

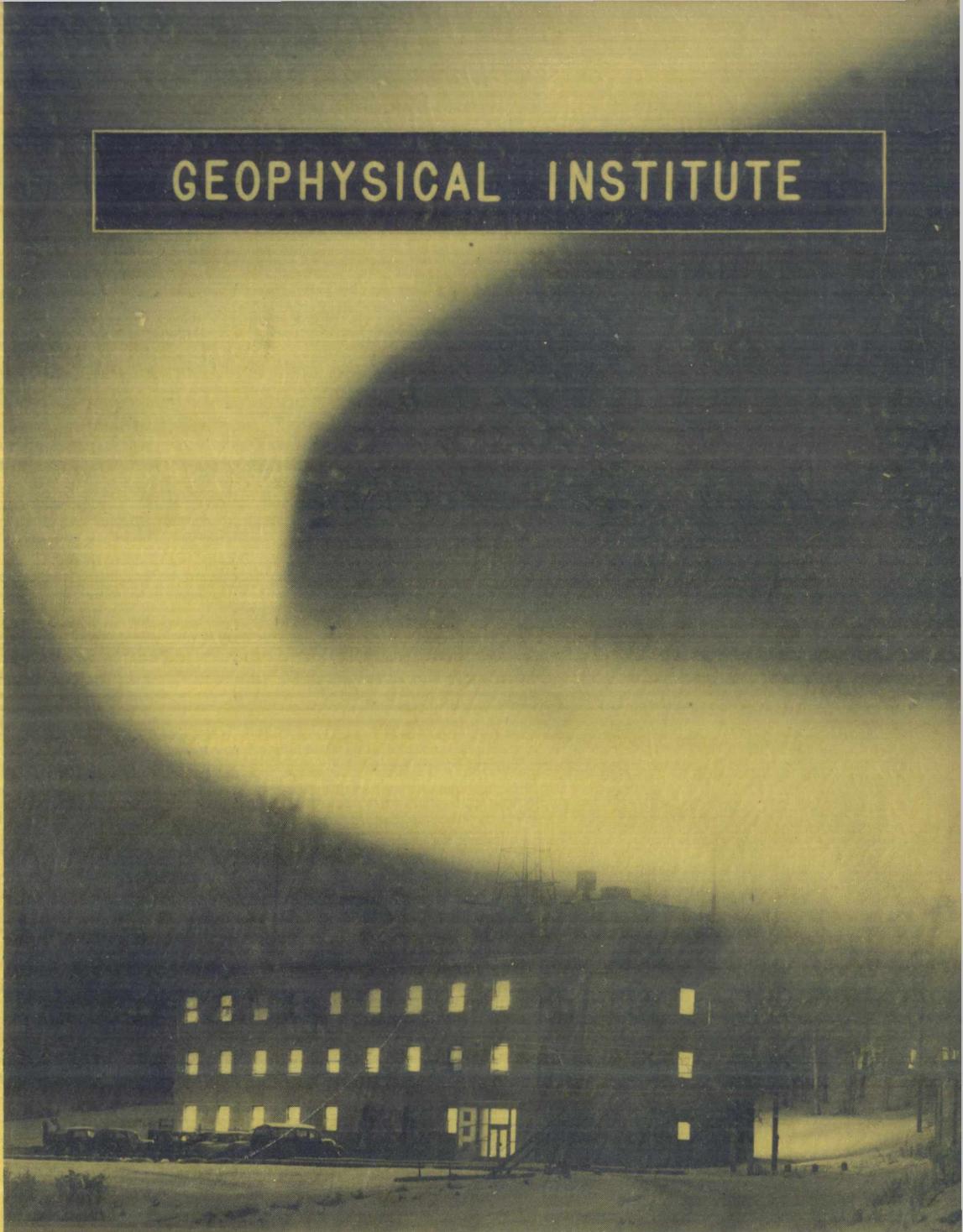
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RADIO PROPERTIES OF THE AURORAL IONOSPHERE

Final Report (Phase I)

February 1959

Air Force Contract No. AF 30(635)-2887

Project No. 5535 - Task 45774

Rome Air Development Center
Griffiss Air Force Base
Rome, New York

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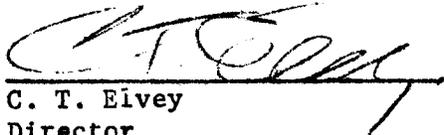

C. T. Eivey
Director

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ABSTRACT AND GENERAL INTRODUCTION

It has been found in recent years that a study of the fluctuations in the signals received from radio stars affords a powerful means of investigating the irregular structure of the ionosphere. In 1955 studies of this type, using frequencies of 223 Mc and 456 Mc, were initiated at the Geophysical Institute, with a view to investigating the small-scale structure of the highly disturbed auroral ionosphere. The purpose of this report is to present a complete description of the initial experimental arrangement. Further developments of the equipment and some results of analysis of the data have been presented in Quarterly Progress Reports covering the period since 1 June 1956.

The report is divided into three sections. Section I contains a description of the basic philosophy of the experiment with an elementary discussion of the various parameters involved. Section II contains a brief description of the actual field installation, and Section III is devoted to the electronic design features.

The diagrams pertaining to each section are located at the end of the section.

Major staffing on this project during the period covered by this report has been:

Project Supervisor	C. Gordon Little G. C. Reid (since July 1, 1958)
Assistant Project Supervisor	Robert P. Merritt
Early construction and installation of 223 Mc equipment	John Lansinger J. H. Pope
Early construction and installation of 456 Mc equipment	Ernest Stiltner
Routine operation since summer of 1956	Ernest Stiltner
Electronic technicians	Don Dyer Norman Sanders

SECTION I

Investigation of the Ionosphere Using Extraterrestrial Radio Sources

1.1 Introduction

The conventional method of ionospheric investigation relies on the return of a transmitted radio signal by a reflecting layer in the ionosphere. While the information provided by such experiments has formed the basis of our knowledge of the upper atmosphere, the method itself imposes certain inherent limitations on this information. For instance, the outer regions of the ionosphere, above the F2 region maximum, are completely inaccessible to ionospheric sounding techniques, and also very little information can be obtained regarding the fine scale structure of any region of the ionosphere. Such information might readily be obtainable from the study of VHF or UHF radio waves which had traversed the entire ionosphere, between transmission and reception. This condition is fulfilled by the radiation from the so-called 'radio stars', which for the present purpose can be considered as merely extraterrestrial noise sources of small angular dimensions.

The intensity of the radiation received from the radio stars at any frequency often shows irregular fluctuations of variable amplitude and period. These fluctuations, which at first were thought to be caused by variations in the intensity of the source itself, were soon shown to be produced by localized irregularities in the ionization of the upper ionosphere.⁽¹⁾ The phenomenon is thus analogous to the twinkling of optically visible stars, and is usually described as radio star 'scintillation'.

Most of our basic knowledge concerning the irregularities responsible for these scintillations has come as a result of investigations carried out at Cambridge and Manchester, England, and in Australia. Summaries of the

results of this work, with complete bibliographies, have appeared in the literature^(3,4), and will not be discussed here except to remark that many of the discrepancies in the observations have been attributed to differences in the latitude of the ionospheric regions traversed by the line of sight to the source. In particular, scintillation activity appeared to be much more pronounced when the line of sight approached the auroral zone⁽⁵⁾.

The basic purpose of the present experiment is the investigation of radio star scintillation phenomena as observed within the auroral zone. The results of this investigation should contribute materially to our knowledge of the conditions existing in the highly disturbed auroral ionosphere. College is particularly well situated for this work since it lies close to the center of the normal auroral zone, and the lines of sight to the major northern radio stars intersect the upper ionosphere in a range of latitudes encompassing the entire auroral zone.

1.2 Extraterrestrial Sources

Four major extraterrestrial radio sources are visible at the latitude of College. The names and positions of these sources are listed in Table 1, together with an estimate of the flux densities S , in watts meters⁻² (c/s)⁻¹, as quoted by Whitfield⁽⁶⁾ for a frequency of 100 Mc.

Table 1: The Intense Radio Sources of the Northern Sky

<u>Source</u>	<u>R.A.</u>		<u>Decl.</u>		$\frac{S}{\times 10^{-25}}$
	h	m	°	'	
Cassiopeia-A	23	21	+58	32	1900
Cygnus-A	19	58	+40	36	1180
Taurus-A	05	31	+21	59	170
Virgo-A	12	28	+12	40	178

These radio stars, unlike optically visible stars, are not point sources, but subtend appreciable angles as seen from the earth, and consequently their positions in the sky cannot be specified very accurately. Measurements by various observers^(7,8,9) have indicated that the Cygnus source has the smallest angular dimensions of those tabulated above, having a diameter of about 1' of arc. The Cassiopeia, Taurus and Virgo sources respectively have diameters of about 4', 4' and 5'. The angular dimensions of the source might be expected to have an appreciable effect on the magnitude of the observed scintillation. If the angular diameter of the source is much larger than the angular dimensions of a single ionospheric irregularity as seen by an observer, then no scintillation would be produced, since the scintillation of different parts of the source would be uncorrelated. As the source diameter decreases the degree of scintillation will increase, becoming a maximum for a point source. An optical analogy is the lack of visible twinkling of the planets, which have appreciable angular dimensions as seen from the earth.

Previous estimates of the size and height of the ionospheric irregularities responsible for radio star scintillation have indicated that angular dimensions of the order of a few minutes of arc are quite possible, and preliminary observations at College have confirmed that the observed scintillation amplitude is indeed dependent on the angular dimensions of the source.

Radio-frequency spectra:

Reliable information concerning the frequency spectrum of the radiation from even the most intense radio stars is rather scanty. Recent work

by Whitfield⁽⁶⁾, however, has shown that a frequency dependence of the general type

$$S \propto f^\alpha$$

gives a good representation of the spectra of the major radio stars at frequencies above 30 Mc. Here S is the flux density received on the earth, f is the frequency, and α is a constant for any particular source, varying from one source to another. Whitfield's results for the four intense northern sources are summarized in Table II.

Table II. Spectral Characteristics of the Four Intense Northern Radio Stars.

<u>Source</u>	<u>Flux Density at 100 Mc</u> ($\times 10^{-25} \text{ w m}^{-2} (\text{c/s})^{-1}$)	<u>α</u>
Cassiopeia A	1900	-0.80
Cygnus A	1180	{ -0.66 ($f < 350 \text{ Mc}$) -1.02 ($f > 350 \text{ Mc}$)
Taurus A	170	-0.28
Virgo A	178	-0.74

These results can be used to predict the signal which will be received from any of the above radio stars at any frequency, using an antenna of known characteristics and a receiver of known bandwidth.

Apparent Positions:

At the latitude of College ($64^\circ 52' \text{ N}$), the two most intense sources (hereafter referred to as Cassiopeia and Cygnus) are circumpolar, so that continuous monitoring of their signals can be carried out. The maximum and minimum elevations of the four sources above the horizon (neglecting refraction effects) are shown in Table III.

Table III. Maximum and Minimum Elevations of the Sources as Seen from College.

<u>Source</u>	<u>Maximum</u>			<u>Minimum</u>		
Cassiopeia	83°	40'	S	32°	24'	N
Cygnus	65°	38'	S	15°	22'	N
Taurus	47°	18'	S	below horizon		
Virgo	38°	03'	S	below horizon		

Fig. 1.1 shows a plot of elevation as a function of azimuth for various declinations; the apparent tracks of the four radio stars are shown by broken lines. The elevations of the sources at upper meridian transit are given by the intersections of the broken lines with the vertical line corresponding to an azimuth of 180° (south).

As the year progresses, the upper meridian transit of each source will occur at progressively earlier local standard times, the shift amounting to approximately 4 minutes per day. Throughout the course of one year, upper transit will have occurred at all hours of the day for any source. This is illustrated in Fig. 1-2, which shows the Alaska Standard Time of upper transit of the four sources at College as a function of time of year.

1.3 Instrumental Techniques for the Study of Radiation from Radio Stars:

A simple high-gain receiver fed by an antenna directed towards any point in the sky will record a signal containing five components:

- (1) noise due to the equipment itself;
- (2) background galactic noise;
- (3) radiation of terrestrial origin, including that from transmitters whose frequency is in the pass-band of the receiver;

(4) radiation from the sun;

(5) radiation from radio stars located in the antenna beam.

The last of these differs from the others in having its origin in a source of small angular dimensions, and this fact makes its separation relatively easy. In principle, this separation could be carried out partially by using an antenna with a beam-width comparable with the angle subtended by the source itself. Such an antenna, however, is very difficult to construct, and problems involved in tracking a radio source would be enormous.

Interferometer Methods:

The use of interferometer techniques has proved much more fruitful in the study of radio stars, and even fairly weak sources can be detected using quite simple interferometers. The simplest type of interferometer consists of a sensitive receiver connected to two identical antennas separated by a distance of several wavelengths. The radiation pattern of the two antennas consists of a multiplicity of lobes, the envelope of whose maxima is the radiation pattern of a single antenna. The lobe structure is caused by interference between the waves incident on the two antennas, alternate maxima and minima being produced when the direction of the source is such that these waves have a phase difference of $n\pi$ (n integral). The power received from a point source by a simple total-power interferometer of this type can easily be shown to be given by

$$P = P_0 \left[1 + \cos \frac{2\pi d \sin \phi}{\lambda} \right]$$

where P_0 is the power received by a single antenna from the same source, d is the antenna separation, λ is the wavelength, and ϕ is the angle between the line of sight to the source and the normal to the interferometer baseline

in the same plane. To this received power must be added that received from all the other sources listed above, so that the radio star signal appears as a periodic waveform superimposed on a steady background level.

This background of non-coherent signals can be eliminated by use of the phase-switching technique introduced by Ryle⁽¹⁰⁾. The basic phase-switch interferometer (see fig. 3-1) uses two antennas connected via cables of equal electrical length to a common receiver. An extra half wavelength of cable is alternately switched in and out of one antenna cable at some low switching frequency, usually in the audio range. This has the effect of interchanging maxima and minima of the interferometer lobes at the switching frequency, so that if a point source is present in the antenna beam, the receiver output will contain a switching frequency component whose amplitude at any given time will be a function of the signal from the point source. This low frequency signal is amplified in a selective audio amplifier tuned to the switching frequency.

As the apparent position of the source moves, due to the rotation of the earth, the phase of this signal relative to that of the switching voltage will vary continuously, and by feeding the audio amplifier output into a phase sensitive detector and using the switching voltage as a reference, a DC voltage is produced which is a positive maximum when the two signals are in phase and a negative maximum when they are 180° out of phase. When they are in phase quadrature, the output will be zero.

A pen recorder on the output of the phase sensitive detector will thus record a quasi-sinusoidal waveform as a point source passes through the interferometer lobes; the amplitude of this waveform is proportional to the signal received from the source, and its frequency is determined by the

angular separation of the lobes, i.e. by the antenna separation in wavelengths. A full theoretical treatment of the phase-switch interferometer will be found in Ryle's paper⁽¹⁰⁾.

Fig. 1-3 shows typical examples of phase-switch interferometer records produced by the Cygnus radio source at a frequency of 223 Mcs.

