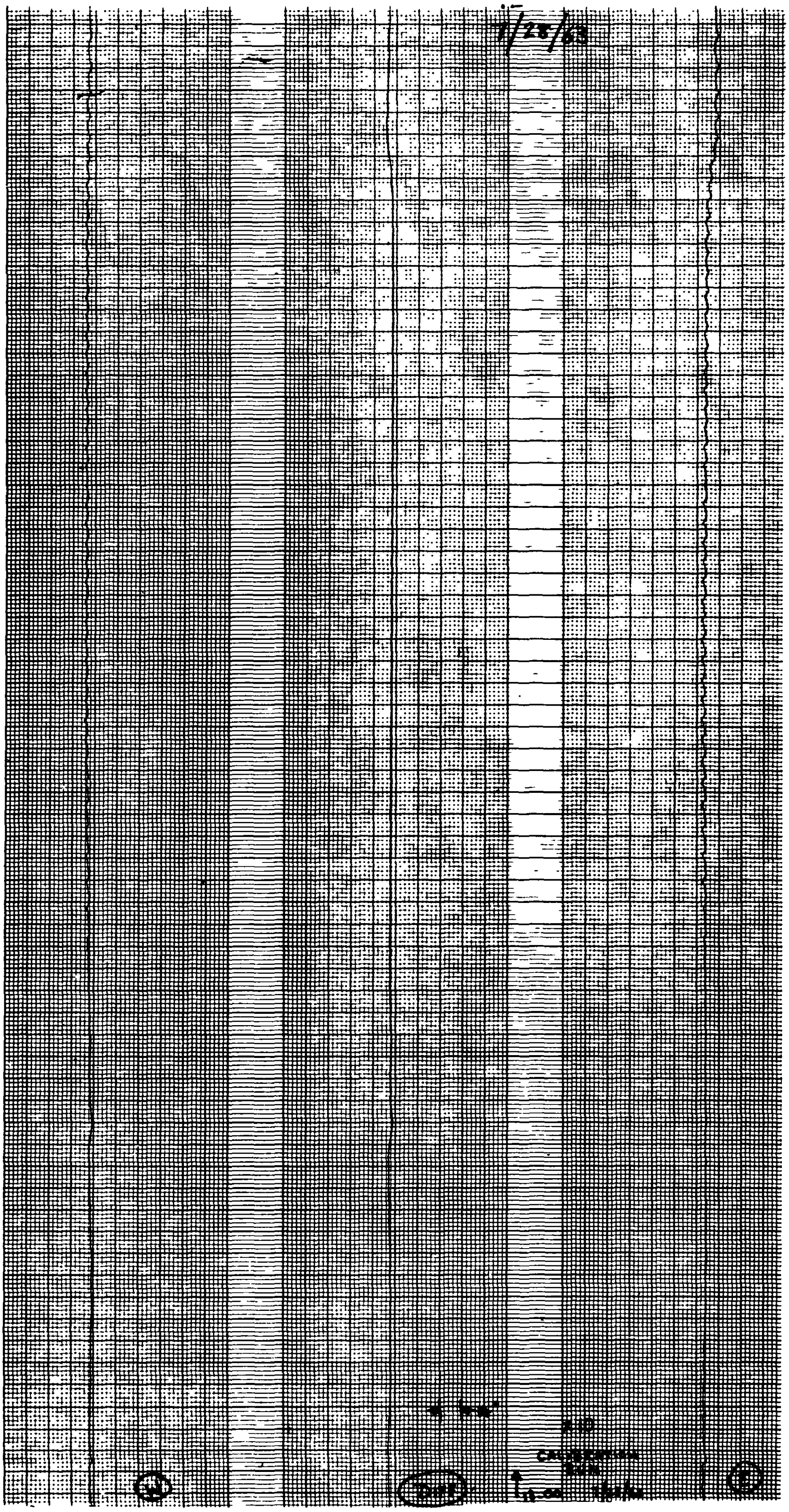


FIG. II

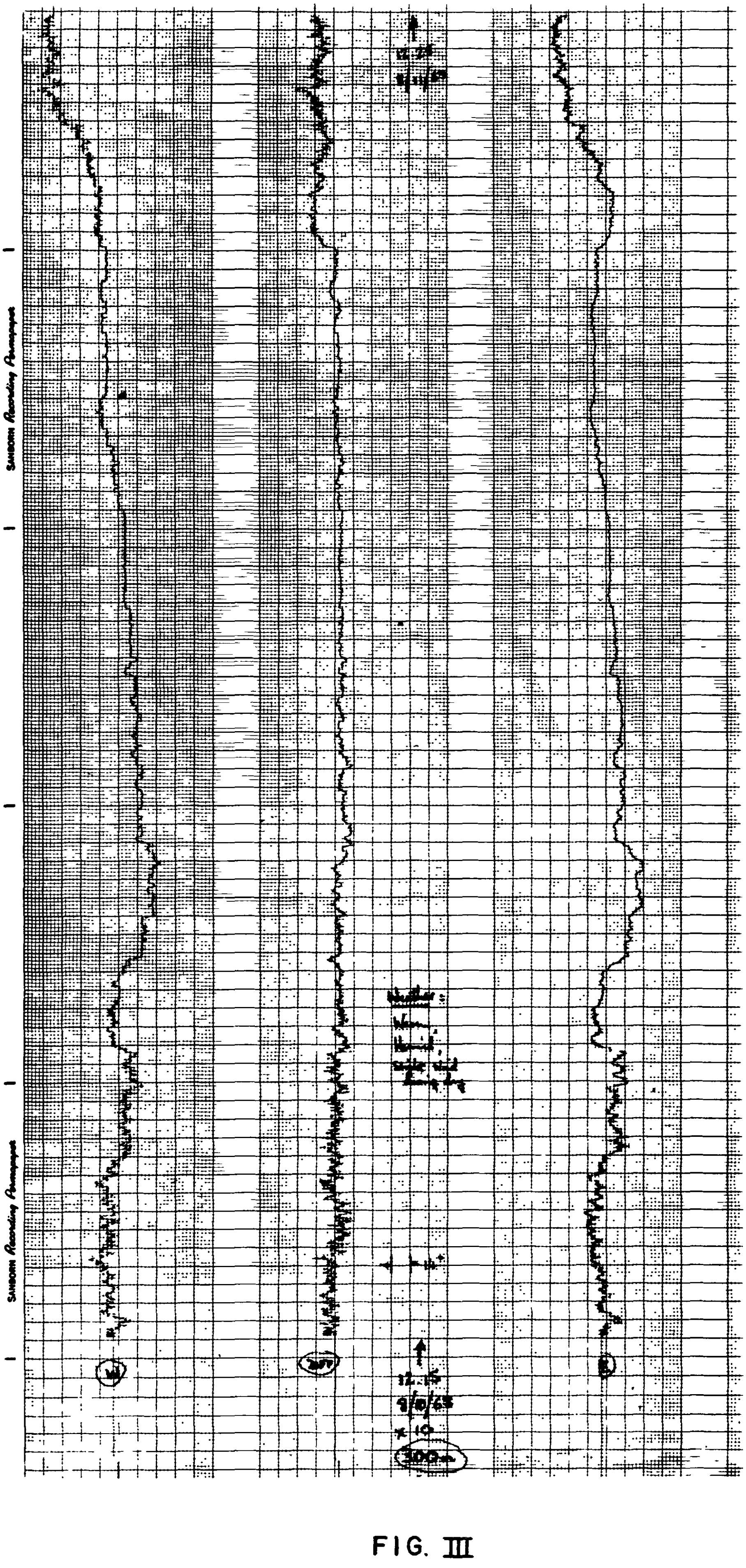

SANBORN Recording Paper
12.25
9/11/65
Weather:
Warm,
Humid,
Light wind
Sunny day
12.15
9/10/65
x 10
300 m
SANBORN Recording Paper