Advantages of the phase-switch interferometer:

The phase-switch interferometer possesses certain very attractive properties which have caused it to become perhaps the most widely used instrument for radio star tracking. In the first place, while any source whose angular dimensions are small compared with the width of an individual lobe is recorded, sources whose angular dimensions are larger than this produce no output, since different portions of the source give rise to signals of opposite phase which interfere destructively. Hence the contribution of the general galactic noise background to the recorded signal is eliminated, provided that this background possesses no structure of dimensions comparable with the lobe size. As the galactic noise can be many times larger than the desired radio star signal, this represents a major advantage over the simple total power interferometer. Secondly the system is comparatively insensitive to man-made interference, especially when this is present on only one antenna. Certain types of interference, however, cannot be suppressed, and their effects must be tolerated. The interference produced by electrical storms is of this nature, as is the radio-frequency radiation from the disturbed sun, though the latter can usually be identified by the sinusoidal trace it produces as the sun moves through the interferometer lobes. If the radio stars of interest are sufficiently far from the ecliptic plane (e.g. Cassiopeia and Cygnus) and fairly directive

antennas are used, the sun is rarely a major source of interference. However, if the stars are in or close to this plane (e.g. Taurus and Virgo), observation may be impossible at certain times of year, especially when frequencies in the upper part of the VHF region are being used.

A third advantage of the phase-switch interferometer over the simple total power system arises from the fact that when the waves incident on the two antennas are in phase quadrature, the output of the phase sensitive detector becomes zero. Knowing the spacing between the interferometer lobes, the time intervals between crossings of the zero line can be predicted, thus giving a measure of angular position. The actual crossing times have been found to fluctuate about the predicted times, corresponding to an apparent fluctuation in the position of the radio star. This effect is caused by the same diffraction mechanism as that responsible for the amplitude scintillations, and will be referred to as angular scintillation of the radio star.

The phase-switch interferometer thus gives us information on two different aspects of scintillation: (a) amplitude scintillation, or variations in the power received from a radio star, and (b) angular scintillation, or variations in the instantaneous angle of arrival of the wave-front from a radio star. Unfortunately, these two types of information are not available continuously, or even simultaneously, since we obtain maximum amplitude information when the waves incident on the two antennas have a phase difference of $n\pi$ (n integral) and pure phase, or angle of arrival, information only when this phase difference becomes $(n + \frac{1}{2})\pi$. Since these two conditions are mutually exclusive, the two types of scintillation can be compared only on a statistical basis, and not directly. This difficulty can

be removed by extending the phase-switching technique to that of phase-sweeping, in which the interferometer lobes are swept continuously across the antenna beam, instead of merely interchanging positions. By using this technique, continuous amplitude and phase information can be obtained. Equipment of this type has been described in an earlier report⁽¹¹⁾ and will not be further discussed here.

A fourth advantage over the total power interferometer lies in the suppression of the receiver noise component in the recorded output. At the higher frequencies in the absence of interference, this noise becomes the largest component in the output of a total power interferometer, and variations in its magnitude can completely swamp the radio star signal, as can variations in the gain of the receiver. A further difficulty arises in the case of the total power interferometer when large resolving powers and consequently large antenna separations are required. This comes about because of the introduction of considerable attenuation in the two antenna cables, and leads to a further decrease in the radio star signal relative to the receiver noise. In theory, this could be overcome by the use of separate preamplifiers at each antenna, having sufficient gain to compensate for the cable loss. In practice, however, these preamplifiers would be required to have extremely stable gains and noise figures to be usable. In the phase-switch case, however, these requirements become very much less stringent, and any reasonable antenna separation can be used, suitable preamplifiers being employed to boost the signal at the receiver input to any desired level. The restrictions on variations of the preamplifier gains and noise figures in the phase-switch case are such that they shall contain a negligibly small Fourier component at the switching frequency. This condition is normally realized without any special attention to design.

1.4 Interferometer Parameters:

Three basic parameters are involved in the design of any twin-wave interferometer. These are:

- (1) the characteristics of the individual antennas;
- (2) the spacing between the antennas;
- (3) the orientation of the baseline, or line joining the antennas.

In choosing the type of antenna, two factors must be borne in mind - the operating frequency and the degree of directivity required. These two quantities are related by the equation

$$g = \frac{4\pi A}{\lambda^2}$$

where g is the antenna gain in a particular direction, A is the effective receiving area of the antenna for the same direction, and λ is the wavelength. Hence in theory it is possible to achieve any desired gain in a chosen direction at a given wavelength merely by making the effective antenna area sufficiently large. In practice, however, the required area increases as the square of λ , and becomes prohibitively large for high-gain antennas at long wavelengths.

A fairly high degree of directivity is desirable for the purposes of this experiment in order to obtain as large a signal as possible from the radio star under observation, and also to exclude as far as possible the effects of the other intense radio stars and of solar and man-made interference. For practical purposes, the radio stars in the northern sky are four in number, and the degree to which any one of them can be selected for study is illustrated in Table III, which lists the angular separations between them as seen from the earth.

Table III. Angular Separations between the Intense Radio Stars.

Source	CASS		CYG		TAU		VIR	
CASS	-		36°	23'	72°	32'	107°	13'
CYG	36°	23'	-	-	100°	36'	97°	53'
TAU	72°	32'	100°	36'	-	-	97°	52'
VIR	107°	13'	97°	53'	97°	52'	-	-

Since Cassiopeia and Cygnus have a much greater intensity than the other two sources, and since their angular separation of 36° 23' is the smallest of all the separations, the major requirement for observation of these sources is that the effective beamwidth of the antenna shall be considerably less than this amount. If we wish to observe the other two sources, however, the elimination of possible side lobes in the direction of the much stronger Cassiopeia and Cygnus sources is essential. In order to avoid interference from solar noise, the minimum distance of the sun from the source must be considerably greater than the antenna beamwidth. It can readily be shown that the minimum angular separation, X, between the sun and a star of declination δ and right ascension H is given by

$$\sin X = \frac{\cos I \sin (\delta - \delta_s)}{\cos \delta_s} ,$$

where I is the inclination of the ecliptic to the celestial equator ($23 \frac{1}{2}^\circ$), and δ_s is the declination of the sun when its right ascension is H. Substituting appropriate values for Cassiopeia and Cygnus into this equation, we find that the closest approaches of the sun to each of these sources are respectively 55° and 59°, so that with a fairly narrow beam, little solar

interference is to be expected under normal conditions. Under very disturbed solar conditions, however, occasional interference may occur when the sun is near its position of closest approach to the sources, i.e. in March for Cassiopeia, and in January for Cygnus. In contrast, the sun passes within 1° of the Taurus source in June, and within 15° of the Virgo source in October, and observation of these sources would become extremely difficult even with highly directive antennas.

The two frequencies which have been chosen for this investigation are 223 Mc and 456 Mc. At these frequencies, a sufficiently directive beam is achieved by the use of dipole antennas, mounted at the focus of 28 ft. paraboloidal reflectors. The approximate beamwidth, θ , of a parabolic antenna of this type between half-power points is given in degrees by

$$\theta = \frac{7 \times 10^4}{fD}$$

where f is the frequency in megacycles and D is the aperture diameter in feet. For a 28-ft. paraboloid, this relation gives values for the beamwidth of about 11° at 223 Mc and 6° at 456 Mc.

When directive antennas are employed, the necessity for tracking the source arises. Each antenna is provided with a polar drive mechanism which moves the antenna beam along a circle of constant declination at the rate of one complete revolution per sidereal day. The details of the antenna mounts will be described in a later section.

Antenna spacing:

In any twin-wave interferometer, the antenna spacing alone determines the angular width of the lobes when the operating frequency is given. Obviously, the width of the individual lobes must be larger than the angular width of the source. If this condition is not satisfied, different portions of the source will produce audio signals of different phases at the phase sensitive detector input, and the visibility of the interference fringes will decrease. On the other hand, if the individual lobes are very wide, the number of zero crossings per hour becomes small, and angular scintillation information is lost. Also, if the lobes become too wide, any structure which exists in the galactic noise background may become noticeable, leading to obscuration of the star signal.

The interferometer to be described uses an antenna separation of 300 feet at both operating frequencies (223 and 456 Mc). This separation produces 135 lobes from horizon to horizon in the E-W plane through the antennas at 223 Mcs and 277 lobes at 456 Mcs. The minimum angle between phase-quadrature positions (corresponding to zero crossings on the output recording) is 25' at 223 Mcs and 12' at 456 Mcs.

Orientation of the interferometer baseline:

In designing an interferometer to study angular scintillation or to make absolute measurements of ionospheric refraction, it is important to remember that only one component of refraction can be measured. This component is orthogonal to the lobe structure in the direction of the source. Information about the component at right angles to this can be obtained only by the use of a second interferometer on an orthogonal baseline.

In common with most interferometers currently in use for radio astronomical studies, the present equipment has an east-west antenna baseline in order to obtain the maximum number of lobe crossings for any celestial source. Hence the refraction component measured is horizontal for a source at meridian transit, and vertical for a source rising in the east or setting in the west. The addition of a second interferometer on a north-south baseline would allow measurement of the horizontal refraction component at rising and setting, and the vertical component at meridian transit.

Figs. 1-4 and 1-5 show the lobe structure of the interferometers which are now in operation at College. Assuming that the cables to the two antennas are of equal electrical length in one switch position, then the relation between the angle to the baseline normal, ϕ , and the interferometer parameters is given by

$$d \sin \phi = n \lambda$$

where d is the antenna spacing and λ is the wavelength. For a lobe maximum, n is an integer. The hyperbolic curves in Figs. 1-4 and 1-5 are loci of constant n , and have been drawn at intervals of $n = 10$ for 223 Mcs and $n = 20$ for 456 Mcs.

The altitude and azimuth of a star of known declination δ as seen by an observer at latitude Λ are given by

$$\begin{aligned} \sin \alpha &= \sin \Lambda \sin \delta + \cos \Lambda \cos \delta \cos H \\ \sin \theta &= - \frac{\cos \delta \sin H}{\cos \alpha} \end{aligned}$$

where α is the altitude, θ is the azimuth from north, and H is the hour angle of the star past meridian transit. θ is measured positively to the east of north and negatively to the west of north.

The broken curves in Figs. 1-4 and 1-5 are the apparent tracks of the four intense northern radio stars as seen from College.

1.5 Limitations on Accuracy

Theoretical limitations on detectable amplitude scintillation:

An inherent limitation is placed on the amount of scintillation which can be detected in the signal from any radio star. This limitation arises from the random nature of the signal itself and of the noise from the galactic background and from the receiver, and results in an absolute maximum signal-to-noise ratio attainable from any specified equipment looking at a given radio star.

By using simple arguments, Dicke⁽¹²⁾ and Ryle and Vonberg⁽¹³⁾ have shown that the fluctuation in the noise power received in a simple system will be approximately $(t \cdot \Delta f)^{-1/2}$ of the mean noise power, where Δf is the effective input bandwidth of the system and t is the output time-constant. Their reasoning may be summarized by saying that in using a bandwidth of Δf cycles per second, we effectively obtain Δf independent readings per second. By averaging over a time t , we are measuring the mean of $(t \cdot \Delta f)$ independent readings, and by simple statistical theory, the fluctuation in this mean value is $(t \cdot \Delta f)^{-1/2}$ times the mean value.

In evaluating the expected signal-to-noise ratio in our case, it is more convenient to work in terms of antenna temperature rather than directly in terms of power. If the power incident from a source is S watts $m^{-2} (c/s)^{-1}$, then the power delivered into a receiver of bandwidth Δf by an antenna of effective area A is given by

$$P = \frac{1}{2} SA \Delta f \quad (1)$$

Here S specifies the total radiation incident having all polarizations; the antenna, which operates on a single polarization, absorbs only half of this.

The power delivered in the same bandwidth by a resistor at ambient temperature T_A is given by

$$P = kT_A \Delta f \quad (2)$$

Eliminating P between these equations, we have

$$T_A = \frac{SA}{2k} \quad (3)$$

where T_A is now the increase in the effective temperature of the antenna due to the radio star.

The effect of the galactic background is to raise the antenna temperature by a further amount T_G , and the noise of the receiver itself will produce an extra equivalent temperature of $(N-1)T_O$, where N is the noise factor of the receiver and T_O is usually taken as 300°K. The total power at the receiver input is then given by

$$P_o = k \Delta f \left[T_A + T_G + N T_O \right] \quad (4)$$

In practice, at the frequencies with which we are concerned, T_G is very much less than $N T_O$, and can be ignored.

The RMS fluctuation present at the receiver output is then

$$\Delta P = gk \Delta f \left[T_A + N T_O \right] (t \cdot \Delta f)^{-1/2} \quad (5)$$

where g is the total gain of the system.

In the case of the phase-switch interferometer, the situation is rather more complicated. The use of the switching technique effectively means that we are receiving useful information for only half of the total time, so that as far as random noise is concerned, the number of independent

readings per second is $\frac{1}{2} \Delta f$ instead of Δf . This has the effect of increasing ΔP in equation (5) by a factor of $\sqrt{2}$. Also, since we make use of two preamplifiers, ΔP is doubled. The combined effect of these two factors is to change equation (5) to:

$$\Delta P = 2.8 g k \Delta f \left[T_A + N T_0 \right] (t. \Delta f)^{-\frac{1}{2}} \quad (6)$$

Using a single antenna, the signal power present at the output due to the radio star would be

$$P = g k \Delta f T_A \quad (7)$$

The maximum output of the phase-switch interferometer will be four times this amount, since the signals present at the two antennas are in phase, so that

$$P = 4 g k \Delta f T_A \quad (8)$$

Combining equations (6) and (8), we obtain an expression for the maximum signal-to-noise ratio

$$\left(\frac{\Delta P}{P} \right)_{\max} = \frac{1.4 T_A (t. \Delta f)^{1/2}}{T_A + N T_0} \quad (9)$$

It should be noted that this is the signal-to-noise ratio when the signals received at the two antennas are either in phase or 180° out of phase. At other times, this ratio will have a smaller value, becoming zero at phase quadrature.

In order to use equation (9) to find the minimum detectable scintillation, we must find T_A for each of the four northern radio stars at each of the operating frequencies (223 and 456 Mcs). This has been found by

using equation (3) and taking Whitfield's (6) values of the spectral indices for each of the sources (see page 4). The effective area of each antenna was taken as 30 m^2 (0.5 times the geometrical area), giving a value for $(A/2k)$ of $10^{24} \text{ watts}^{-1} \text{ m}^2 \text{ sec}^{-1} \text{ deg}$. In calculating $(P/\Delta P)_{\text{max}}$, the receiver noise factor was taken as 4, the input bandwidth as 600 kcs, and the output time constant as 1 second.

The results are summarized in Table IV below:

Source	$T_A^{(223)}$	$T_A^{(456)}$	$(P/\Delta P)_{\text{max}}^{(223)}$	$(P/\Delta P)_{\text{max}}^{(456)}$
Cassiopeia A	100° K	57° K	19 db	17 db
Cygnus A	67	38	18	15
Taurus A	13	11	11	10
Virgo A	9.8	5.7	9.6	7.2

The signal-to-noise ratio which can be achieved in practice has been found to show quite good agreement with the above optimum values. For instance, when observing Cygnus at 223 Mcs, the noise is expected to be 18 db below the star signal, or about one sixtieth. The observations carried out at College have shown that this figure is not unreasonable.

Theoretical limitations on detectable angular scintillation:

The small inherent fluctuations in the output signal discussed above will also place a theoretical limitation on the observable angular scintillation, equivalent to a slight flutter in the apparent position of the radio star. To take a very simple example, assume that the form of the output trace produced by a radio star close to meridian transit is a pure cosine wave, so that

$$P = P_{\text{max}} \cos \left(\frac{2\pi\theta}{\alpha} \right) \quad (10)$$

where P is the chart reading at any instant, P_{\max} is the maximum chart reading (corresponding to the crossing of a lobe maximum), θ is the angle of the star past the preceding lobe maximum, and α is the angle corresponding to the succeeding lobe maximum. The slope of the curve is given by

$$\left| \frac{dP}{d\theta} \right| = \frac{2\pi}{\alpha} P_{\max} \sin \frac{2\pi\theta}{\alpha} \quad (11)$$

The maximum slope occurs when the trace crosses the zero line, i.e. when

$(2\pi\theta / \alpha) = n\pi / 2$, and then

$$\left(\frac{dP}{d\theta} \right)_{\max} = \frac{2\pi}{\alpha} P_{\max} \quad (12)$$

The times of zero crossing are used to determine the apparent angular scintillation of the source, as has been mentioned above, so that any fluctuation in the record, ΔP , will produce an uncertainty in the position of the source, $\Delta\theta$.

The relation between these quantities is given by

$$\Delta\theta = \Delta P / \left(\frac{dP}{d\theta} \right)_{\max} \quad (13)$$

leading to

$$\Delta\theta = \frac{\alpha}{2\pi} \left(\frac{\Delta P}{P_{\max}} \right) \quad (14)$$

The quantity $(\Delta P/P_{\max})$ is the reciprocal of the maximum signal-to-noise ratio, values of which have been listed in Table IV above.

For example, P_{\max} is about 18 db greater than ΔP for the Cygnus source at 223 Mcs, so that $(\Delta P/P_{\max})$ is about 0.016 under optimum conditions.

The value of α for the first maximum in the record after transit in the case of the 223 Mcs interferometer is about 0.015 radians, so that we have

$\Delta\theta \simeq 3.7 \times 10^{-5}$ radians, or about 0.13 minutes of arc. This represents

the theoretical limit of accuracy obtainable in measuring the instantaneous position of Cygnus A under the conditions described above. At positions other than near meridian transit, the source crosses the interferometer lobes more slowly, so that $(dP/d\theta)_{\max}$ is less than the above value, leading to a correspondingly higher value for $\Delta\theta$.

Practical experience in measuring angular scintillations has shown that the equipment is capable of giving results which are very close to this theoretical limit.

Practical limitations on accuracy:

In addition to the inherent theoretical limitations in accuracy which have been discussed above, there are certain experimental sources of error which can be minimized by careful attention to design. In theory, the angular position of any lobe maximum relative to the interferometer baseline can be calculated to any required degree of accuracy using the formula

$$\mu d \sin\theta = n\lambda \quad (15)$$

where μ is the refractive index at the antennas, d is the length of the baseline, θ is the angle between the direction of the lobe maximum and the baseline normal, and n is an integer. This differs from the equation on page 15 only by the inclusion of the local refractive index μ , which differs only very slightly from 1 (a typical value for College is about 1.00032). The above formula is only exact for small values of θ , where the plane-earth approximation is valid. In order to calculate the refraction correction for a curved earth, we require not only the local refractive index but also the refractive index profile with height, including the effects of ionospheric refraction. Refraction is expected to become a major source of error only

at low angles of elevation, and no further discussion of its effects will be given here save to refer to a paper by McCready, Pawsey and Payne - Scott⁽¹⁴⁾, in which typical refraction corrections for the troposphere are given for low angles of elevation. These corrections are expected to be independent of frequency in the range with which we are concerned. The combined effects of tropospheric and ionospheric refraction for radio sources at low angles of elevation within the earth's atmosphere have recently been computed by Millman⁽¹⁵⁾. His results can fairly readily be adapted to the case when the source is at infinity.

Apart from the gross uncertainty in source position due to atmospheric refraction, it may be argued that variations in tropospheric refractive index could be responsible for part of the observed scintillation. No detailed examination of this point has been made, but the effects are expected to be very small. The linear dimensions of the turbulent irregularities in tropospheric refractive index responsible for optical star scintillation are of the order of 5 cm, and their height can be taken as about 4 km⁽¹⁶⁾, so that their dimensions are small compared with both the wavelength (66 cm at 456 Mcs) and the antenna separation, and their angular size is small compared with that of the radio stars. In this connection, it is interesting to note that Kazes and Steinberg⁽¹⁷⁾ have reported a phenomenon analogous to scintillation in recordings of solar radiation at a frequency of 9350 Mcs ($\lambda = 3.2$ cm). This scintillation showed a marked dependence on meteorological conditions, and was presumably tropospheric in origin.

The quantities λ and d in equation (15) must be known to a high degree of accuracy if an accurate calculation of lobe position is to be carried out. Since a finite bandwidth must be employed, this requires accurate

definition of the 'centre of gravity' of the band of wavelengths. The geometrical baseline length is known to within 1/4 of an inch in 300 feet, and the constancy of this baseline in both length and orientation has been fairly well assured by the precautions taken in constructing the antenna towers (see next section). However, the true interferometer baseline is given by the line joining the foci of the two parabolic reflectors, i.e. the electrical centers of the dipole antennas. Since the reflectors pivot about a point considerably removed from this, it is obvious that the dipoles describe an arc of a circle as the antennas track the radio source. An difference in relative positioning of the dipoles in the two reflectors will thus produce an apparent diurnal change in baseline length and orientation. Precautions have been taken to avoid this effect, and it is now thought to be of negligible importance. From observations of radio stars at high angles of elevation, when second-order refraction effects can be neglected, the ratio of λ to d can be measured and compared with the predicted value. These measurements indicate an error of only about 1.5 parts in 10^4 .

A more serious potential source of error arises from differential phase drift between the two arms of the interferometer. Consideration of this point is of special importance in regard to the measurement of angular scintillation, since here we are concerned with small random changes in phase, between the two received signals which could easily be masked by differential phase shifts occurring in the equipment. The method which is currently being used to measure angular scintillation^(18,19) should be independent of any steady component of phase drift, but any sudden changes in this drift having a period of the order of an hour or less would be highly undesirable. The tolerance we require in this respect can easily be estimated.

On page 20 the theoretical limiting accuracy in measuring the angular scintillation of Cygnus at 223 Mcs was estimated at 0.13 minutes of arc. If this limit is to be realized in practice, rapid differential phase changes must be small compared with $(2\pi / \lambda) d \sin \theta$, where $\theta = 0.13$ minutes of arc. Inserting appropriate values for λ and d , we find that the phase shifts must be less than 1 electrical degree, corresponding to an effective change in cable length at 223 Mcs of about 4 mm. Since differential phase shifts can occur in the preamplifiers and mixers as well as in the cables, this might seem to be a fairly stringent requirement. However, it must be stressed that we are confirming ourselves to short-term phase shifts. Differential phase drifts over long periods undoubtedly do occur because of the extreme temperature variations at College, if for no other reason, but their significance is not great as far as the present experimental program is concerned. Actual measurements of angular scintillation⁽¹⁹⁾ have shown that the theoretical limit imposed by noise is closely approached, and that short-period differential phase drift is not of major importance.

Another source of error might arise from zero drift and gain drift of the final DC amplifiers. Special attention was paid to this point in the design of the DC amplifiers, as will be described in Section III, and its importance for the measurement of amplitude and angular scintillation is thought to be negligible.

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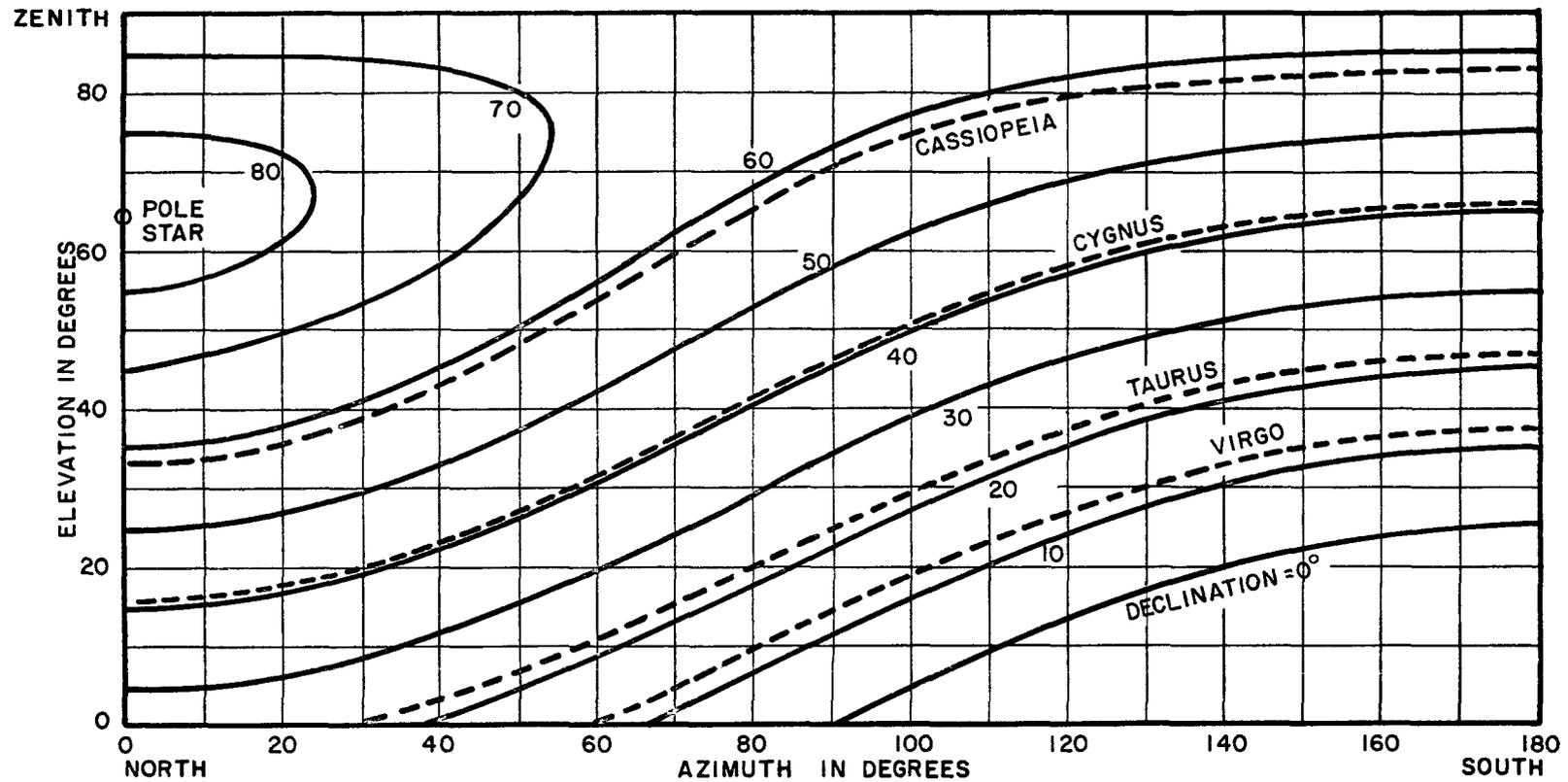


Fig. 1-1. Azimuth-elevation plot for observer at latitude of College, Alaska (65°N).

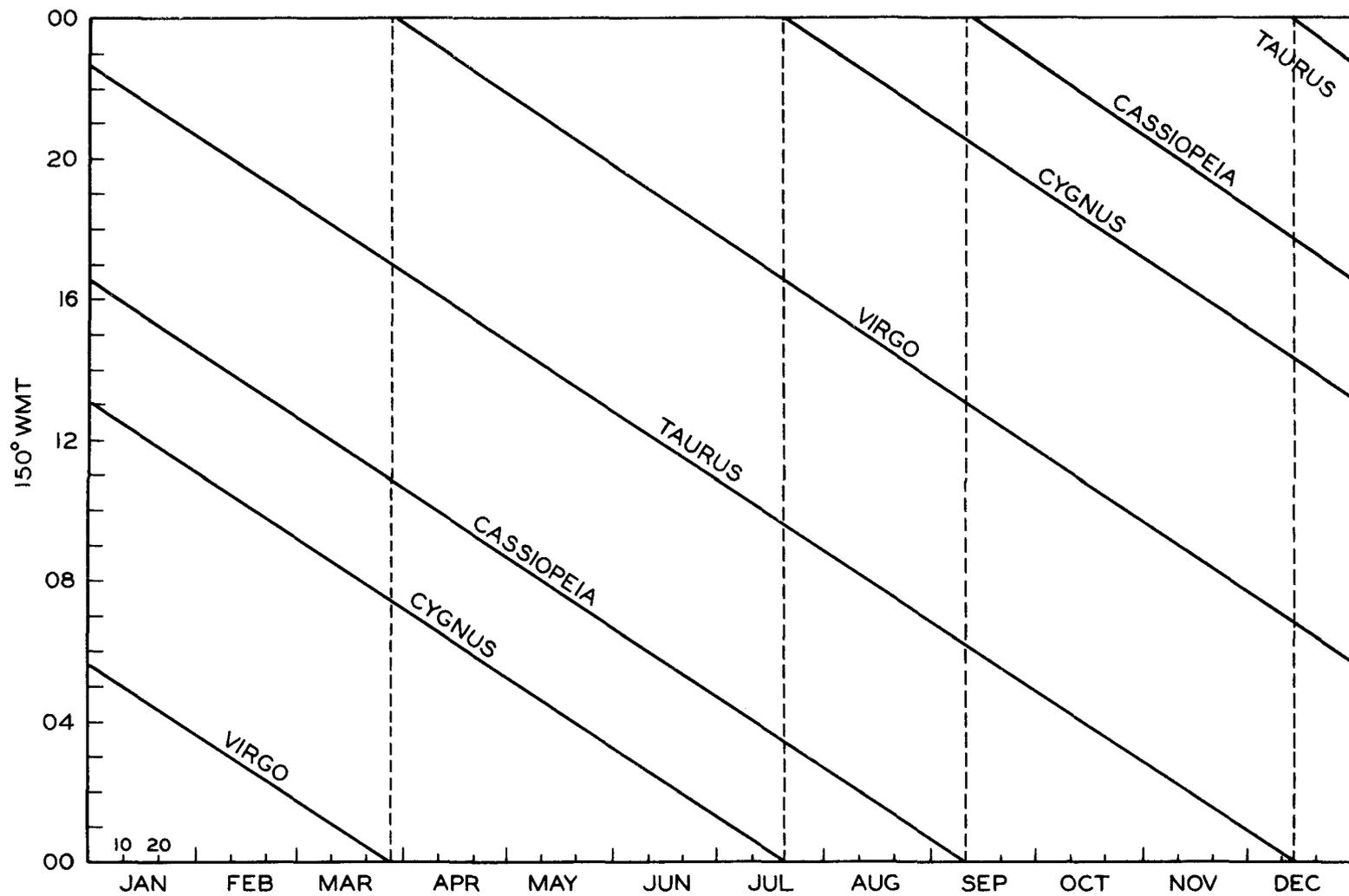


Fig. 1-2. Time of upper meridian transit of the four intense northern radio stars at College, Alaska.