FIG. III

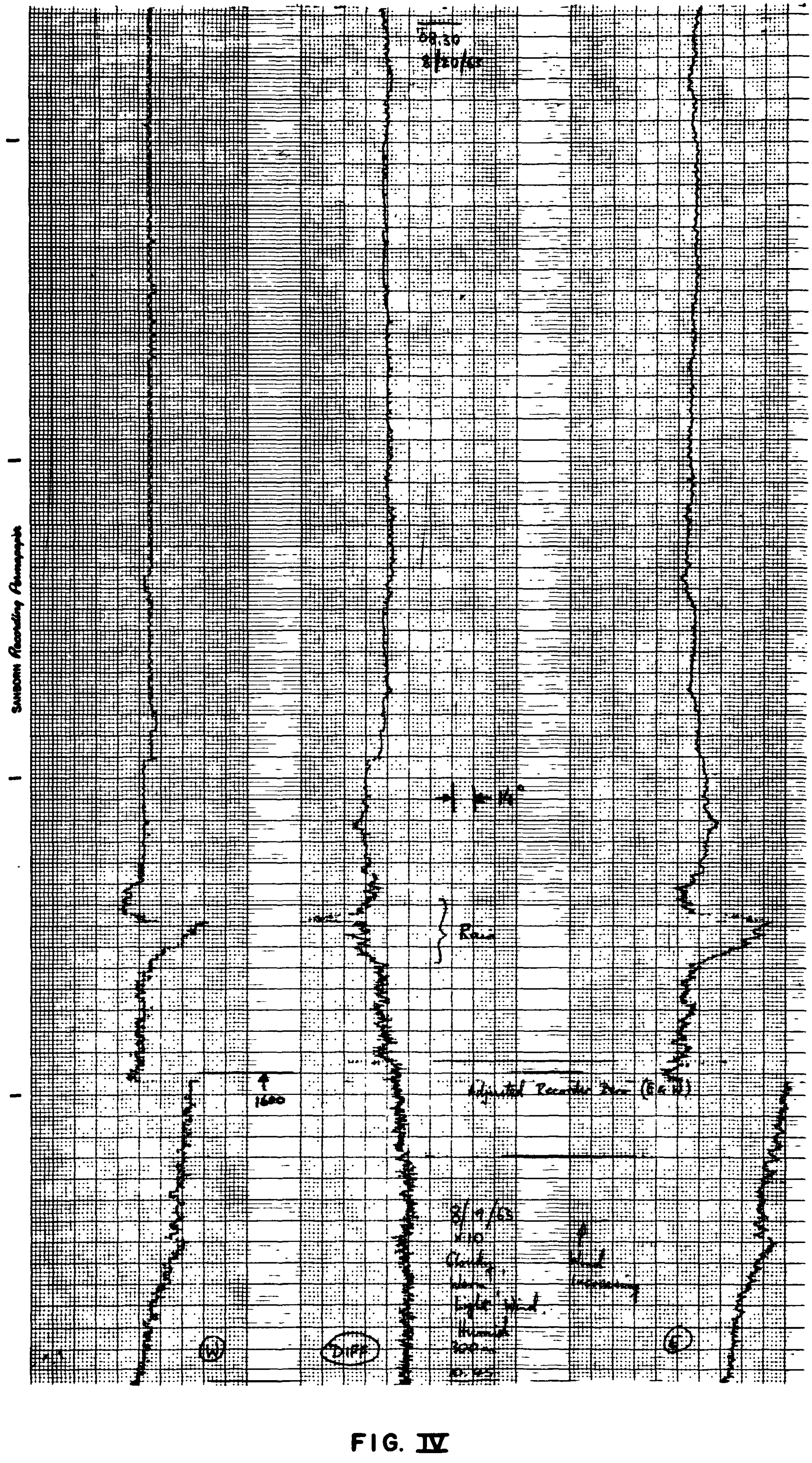

08.30
8/20/63
1/4"
Rain
4
1600
Adjusted Recorder Base (E & W)
8/19/63
x10
Cloudy,
Warm,
Light Wind.
Humid
300 m
10.45
Wind
increasing
W
DIFF
E
SANBORN Recording Permapaper