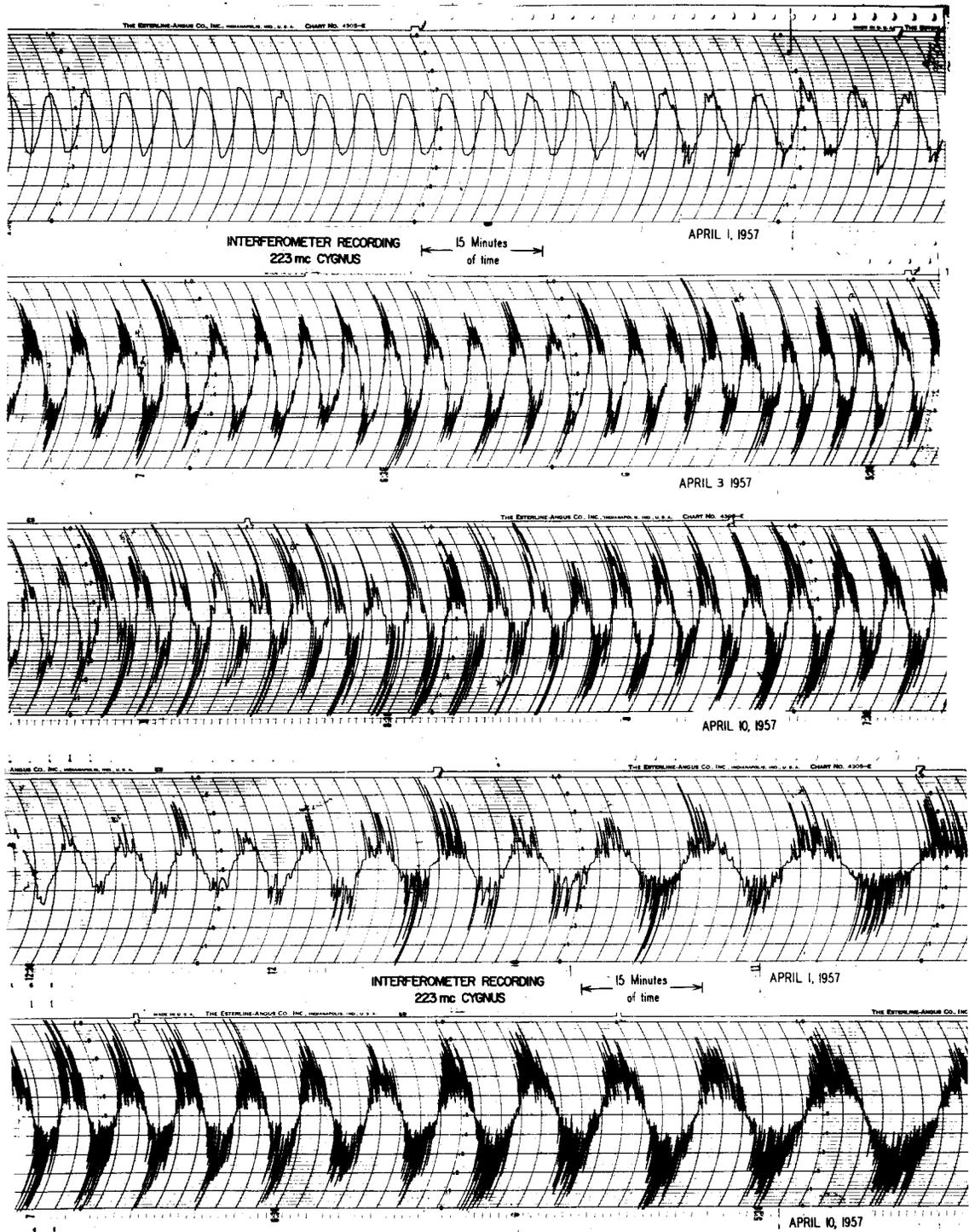


Fig. 1-3. Typical recordings from phase-switch interferometer at 223 Mc.

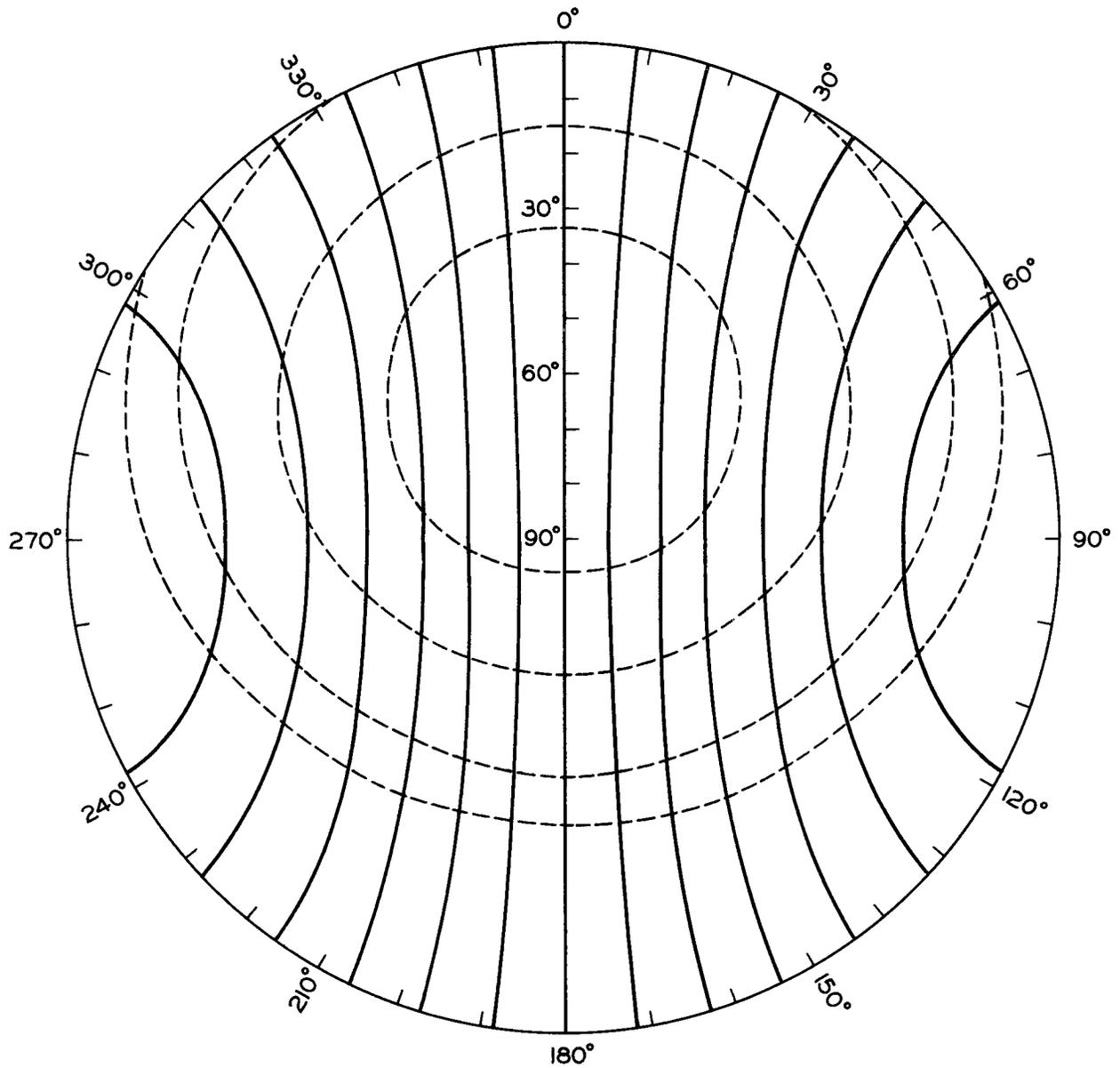


Fig. 1-4. Lobe structure of the 223 Mc interferometer. The solid curves represent every tenth lobe. The concentric broken curves represent the apparent tracks, as seen from College, of Cassiopeia, Cygnus, Taurus and Virgo, numbered outwards from the center.

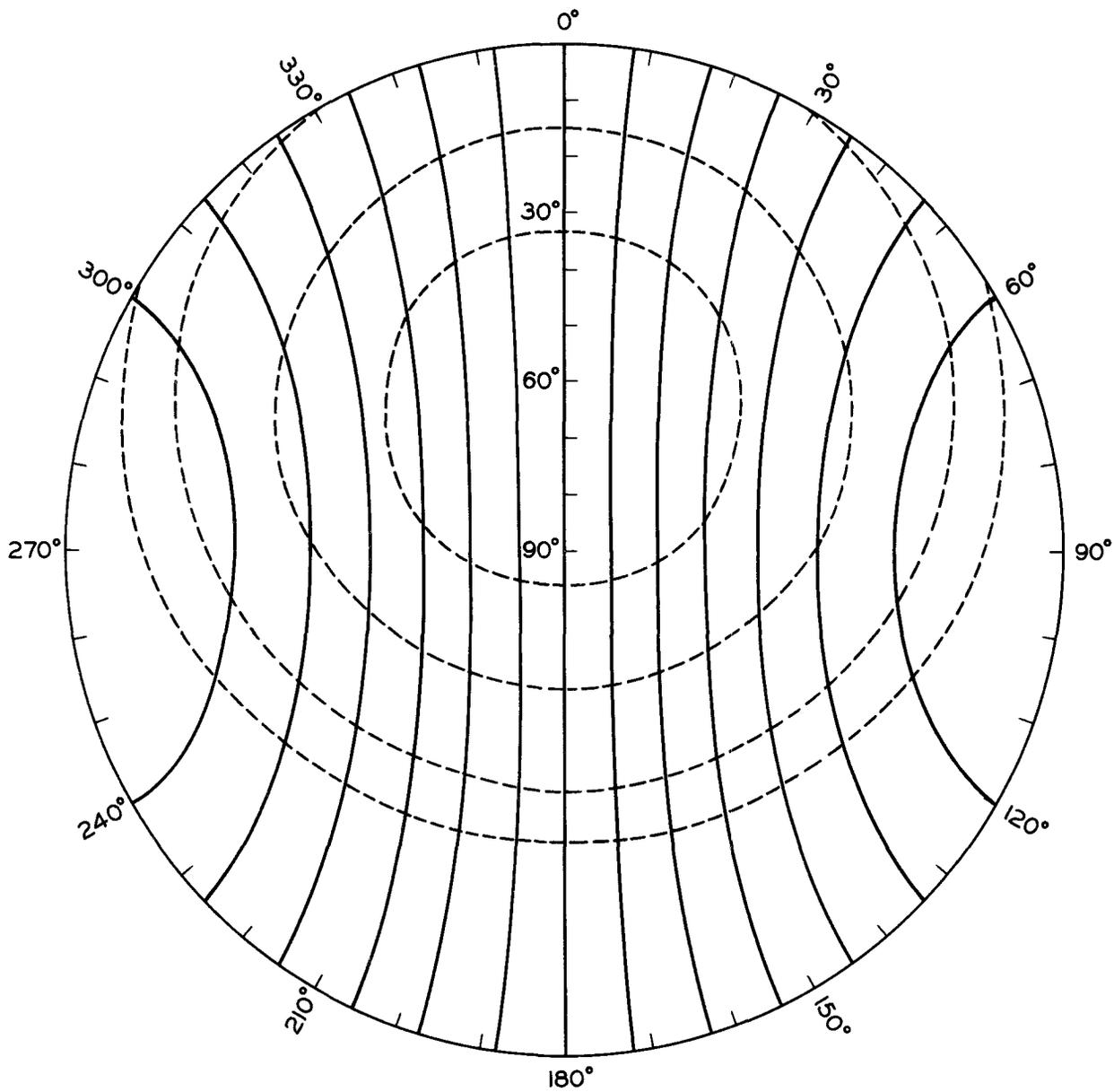


Fig. 1-5. Lobe structure of the 456 Mc interferometer. The solid curves represent every twentieth lobe. The broken curves are as in Fig. 1-4.

SECTION II

The Field Installations

2.1 Introduction:

The choice of location for a permanent field site in a relatively flat area such as the neighborhood of College is governed by three main factors. In roughly decreasing order of importance these are: (a) availability of power, (b) physical accessibility, and (c) ground conditions. A fourth highly desirable feature would be the availability of telephone communication, and in the case of a receiving site, freedom from radio interference. With these factors in mind, it was decided to locate the interferometer equipment at the Ballaine's Lake field site of the Geophysical Institute. This location satisfied most of the requirements listed above, though the ground conditions, which are typical of those encountered in interior Alaska, are far from ideal. The methods which have been employed to overcome the adverse effects of the ground conditions will be described later.

The site is located about one mile north of the Geophysical Institute, and while reasonably remote from heavily-traveled highways, is very easily accessible.

Construction began in the late summer of 1955 with clearing of a short access road and of the radio-telescope site itself. The area contained a heavy growth of small trees (mostly aspen and birch with assorted low bushes and spruce), and clearing was easily accomplished by a large bulldozer, and later extended by a small tractor.

2.2 The Radio-Telescope Towers:

The interferometer antennas comprise two Model 437 28-foot Radio-Telescopes purchased from D. S. Kennedy and Co., Cohasset, Mass. Initial plans for the mounting of the antennas called for fairly massive concrete pedestals, but a survey of the local ground conditions showed that these would probably not meet the rigid tolerances for location and freedom from movement.

Analysis of drillings from two 50-foot test holes showed the ground to consist of permanently frozen silt (permafrost) overlain by nearly saturated muck and silty alluvium. The permafrost table lay at a depth of about 20 feet. If a massive concrete structure were erected on this ground, it would be impossible to avoid subsequent settlement of the nearly liquid soil above the permafrost, and it was decided to use instead lighter steel structures which could be frozen into the permafrost. The decision was also influenced by the high cost of concrete in interior Alaska.

Wooden piles would have been preferable to steel piles for this purpose, since wood is a very poor conductor of heat, and once inserted, very little heat would be conducted into the permafrost. However, no convenient method was available for inserting wooden piling without thawing some of the ground, and this was thought to be undesirable. Steel pipes, on the other hand, could be "drilled-in" by standard well-drilling machinery. The material selected was standard 4-inch steel pipe which was readily available locally and had the further advantage that if any appreciable thawing of the permafrost due to conduction of heat down the piles did occur, refrigerating coils could be inserted in each pile to re-freeze the ground. Additional precautions taken against thawing included covering the ground with an

insulating layer of peat and painting the towers with a reflective coating to minimize heating.

Precautions were also taken against the effects of "heaving" of the top layer of soil during the winter due to the expansion of water on freezing. If the top layer were to grip the piles too tightly, the entire structure might move. To guard against this, the upper ten feet of each pile were wrapped with heavy building paper coated liberally with a melted rubber-asphalt compound to break the bond with the surface layer.

The towers themselves are rigid frameworks of welded 4-inch steel tubing, and are attached to the footings by couplings which were made into turnbuckles by forming a left-hand thread on one end. This construction allows a certain amount of adjustment to compensate for any misalignment which may occur. A horizontal play of 2 or 3 inches in any direction is possible, together with a vertical adjustment of about an inch at antenna level.

The design loads were evaluated from data provided by D. S. Kennedy and Co., designers of the antennas, and proved to be adequate for a winter wind of around 70 miles an hour, corresponding to the maximum steady wind ever recorded at Fairbanks.

The surveying of the baseline for the antennas was carried out with the greatest possible precision. The antennas were required to be on an east-west line whose azimuth was known to within 1/4 inch in 300 feet, corresponding to an angular error of about 13 seconds of arc. Such accuracy requires unusual care and excellent equipment, and can be achieved either by direct measurement from triangulation points established by the United States Coast and Geodetic Survey, or by observing accurately the apparent

position of some celestial object. Since a tie with the Geodetic Survey net would have required a trained field party and comparatively elaborate facilities, a stellar measurement was chosen as the most suitable means of establishing the desired line. Polaris was used as a sighting point both because of its proximity to the pole, and therefore its small angular velocity, and because it is very easily identified. The surveying was completed during the late summer of 1955, and the towers were erected in the early fall.