FIG. IV

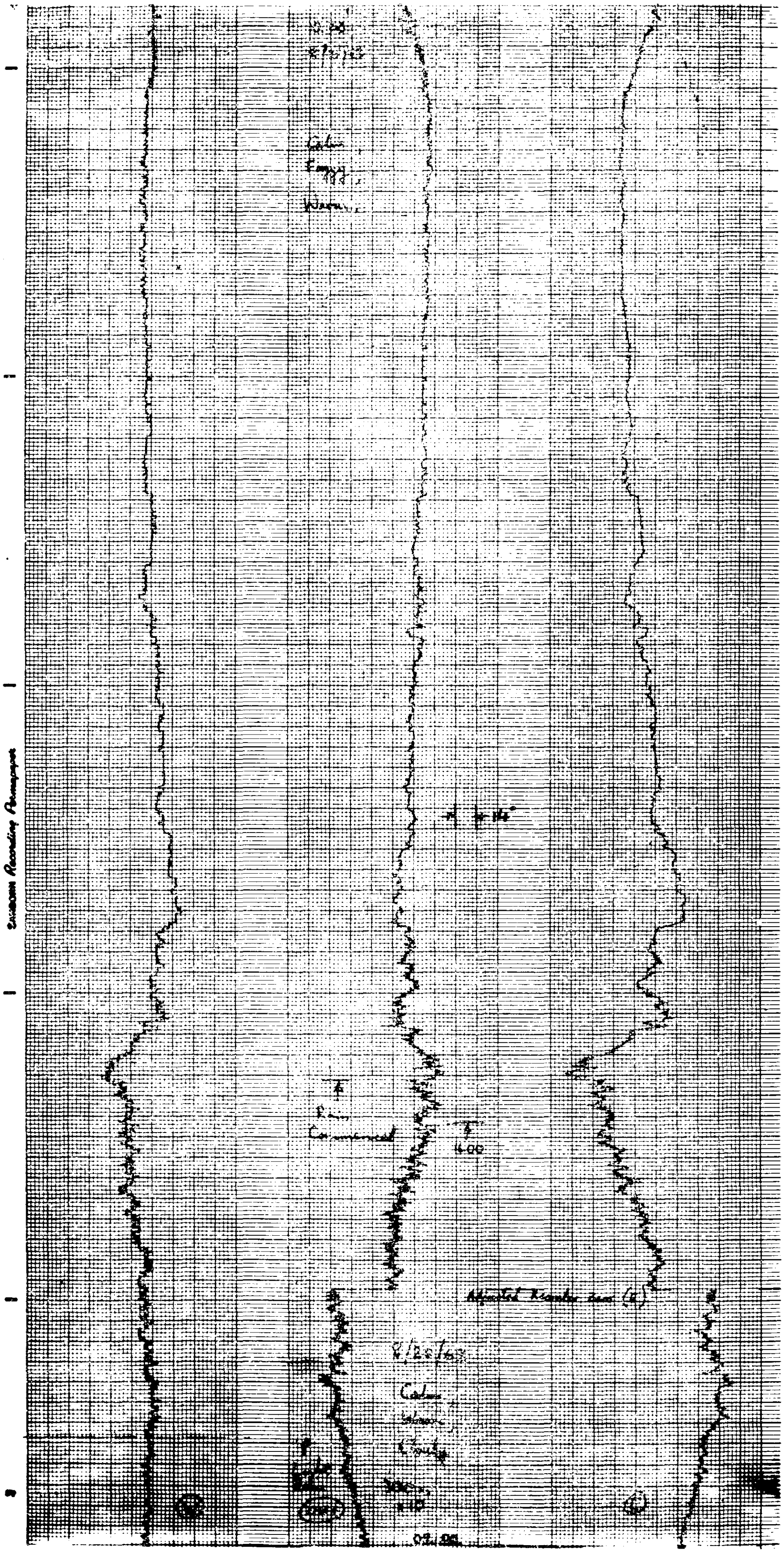

Calm
Warm
Rain Commenced
4:00
Adjusted Recorder Zero (4)
Calm
Warm
Cloudy
02:00
Sanborn Recording Permapaper

FIG. V

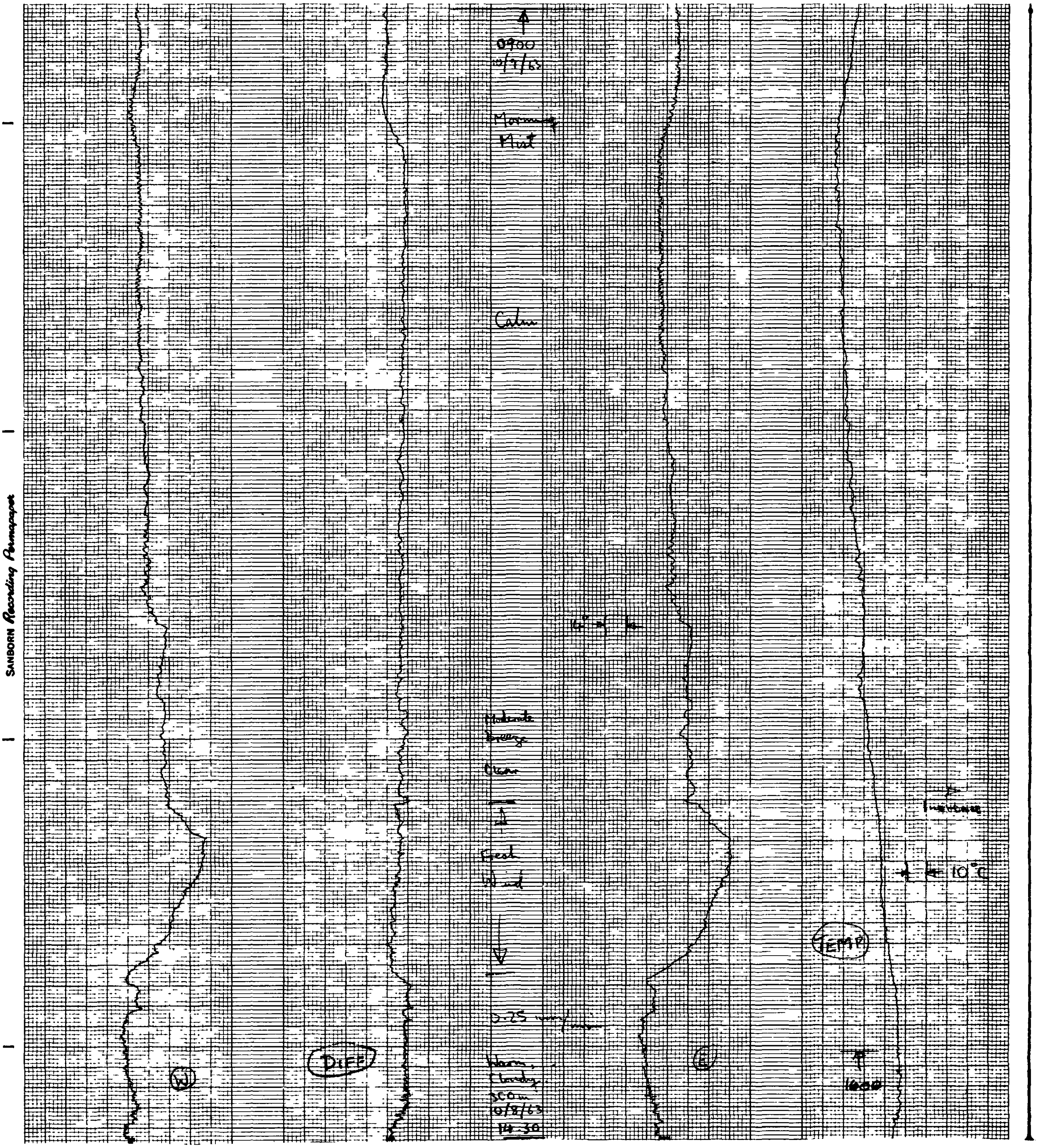

SANBORN Recording Permapaper
0900
10/9/63
Morning
Mist
Calm
6° of
Moderate
Breeze
Clear
Fresh
Wind
0.25 mm/min
Warm,
Cloudy.
300m
10/8/63
14.30
W
DIFF
E
Increase
10°C
TEMP
1600

FIG. VI

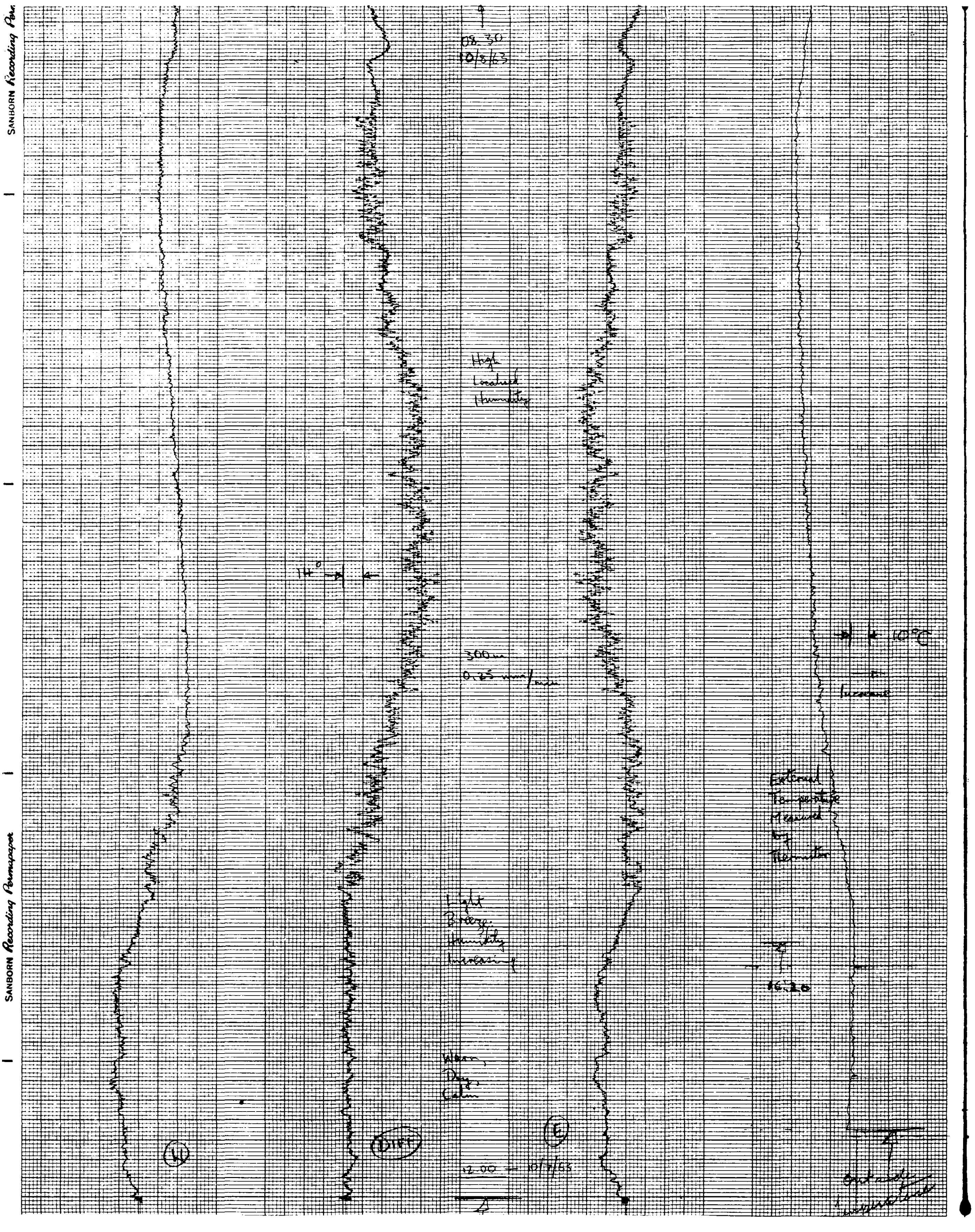
SANBORN Recording Permapaper
08.30
10/8/63
High
Localised
Humidity
14°
300 m
0.25 mm/min
10°C
Increase
External
Temperature
Measured
by
Thermistor
Light
Breeze.
Humidity
Increasing
16.20
Warm,
Dry,
Calm
W
DIFF
E
12.00 — 10/7/63
Outside
temperature
SANBORN Recording Permapaper