In addition to the stability and ease of construction of the steel framework towers, they have the further advantage over the concrete type that a small hut can be built into the base of each tower to house the first stages of the recording equipment, thereby eliminating the need for long RF cables. This arrangement reduces not only the attenuation in the input signal, but also the likelihood of differential phase drift between the antennas. The two 'end-huts' are small insulated enclosures whose temperature is thermostatically controlled, and they contain the RF preamplifiers and mixers together with a small amount of IF amplification at the common frequency of 32 Mcs. The 32 Mcs signals are brought to the central hut by lengths of RG 8A/U cable.

Fig. 2-1 shows a photograph of the complete installation of towers, antennas, end-huts and central hut.

2.3 The Antennas:

As was mentioned above, the interferometer antennas are two Model 437 28-ft Radio Telescopes supplied by D.S. Kennedy and Co., Cohasset, Mass. The reflectors are paraboloids of revolution constructed in the form of a

network truss system entirely of anodized aluminum tubing, and covered with expanded aluminum alloy mesh. Folded dipole antennas cut for frequencies of 223 and 456 Mcs are mounted at the foci of the paraboloids, orthogonal polarizations being used for the two frequencies. The radiation characteristics of the antennas have been discussed in Section I.

The antennas are equatorially mounted, and the driving mechanism, which will not be discussed in detail, permits tracking at constant declination at the rate of one revolution per 23 hours 56 minutes 5.8 seconds of mean solar time (i.e. one sidereal day). In addition, slew motors allow rapid movement of the antenna beam in both right ascension and declination to any pre-determined position; the rates of slew are respectively 0.131 RPM and 0.079 RPM, as compared with 0.000694485 RPM tracking rate. Polar limit switches automatically stop the tracking motors when the horizon is reached to avoid physical damage to the antennas.

The antennas are controlled from a console in the central hut, from which power is fed out to the polar and declination drive assemblies housed in the antenna mounting. To ensure proper operation of these drive mechanisms under the arctic conditions prevailing during the Alaskan winter, space heaters have been installed in the mounts, and very low viscosity grease is used for all moving parts during the winter months.

The installation of the antennas was completed during November 1955. During the course of this work, it was found necessary to rewire much of the control circuitry to minimize voltage drops, and to replace the original declination slew motors by special high starting-torque motors. Satisfactory operation has been maintained since these alterations were carried out.

The central hut, which houses the antenna control panels and the main part of the recording equipment, is situated midway between the two antennas. The building is fully insulated and the interior temperature is thermostatically controlled. 110 VAC 60-cycle power is at present supplied via an external transformer rated at 15 kw, and telephone facilities have been provided. The hut contains a work bench and a basic supply of tools and test equipment, so that maintenance and minor repairs to the equipment can be carried out locally.

2.4 Acknowledgements:

The work of clearing the site and surveying the antenna baseline, as well as the design and construction of the towers and footings were carried out under the supervision of Mr. E. F. Rice and Mr. C. Sargent of the Department of Civil Engineering of the University of Alaska.

Much of the descriptive material above concerning these phases of the project has been abstracted from their Engineering Report on Design, Construction and Surveying of Towers and Footings (Dec. 1956).

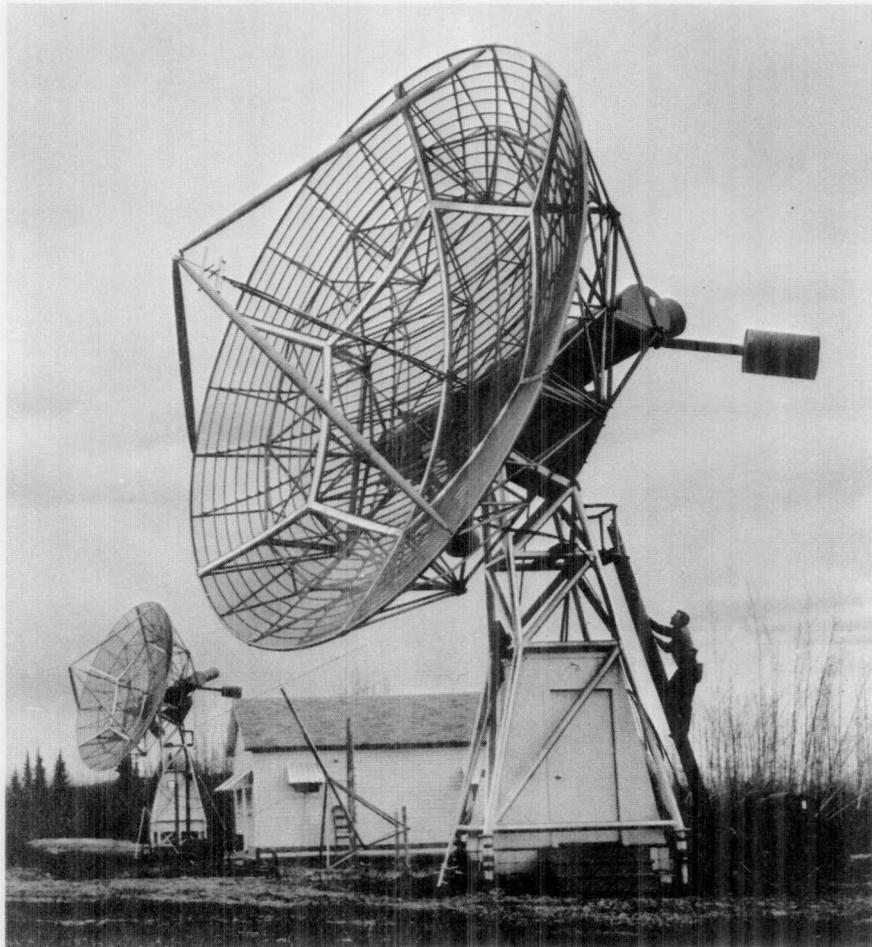


Fig. 2-1. The radio interferometer installation at Ballaines Lake Field Site.

SECTION III

Electronic Design of Phase-Switch Interferometers

3.1 Introduction

The receivers used with this project have been phase-switch interferometers which were designed according to the basic proposal by Ryle as has been discussed in Section I. A block diagram is given in Fig. 3-1 for the 223 Mc channel. Basic operation is as follows: a signal from a distant source (in this case a radio star) is picked up by both antennas and fed to the RF amplifiers. In the RF amplifier chassis, the signal is amplified in low-noise circuitry and converted to a 32 Mc IF signal by being mixed with a 255 Mc local oscillator frequency. Since the same local oscillator signal is used in both mixers, the phase coherence of any incoming signal is maintained at the intermediate frequency. The IF signal is fed to the center building where a phase-switch in one arm reverses the relative phase of the incoming signal in that arm through 180 electrical degrees once every 1/2200th second. The phase-switched IF signal and the IF signal from the other arm are added in a resistive adding pad and then amplified in a 32 Mc IF amplifier. The output of the IF amplifier is demodulated and the resulting audio signal is fed to an audio amplifier tuned to the phase-switching frequency. The output of the tuned audio amplifier goes to a phase-sensitive detector which derives its reference from the same source as drives the phase-switch.

A source of small angular size in the pattern of both antennas yields an 1100 cps signal at the tuned audio amplifier output due to the action of the phase-switch. The phase-sensitive-detector has a dc output proportional

to the input signal multiplied by the cosine of the phase angle between the input and reference signal which is, in turn, dependent upon the position of the source in the antenna lobe pattern. This dc signal is amplified in a dc amplifier with a time constant and fed to the pen recorder. Thus a recording is obtained of the amplitude of the source, or the position of the source in the interference pattern of the antenna system.

The equipment for 456 Mc is the same except for frequencies: RF amplifier: 456 Mc, local oscillator: 424 Mc; IF: 32 Mc; phase-switching frequency: 1000 cps. Because of this equipment similarity, the following discussion will be given only for the 223 Mc channel

3.2 223 Mc Phase-Switch Equipment

223 Mc preamplifier

The RF amplifier chassis (Fig. 3-2) for the 223 Mc channel consists of 3 stages of grounded grid amplification at 223 Mc, using 6AN4 triodes, a crystal diode mixer using a type 1N72 diode, and a single stage of amplification at the IF frequency of 32 Mc using a 6BZ6 RF pentode.

The RF circuitry is of standard grounded-grid design with impedance-matching taps on the cathode and plate coils in the RF section being chosen experimentally for optimum performance. The input of the first stage was adjusted for minimum noise figure as measured with a noise generator having 50Ω output impedance. The cathode tap for the second stage was likewise adjusted for minimum noise contribution from that stage. The third stage cathode tap was adjusted for maximum gain possible from that stage since the slightly higher noise contribution at this point would be negligible.

The bandwidth of the RF section is set large by the use of low values of Plate load resistances which shunt the tuned circuits.

The 223 Mc output of the last 6AN4 is fed into a crystal diode mixer where it is mixed with 255 Mc to obtain the difference frequency of 32 Mc.

The earlier operation of this equipment used a 191 Mc local oscillator frequency. During this early operation, considerable trouble was experienced from the local television station on Channel 11 with a carrier frequency of 199.25 Mc. This caused overloading of the amplifier plus the unusual trouble of the 4th harmonic of the beat between the television station frequency and the local oscillator frequency of 191 Mc falling within the passband of the IF amplifier. Some of the early steps taken to alleviate this television interference included the insertion of a band rejection filter between the second and third RF stages, and a cable filter between the antenna and the pre-amplifier. This cable filter was cut to be an even number of quarter wavelengths at the television frequency while an odd number of $\lambda/4$'s at the receiving frequency and was terminated with a short at the end. The result was that the short circuit would be presented to the television frequency while an open circuit would be presented to the reception frequency of 223 Mc. The combination of these two features gave reasonable rejection of the television signal. To circumvent these additional potentially troublesome circuits, the local oscillator frequency was later changed to 255 Mc which allowed the filters to be removed.

A measure of the local oscillator signal applied to the mixing diodes is obtained by continuous metering of the dc rectified current through the diode. The level was adjusted by starting out with a local oscillator signal of at least twice that necessary and attenuating this signal down to the proper

level with fixed pads. A crystal current level between 1/2 and 1 ma was found to be satisfactory for routine operation.

The output of the mixer is fed into a single stage of pentode amplification tuned to a center frequency of 32 Mc. Again a fairly low value of plate load resistance is used to obtain wide bandwidth.

The output of the 32 Mc amplifier is coupled to the chassis output by means of a 50 ohm link on the plate coil.

Local Oscillator (Fig. 3-3)

The local oscillator signal of 255 Mc is obtained by starting out with a 9,445 Mc signal and multiplying it by 27 in three stages of tripling.

The oscillator consists of a 6CL6 tube connected in an electron-coupled crystal-controlled circuit which develops enough power to drive the next 6CL6 stage with its plate circuit tuned for 28.335 Mc. The output from this first triple stage is used to drive a 6360 twin tetrode tube in push-pull with its plate circuit tuned to 85 Mc. The 85 Mc signal is fed to another 6360 push-pull tripler stage which develops the 255 Mc signal. The 255 Mc signal is divided in a minimum-loss resistive pad to obtain a signal for either pre-amplifier.

IF Preamplifier

A moderately high level signal was necessary for the original phase-switching chassis because of the high losses in the unit. To obtain the necessary level, IF preamplifiers, as in Fig. 3-4, were constructed for installation at each end hut for both frequencies.

These preamplifiers consist of three cascaded stages of common cathode amplification using type 6AH6 RF pentodes. The bandwidth of the entire amplifier chassis was deliberately made in the order of 4 Mc so that any effects of detuning due to aging components would be small.

The input and output links were adjusted for 50 ohm input impedances; a 3 db resistive pad was added to the output link to minimize the effects of aging components on the output impedance.

Phase-switch driver and phase-switch

The basic function of this unit (Fig. 3-5) is to alternately add or subtract 180 degrees of RF phase at the intermediate frequency of 32 Mc. This operation is performed by alternately routing the signal through either a one-half wavelength section of coaxial cable or through a one wavelength section of coaxial cable. The routing is determined by applying either short or open circuits to points one-quarter wavelength from the input in push-pull. The shorts or opens are obtained from a one-quarter wavelength driver cable which is terminated with 1N270 high-conductance diodes. Thus when the 1N270 diodes are driven into conduction, their low impedance is transformed by the driver cable into a high impedance at the phase-switching cable network and vice-versa. The technique of using the driver cables makes the impedances presented to the phase-switching network much larger or smaller than would be available from diodes alone.

Associated circuitry is a diode driving stage using a power triode in push-pull connection. Signal for this chassis is a push-pull square-wave which is obtained from the squaring amplifier.

32 Mc IF Amplifier

After the signal in one arm of the interferometer is phase-switched, both signals are added in a resistive 50 ohm minimum-loss adding pad and fed to the IF amplifier which is given in schematic form in Fig. 3-6.

The basic structure consists of five stages of common-cathode amplification feeding into a balanced demodulator.

The first two stages are standard video amplifiers designed for 50 ohm chassis input and to provide voltage gain. The next two stages consist of remote-cutoff pentodes in a variable-gain circuit. In this circuit, the cathodes obtain a bias voltage from a voltage divider from B+. A rotary switch and resistor arrangement was used to permit fixed gain steps, a feature which has proved useful in routine operation of the equipment.

This amplifier chassis has been modified for relatively narrow bandwidth from previous design by making the second 6BA6 plate load resistor large in comparison to the other. Thus bandwidth is determined by this stage.

The last amplifier stage provides more wide-bandwidth voltage gain and feeds to the balanced demodulator which consists of four 1N34 diodes in a full wave rectifier circuit. The demodulator output is integrated in a 10 microsecond RC network and fed to the output connector through an RF choke to minimize 32 Mc radiation.

1.1 Kc Amplifier and Phase-sensitive Detector

The output of the IF amplifier consists of receiver noise components passed by the ten microsecond integration and a small 1.1 kc square wave signal which carries the received signal information. This signal is amplified in the amplifier portion and fed push-pull to a phase-sensitive detector. The circuit for this chassis is given in Fig. 3-7. A signal is obtained from the same source as that used to drive the phase-switch, and is used as a reference signal for the phase-sensitive detector.

Operation of this circuit is as follows:

The circuit is basically a balanced-bridge network which is alternately turned on or off by the reference signal. With no input signal, the circuit has no residual dc output because the bridge is balanced. When an input signal is applied, the balanced condition is changed, depending on the relative times of conduction between signal and reference, since the input tends to reverse bias one of the conducting diodes. For the case of a sine-wave input signal, the interval of conduction is directly proportional to the cosine of the angle between the two signals, therefore, when the time constant in the output circuit is considered, an output signal is obtained which is dependent upon both the phase and magnitude of the input signal. For the condition of both signals being in phase (or 180° out of phase), the dc output signal will be a maximum, and for the condition of the two signals being 90° out of phase, the output will be zero because appropriate diodes will be conducting equal amounts of time. The dc output of the phase-sensitive detector is fed to the dc amplifier.