FIG. VII

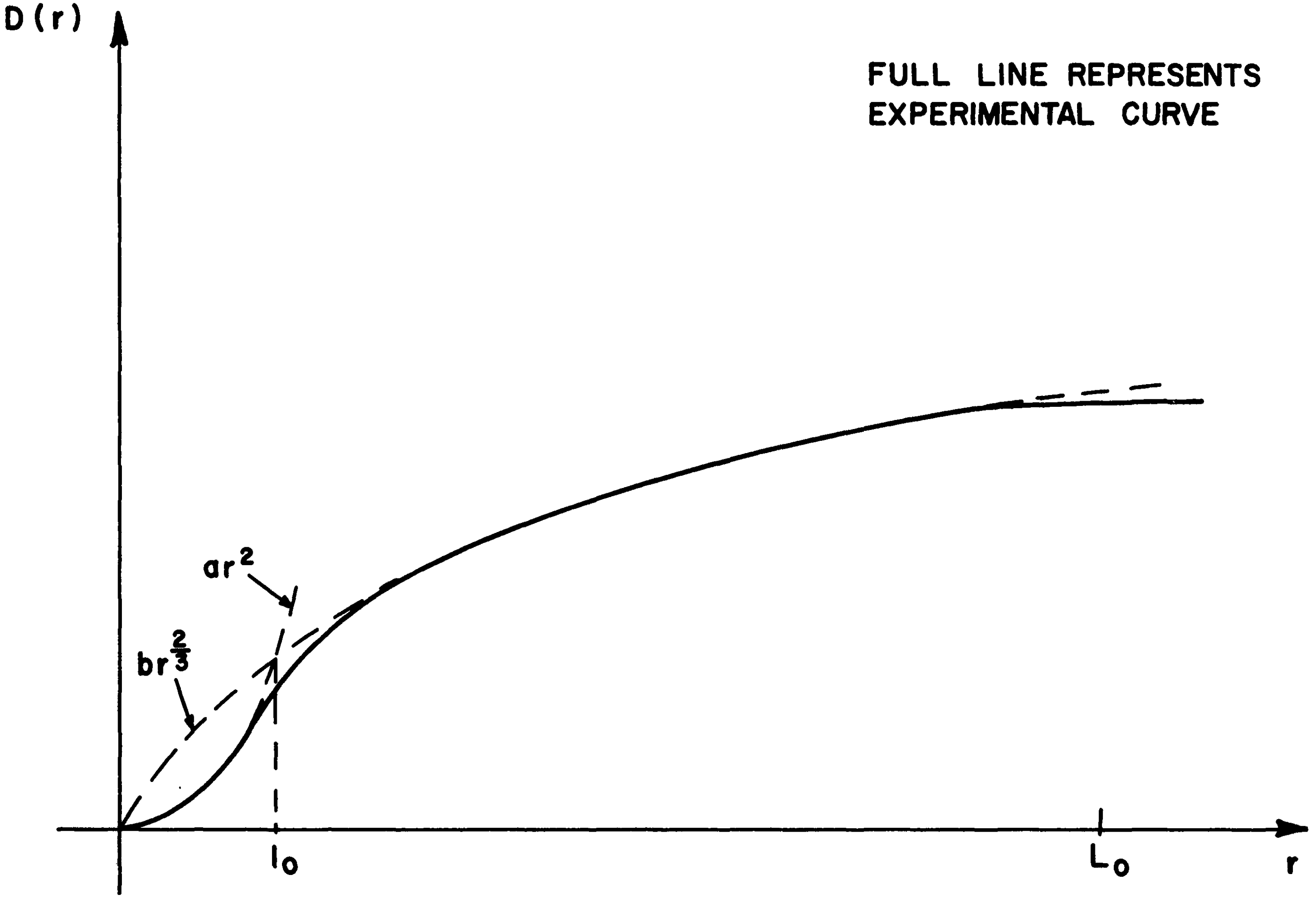

D(r)
FULL LINE REPRESENTS
EXPERIMENTAL CURVE
ar^2
$br^{\frac{2}{3}}$
l_0
L_0
r

FIG. VIII

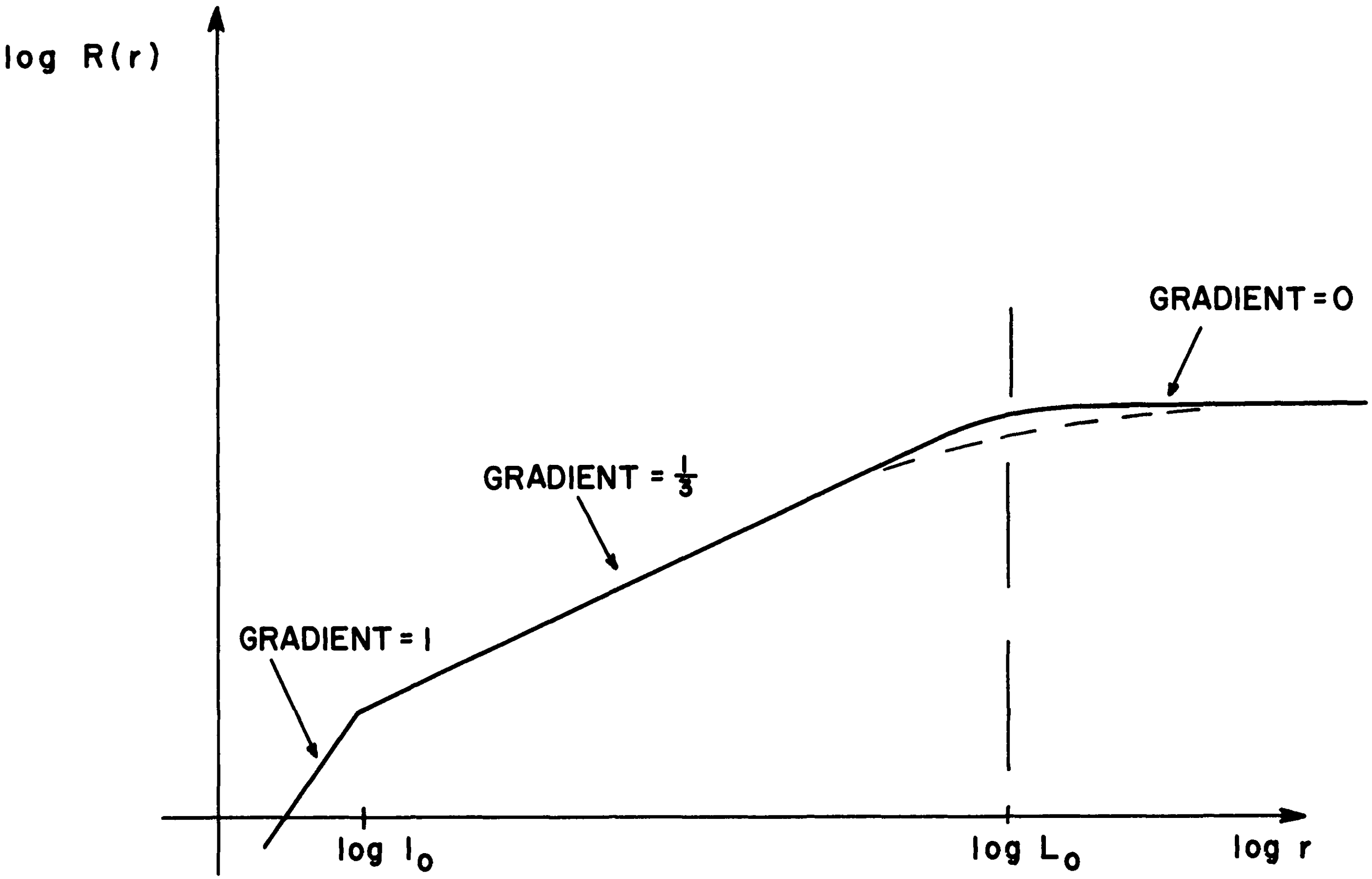

log R(r)
GRADIENT = 0
GRADIENT = $\frac{1}{3}$
GRADIENT = 1
log l_0
log L_0
log r

FIG. IX

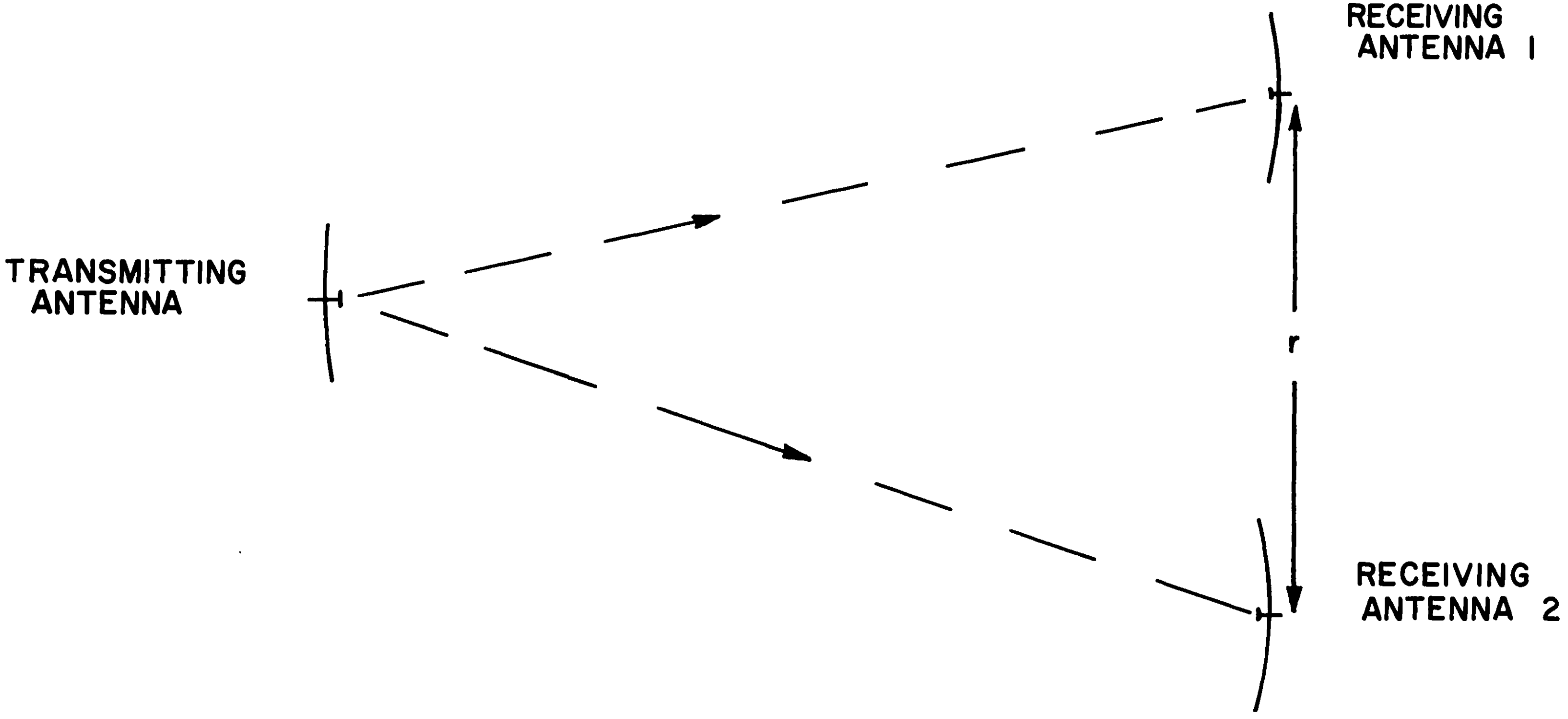

RECEIVING ANTENNA 1
TRANSMITTING ANTENNA
r
RECEIVING ANTENNA 2

FIG. X