Tuning Fork Oscillator

The audio frequency used for driving the phase-switch and supplying a reference signal to the phase-sensitive detector is derived from a tuning fork oscillator as given in Fig. 3-8. The tuning fork is mechanically designed for resonance at the switching frequency of 1100 cps. The associated circuitry is designed to give a phase-stable positive feedback signal to the fork so as to maintain constant-amplitude oscillation. The output is fed to the squaring amplifier for driving the phase-switch and also to the reference voltage amplifier to provide a reference signal for the phase-sensitive detector.

1.1 Kc Squaring Amplifier

The signal from the tuning fork oscillator is amplified and clipped in this unit (Fig. 3-9) to provide a balanced square wave at the switching frequency for the phase-switch driver unit.

The input signal is divided into two parts - one to feed the reference voltage amplifier, and the other to be amplified by three stages of pentode gain, of which the last two clip the signal sharply so that a fast rise-time square-wave signal is developed. This square wave is fed to a split-load phase inverter which provides the push-pull signal to the phase-switch driver.

1.1 Kc Reference Voltage Amplifier

This chassis (Fig. 3-10) provides a controllable phase signal at the switching frequency as a reference signal for the phase-sensitive detector.

The signal from the squaring amplifier reference output is first fed into a phase-shifting amplifier which yields an output of constant amplitude with controllable phase. Operation of this phase-shifter is as follows: A push-pull signal is developed by the split load amplifier and fed into the phase-shifting network consisting of a RC network with values chosen so that for maximum resistance, a phase-shift of approximately 90° is obtained. When the resistance is decreased to zero, the signal obtained is essentially that from a cathode follower, i.e. the phase shift is zero.

After the phase-shifting stage, the signal is fed into a phase reversing stage which gives either a signal with zero phase-shift or else a signal with 180° of phase-shift. Again push-pull signals are developed in a split-load amplifier. The two signals are coupled to either end of a 500K potentiometer with the tap feeding the next stage. With the tap set close to the cathode end of the potentiometer, the signal has no phase shift. For the condition

of the tap set near the plate end, the signal will have a 180° phase-shift. Center position results in the two push-pull signals cancelling, so that the control also serves as a gain control.

DC Amplifier

The unit which has been used in the 223 Mc phase-switch equipment for the major portion of the operation time to date is given in schematic form in Fig. 3-11. The circuit is that of a two-stage balanced amplifier with direct coupling between the stages. A bias voltage of -150 volts is used to allow low-loss direct coupling between stages. The gain of this circuit is approximately five and stability is of the order of one to five percent per week, depending upon room temperature.

In an effort to increase the long-term stability of the equipment, all dc amplifiers have been replaced with a simpler circuit using two triodes in a single stage balanced circuit. This dc amplifier has a stability an order of magnitude better than the old circuit, and using only one twin-triode, needs no negative bias supply. The latter feature has allowed the removal of the minus 150 volt bias power supply, a unit which has been a source of trouble on several occasions.

The circuits of the old dc amplifiers for the 223 Mc total power, 456 Mc phase-switch, and 456 Mc total power are given respectively in Figs. 3-13, 3-23, and 3-25. These units have all been replaced with the single-twin triode amplifier previously mentioned with resultant increases in overall equipment stability.

Monitor

Early operation of the original equipment proved that there was some need for aural monitoring of the incoming signal plus a means of continuously recording the receiver noise level as a check on sporadic interference.

Both of these functions are provided by the monitor chassis, Fig. 3-12. An RF signal from the IF amplifier is amplified by two stages of RF gain, demodulated with the audio portion of the signal being fed to an audio amplifier and speaker and with the dc signal being fed to a total power dc amplifier which in turn feeds a pen recorder.

Thus an audio signal is obtained, which can aid in the identification of interference, and a continuous recording is obtained of receiver noise level plus any interference to serve as an indication of equipment operation.

Possibly something should be said of the various types of interference which have been encountered during the operation to date.

The early operation on 223 Mc showed the existence of an overloading effect from the local television station on Channel 11. During the times when the station was broadcasting, and the antennas were aimed in its general direction, the records were unusable for scintillation studies. After verifying that the station was not radiating spuriously, several types of filters to attenuate the television frequencies were tried. A tuned cable arrangement as described before was found most effective. The change in local oscillator frequency from 191 Mc to 256 Mc brought about a further reduction in television interference, since the 4th harmonic of the beat between 191 Mc and the television signal fell within the passband of the IF amplifier.

Sporadic interference has been received at 223 Mc from military aircraft and dispatching transmitters in the area.

Occasional interference is picked up on the 223 Mc channel from such sources as farm tractors, automobile and airplane ignition and improper operation of local equipment, plus some from unknown causes.

On the 456 Mc channel, early operation was plagued by a very low level signal, approximately equal to the star signal in magnitude, which appeared at random times. This was eventually traced to being the third harmonic of a local taxicab company operating around 152 Mc. This trouble was cleared up by contacting the transmitter operators.

To date, this frequency has been fairly free of interference with only occasional interruptions due to such items as vehicles and other local operations.

3.3 456 Me Phase-Switch Equipment:

The 456 Mc phase-switch equipment is identical to the 223 Mc equipment in basic operating theory and generally so in layout and operation.

The main differences arise in the operating frequency, which is 456 Mc instead of 223 Mc; the phase-switching frequency, 1000 c/s instead of 1100 c/s, and the local oscillator frequency of 424 Mc instead of 255 Mc for the 223 Mc equipment.

Schematics of the individual chassis are as follows:

456 Mc RF amplifier	Figure 3 - 14
424 Mc Local Oscillator	3 - 15
32 Mc IF Preamplifiers	3 - 16
32 Mc Phase-switch and Driver	3 - 17
32 Mc If Amplifier	3 - 18
1000 c/s Amplifier and Phase-Sensitive Detector	3 - 19
1000 c/s Tuning Fork Oscillator	3 - 20
1000 c/s Squaring Amplifier	3 - 21
Reference Voltage Amplifier	3 - 22
Phase-Switch DC Amplifier	3 - 23
Monitor chassis	3 - 24
Total Power DC Amplifier	3 - 25

Auxiliary equipment includes target transmitters for both frequencies, a sidereally-driven clock, a power supply for the 456 Mc RF chassis, and commercial dc power supplies and AC regulators.

3.4 Auxiliary Equipment

A valuable aid in tuning the equipment up to optimum performance has been the target transmitters, located a mile south of the receiving site. They are switched on and off from the receiving site by means of a land line.

The 223 Mc target transmitter, Fig. 3-26, starts with a crystal-controlled oscillator at 11.150 Mc, and multiplies the frequency by 20 in one stage of times five and two stages of times two. The amplitude of the output is controlled by returning the cathodes of both of the last two stages to an adjustable voltage-divider.

The 456 Mc target transmitter, Fig. 3-27, starts with a crystal oscillator at 38.000 Mc and multiplies this frequency by 12 to obtain 456 Mc. Output amplitude is controlled by varying the screen potential on the first 6AG5.

The sidereal clock uses two chassis to drive a wall clock at a sidereal rate. The generator, Fig. 3-29, has a tuning fork operating at 1203.2854 cps. This frequency is divided by 20 to obtain the sidereal clock frequency of 60.16427 cps.

The clock frequency is fed to a power amplifier, Fig. 3-30, which develops enough power to drive one or two clocks as desired.

Fig. 3-31 gives the schematic of the power supply for the 456 Mc RF chassis which provides power for the 416B and also for the IF preamplifier. A special feature of the circuit is the turn-on sequence for the 416B power. When power is first applied to the chassis, heater current to the 416B is fed

through both a ballast tube and 5 ohm resistor, and a 47 ohm resistor is shunted across the heater to ground. With this arrangement the current through the heater of the tube is limited to the operating level even when the heater is cold. As soon as the B+ power supply reaches proper voltage, a relay in the 416B heater circuit is operated to put this part of the circuit in full operation.

While this procedure has been going on, a negative protective bias of greater than cutoff voltage has been applied between the cathode and grid of the 416B. After a time delay determined by V8, during which the heater circuit has gone into operating condition, the protective bias is slowly decreased at a rate determined by C4 and R2 to the proper operating bias of the tube as determined by the setting of R2. Thus the 416B tube always operates well within the manufacturer's recommended limits even though there is no one present after power interruptions.

BLOCK SCHEMATIC OF 223mc AND 456mc PHASE-SWITCH INTERFEROMETERS

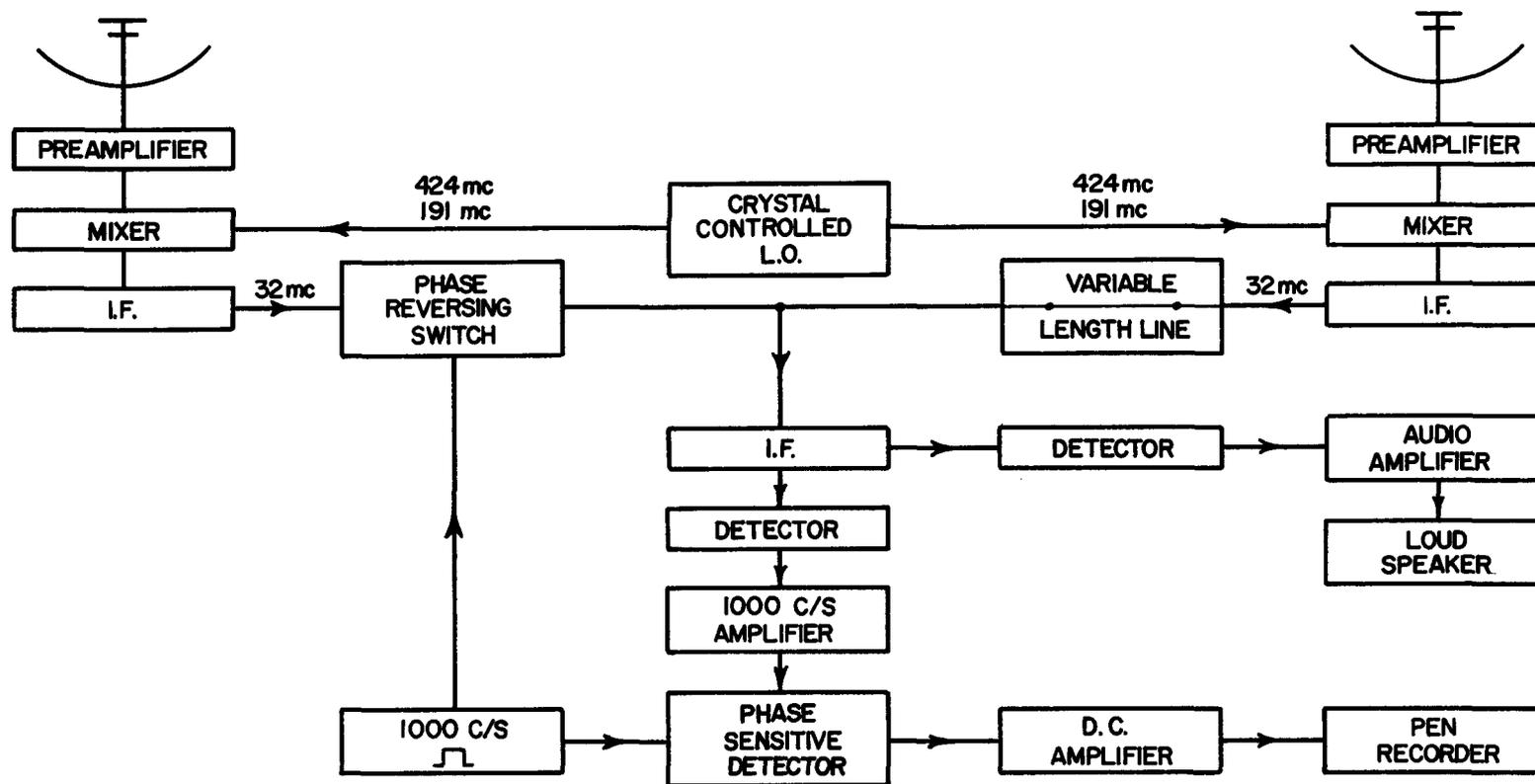
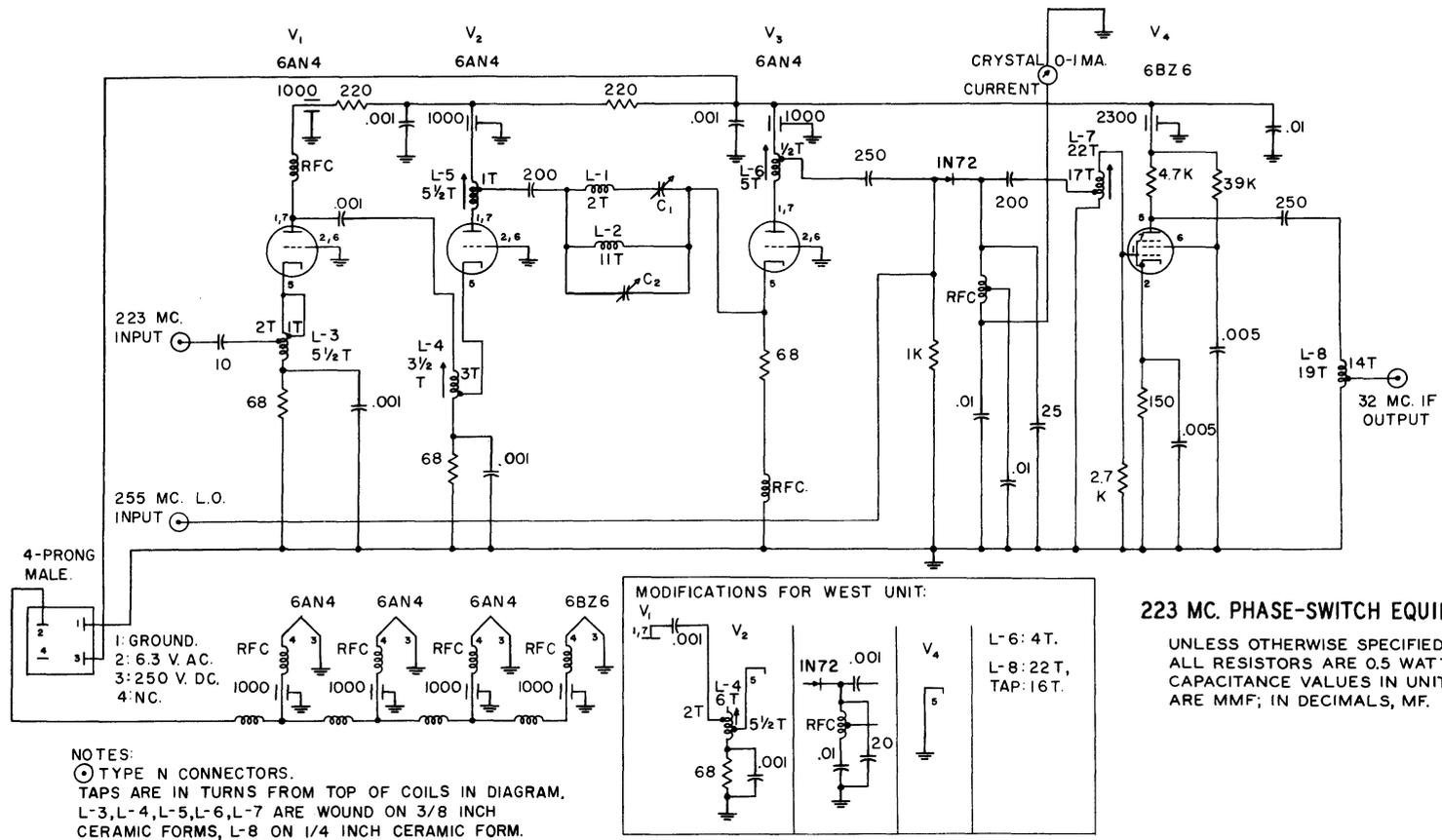


Fig. 3-1



EAST HUT PREAMPLIFIER.