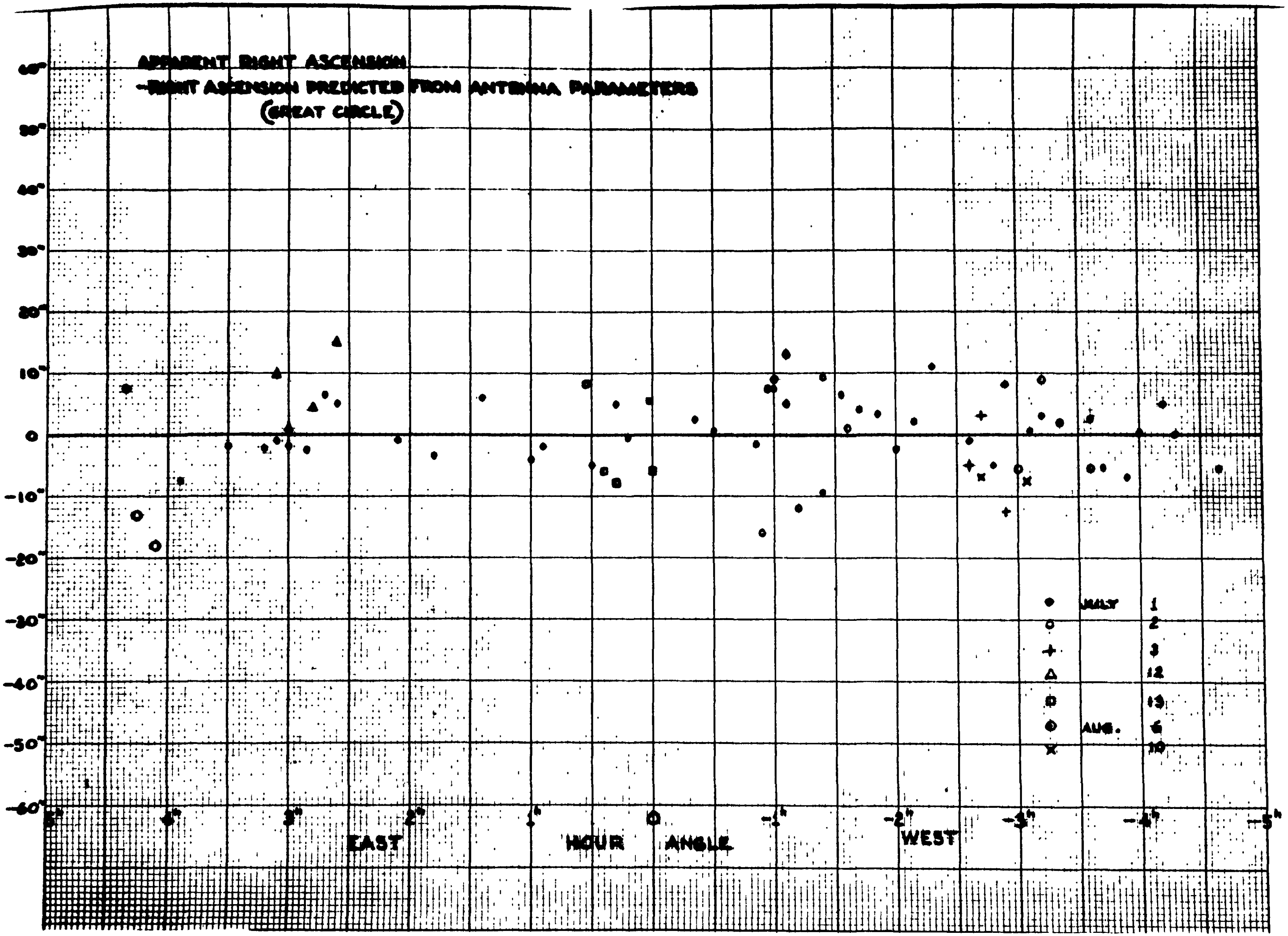
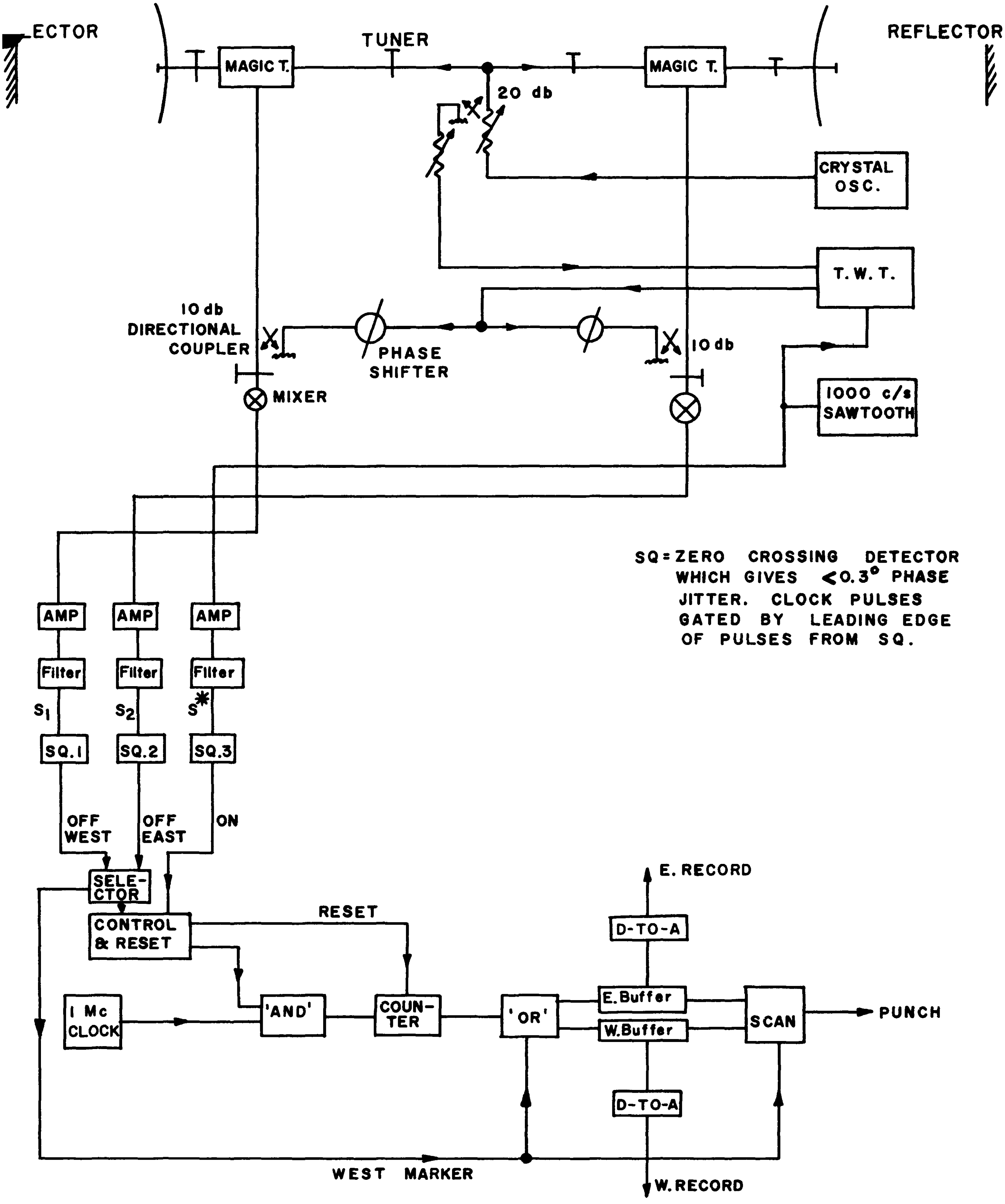
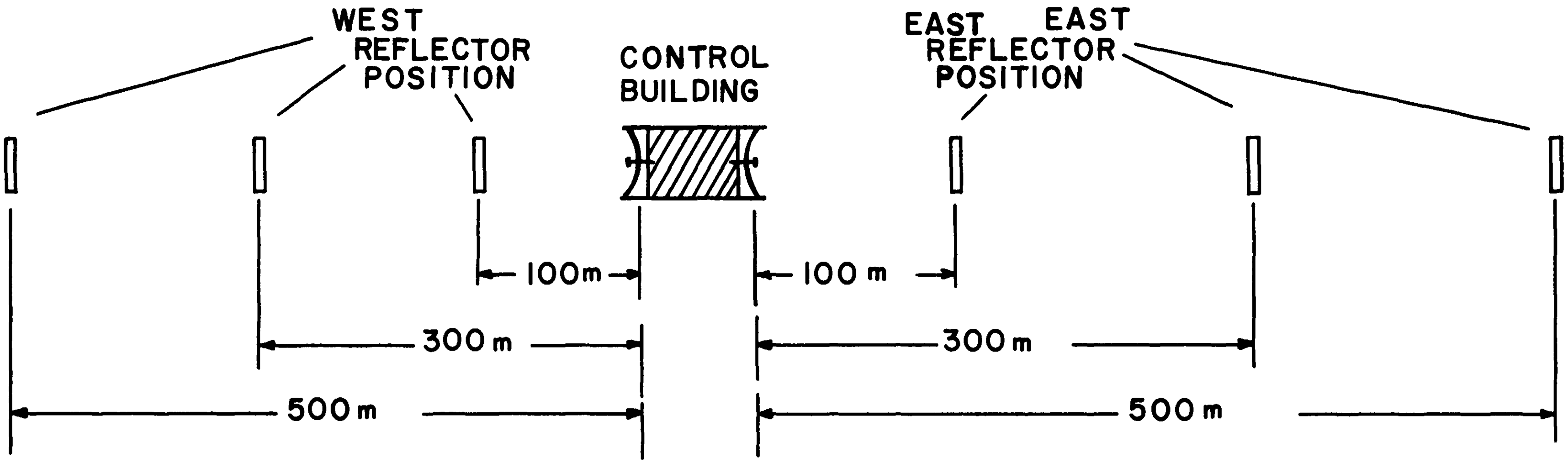

APPARENT RIGHT ASCENSION
- RIGHT ASCENSION PREDICTED FROM ANTENNA PARAMETERS
(GREAT CIRCLE)
60°
50°
40°
30°
20°
10°
0
-10°
-20°
-30°
-40°
-50°
-60°
5ʰ
4ʰ
3ʰ
2ʰ
1ʰ
0
-1ʰ
-2ʰ
-3ʰ
-4ʰ
-5ʰ
EAST
HOUR ANGLE
WEST
● JULY 1
○ 2
+ 3
△ 12
◘ 13
⊕ AUG. 6
× 10

FIG. XI

FIG. XII

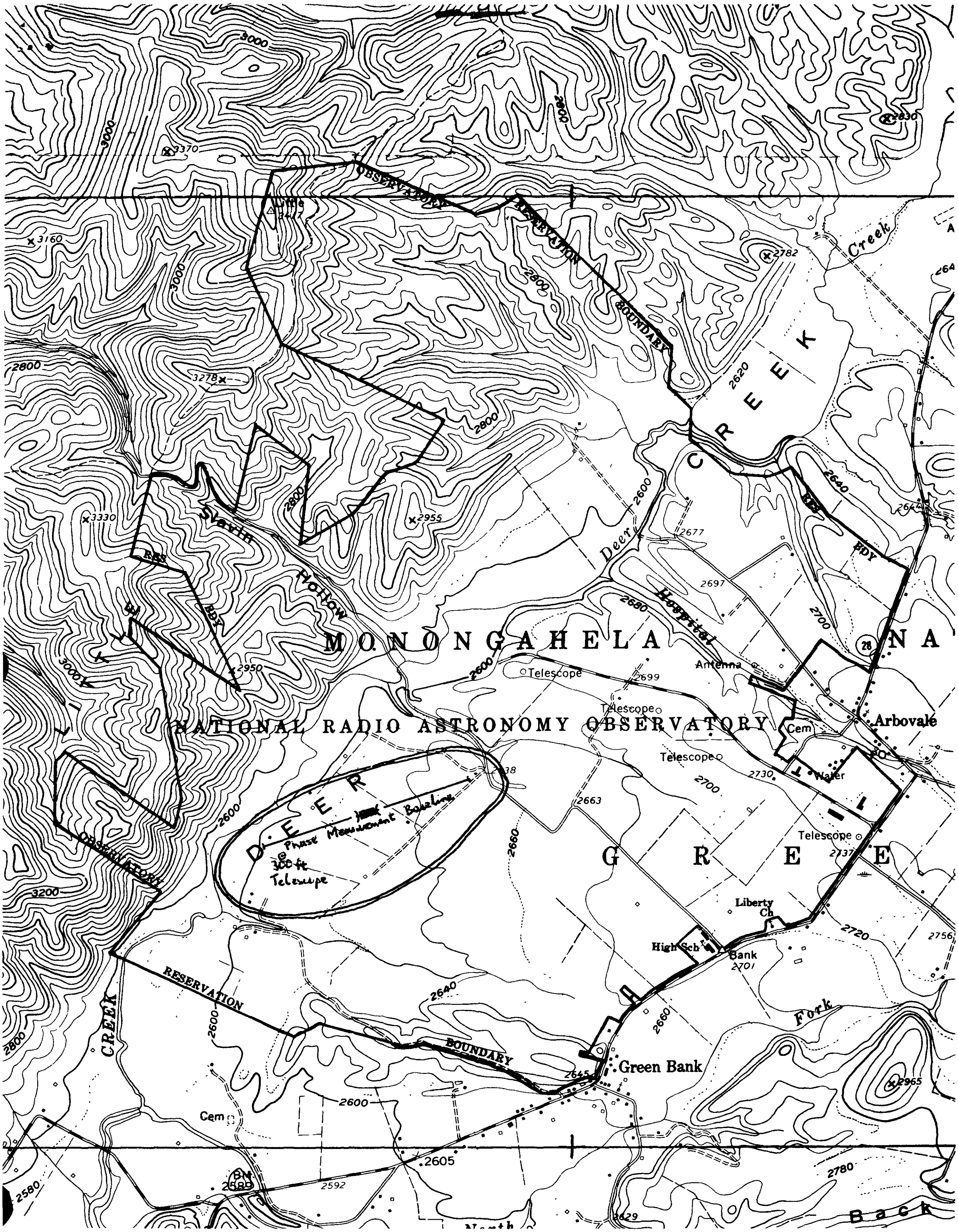


SQ = ZERO CROSSING DETECTOR WHICH GIVES < 0.3° PHASE JITTER. CLOCK PULSES GATED BY LEADING EDGE OF PULSES FROM SQ.



NOT DRAWN TO SCALE

FIG. XIII



Phase Measurement Baseline
300 ft Telescope
DEER
OBSERVATORY RESERVATION BOUNDARY
RES BDY
MONONGAHELA NA
NATIONAL RADIO ASTRONOMY OBSERVATORY
GREE
CREEK
Deer Creek
Svavin Hollow
Hospital
Telescope
Telescope
Telescope
Telescope
Antenna
Cem
Water
Arbovale
PO
Liberty Ch
High Sch
Bank
Green Bank
Cem
BM
Fork
Back
North
28
3000
3370
3417
3160
2800
3278
3330
2955
2950
3000
3200
2830
2782
2620
2640
2600
2677
2697
2680
2700
2699
2730
2663
2660
2738
2737
2720
2756
2701
2645
2605
2592
2589
2580
2629
2780
2965

FIG. XIV