Fig. 3-2

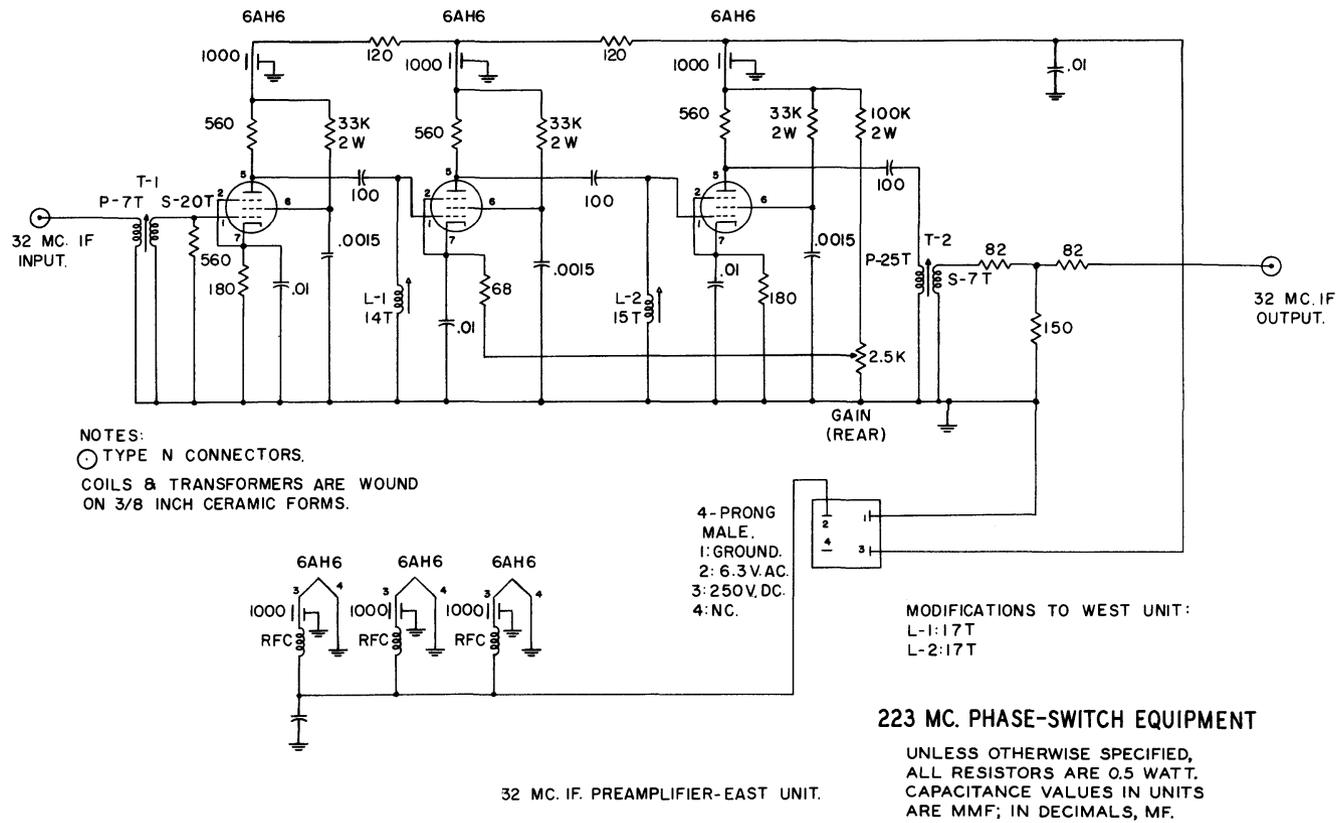
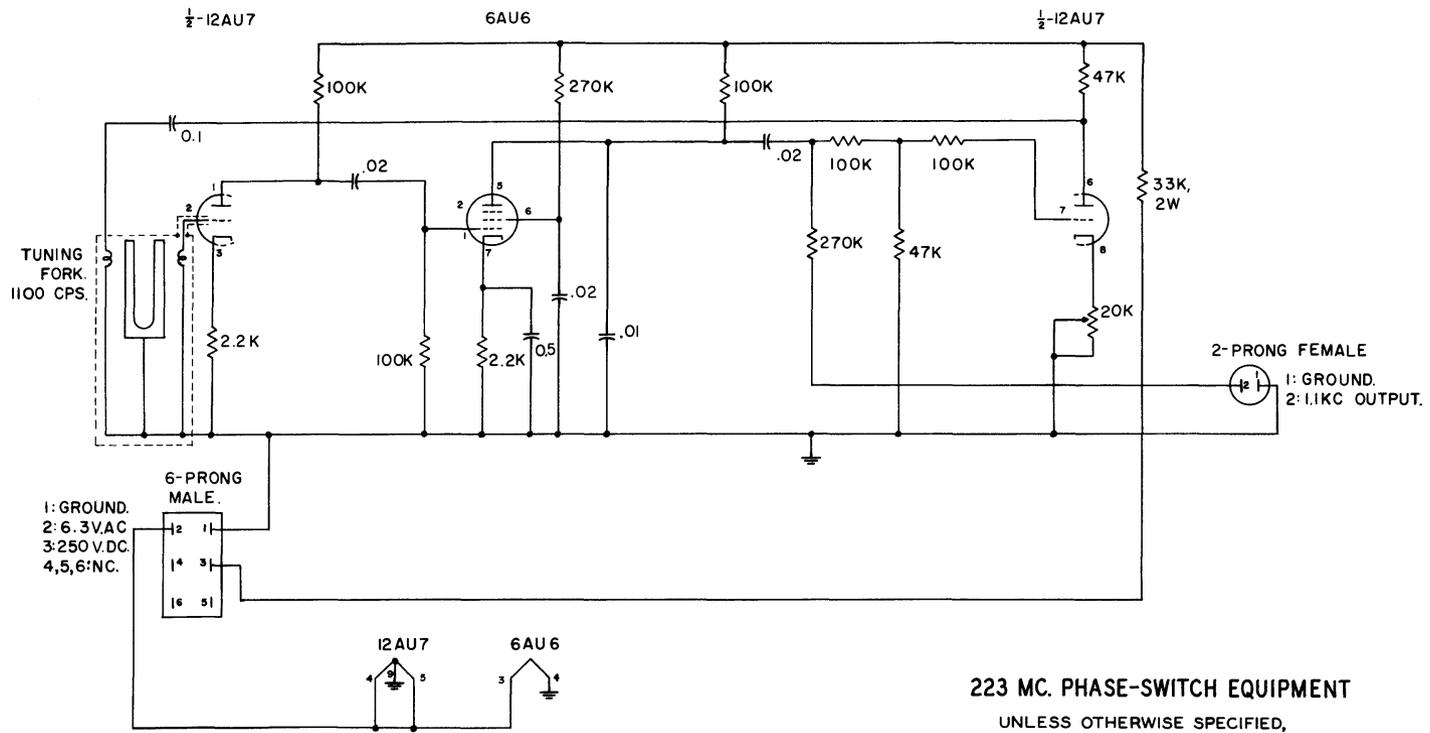


Fig. 3-4



223 MC. PHASE-SWITCH EQUIPMENT

UNLESS OTHERWISE SPECIFIED,
 ALL RESISTORS ARE 0.5 WATT.
 CAPACITANCE VALUES IN UNITS
 ARE MMF; IN DECIMALS, MF.

TUNING-FORK OSCILLATOR.

Fig. 3-8

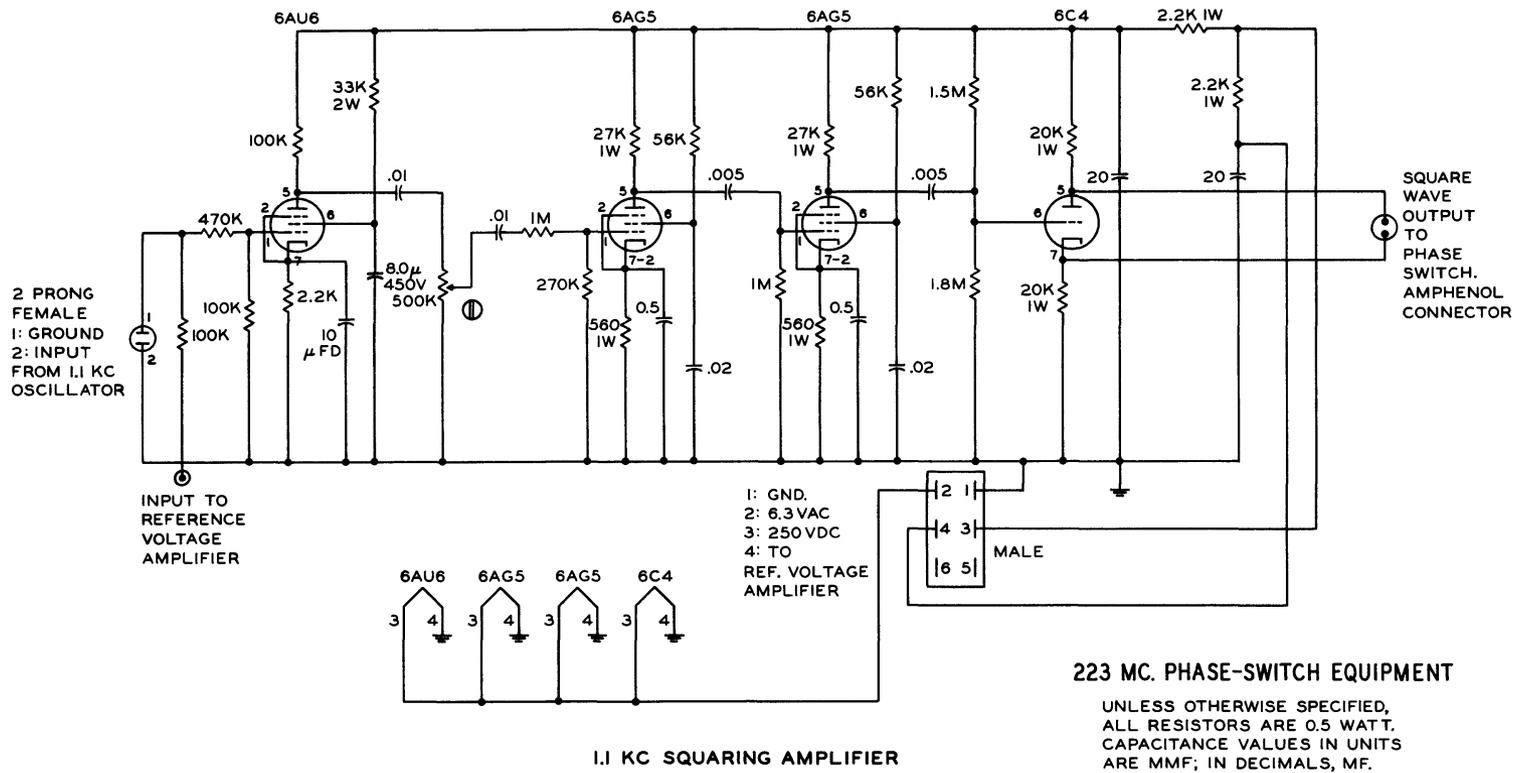
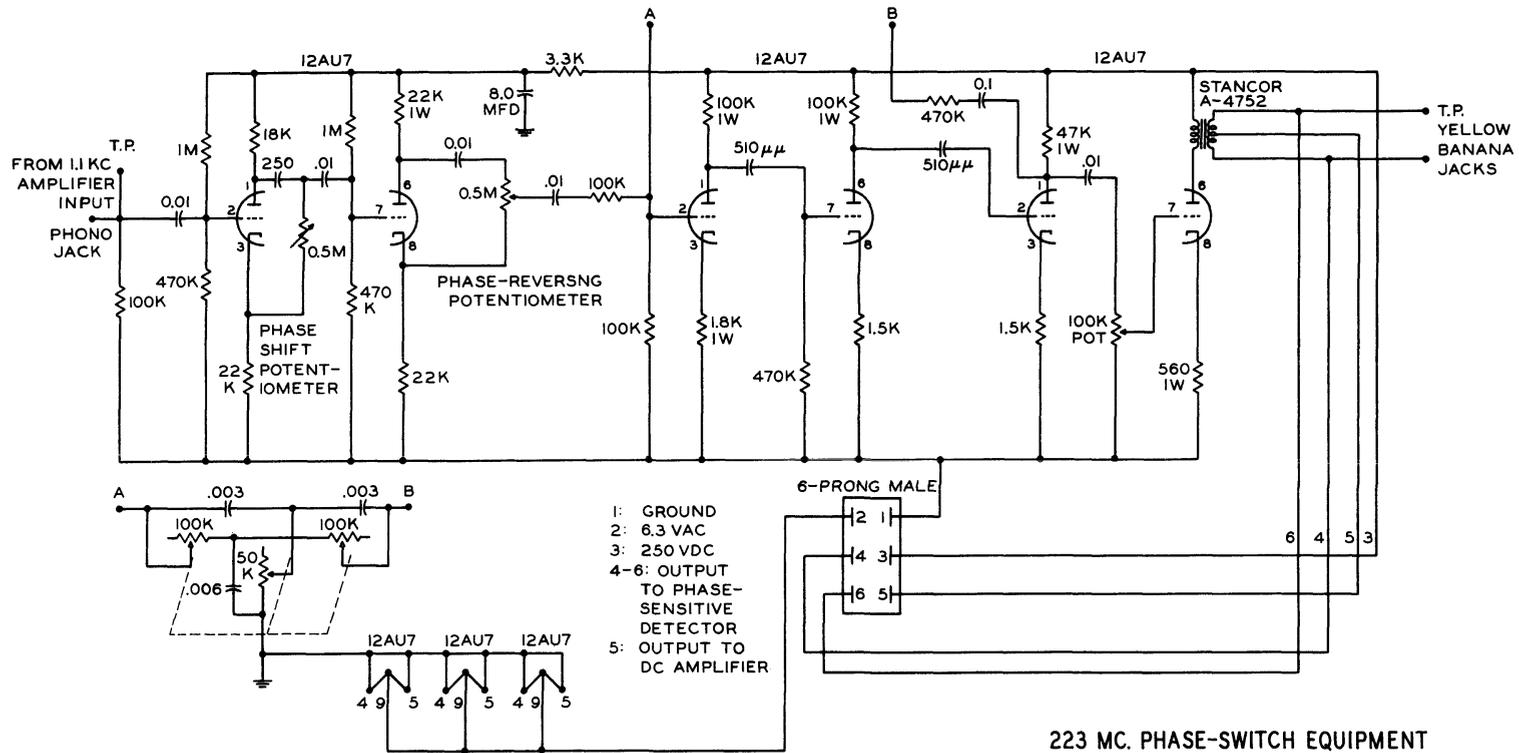


Fig. 3-9

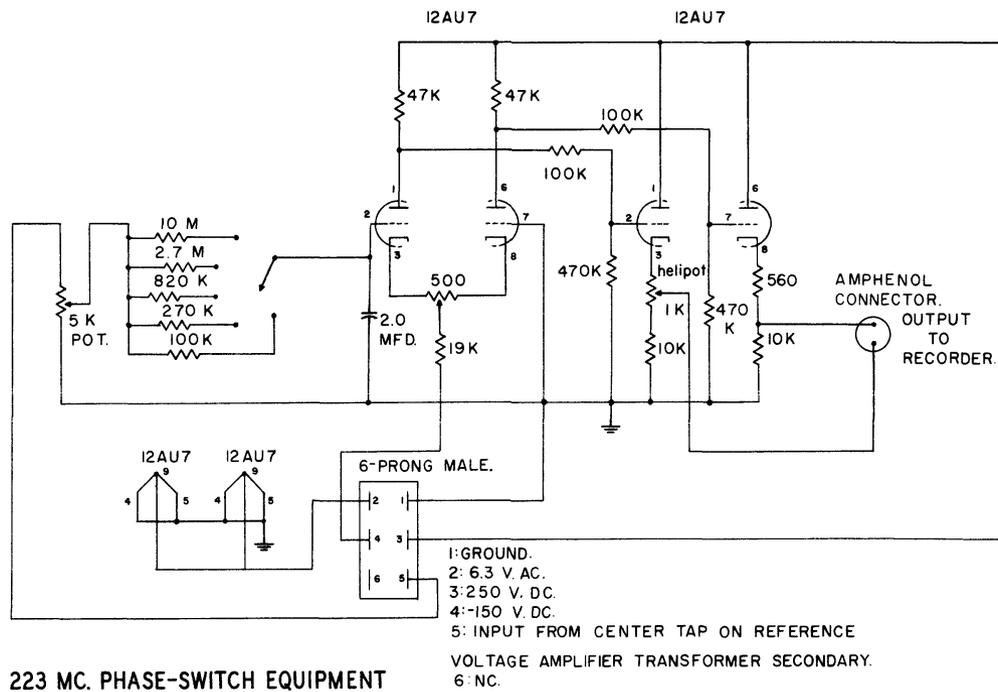


1.1 KC REFERENCE VOLTAGE AMPLIFIER

223 MC. PHASE-SWITCH EQUIPMENT

UNLESS OTHERWISE SPECIFIED,
ALL RESISTORS ARE 0.5 WATT.
CAPACITANCE VALUES IN UNITS
ARE MMF; IN DECIMALS, MF.

Fig. 3-10

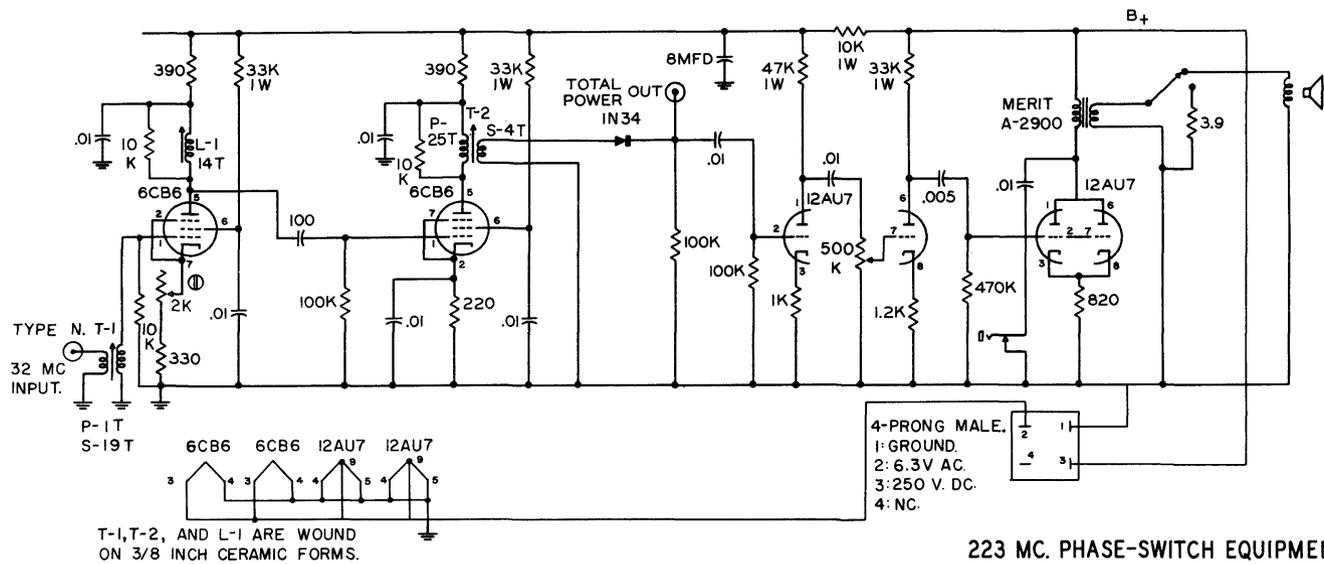


223 MC. PHASE-SWITCH EQUIPMENT

UNLESS OTHERWISE SPECIFIED,
 ALL RESISTORS ARE 0.5 WATT.
 CAPACITANCE VALUES IN UNITS
 ARE MMF; IN DECIMALS, MF.

DC AMPLIFIER FOR MAIN TRACE.

Fig. 3-11

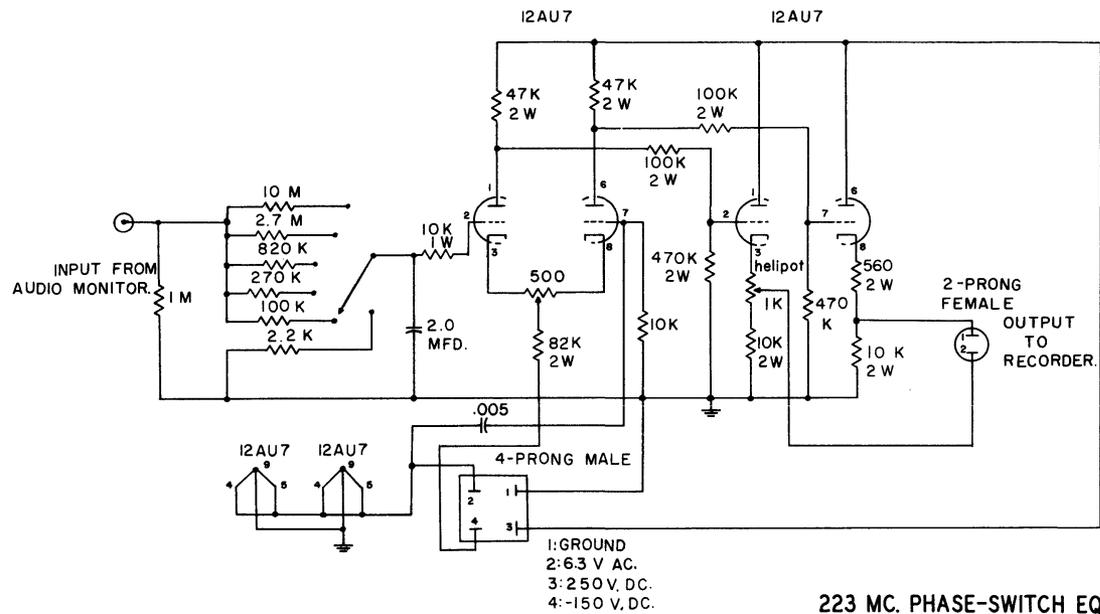


AUDIO MONITOR AND TOTAL POWER.

223 MC. PHASE-SWITCH EQUIPMENT

UNLESS OTHERWISE SPECIFIED,
ALL RESISTORS ARE 0.5 WATT.
CAPACITANCE VALUES IN UNITS
ARE MMF; IN DECIMALS, MF.

Fig. 3-12



223 MC. PHASE-SWITCH EQUIPMENT

UNLESS OTHERWISE SPECIFIED,
ALL RESISTORS ARE 0.5 WATT.
CAPACITANCE VALUES IN UNITS
ARE MMF; IN DECIMALS, MF.

DC AMPLIFIER FOR TOTAL POWER TRACE.

Fig. 3-13

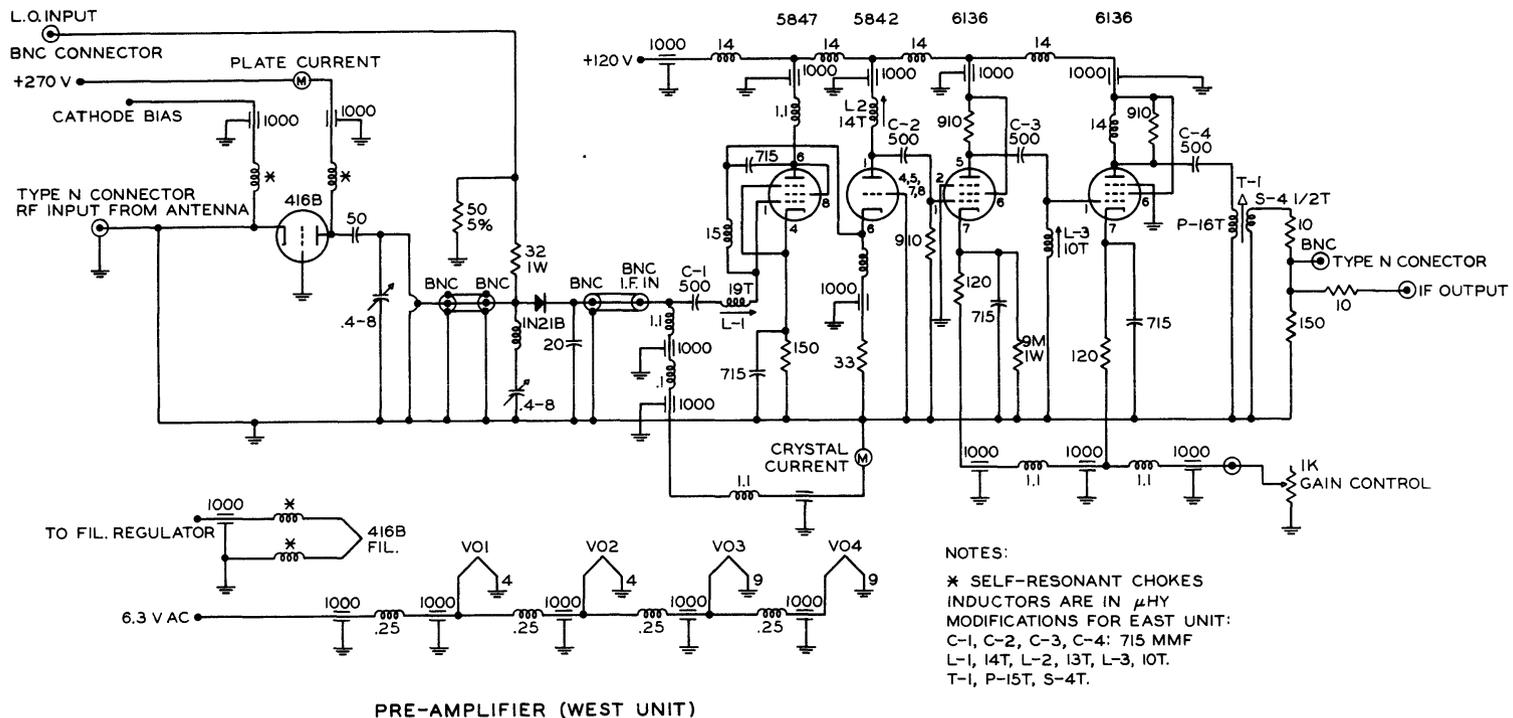


Fig. 3-14

456 MC. PHASE-SWITCH EQUIPMENT

UNLESS OTHERWISE SPECIFIED,
 ALL RESISTORS ARE 0.5 WATT.
 CAPACITANCE VALUES IN UNITS
 ARE MMF; IN DECIMALS, MF.

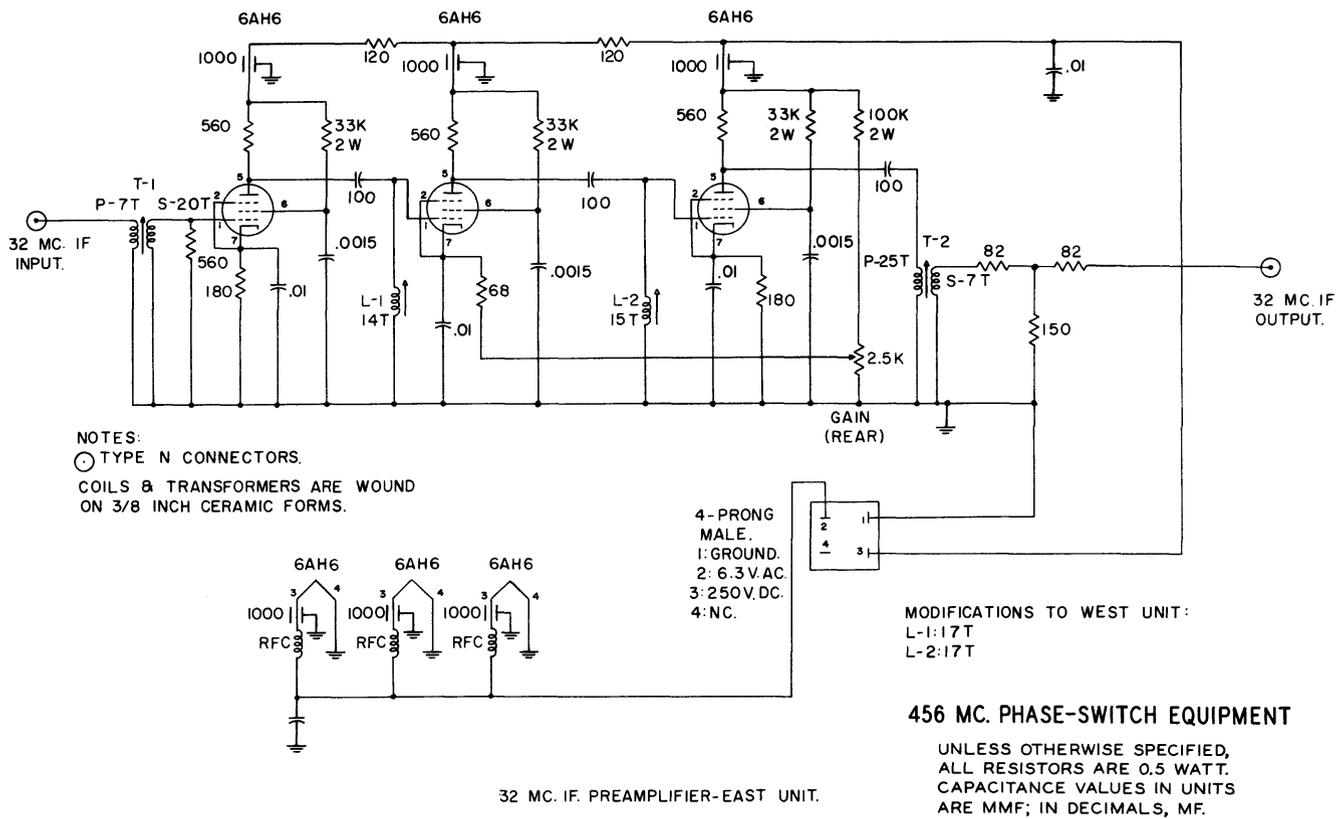


Fig. 3-16

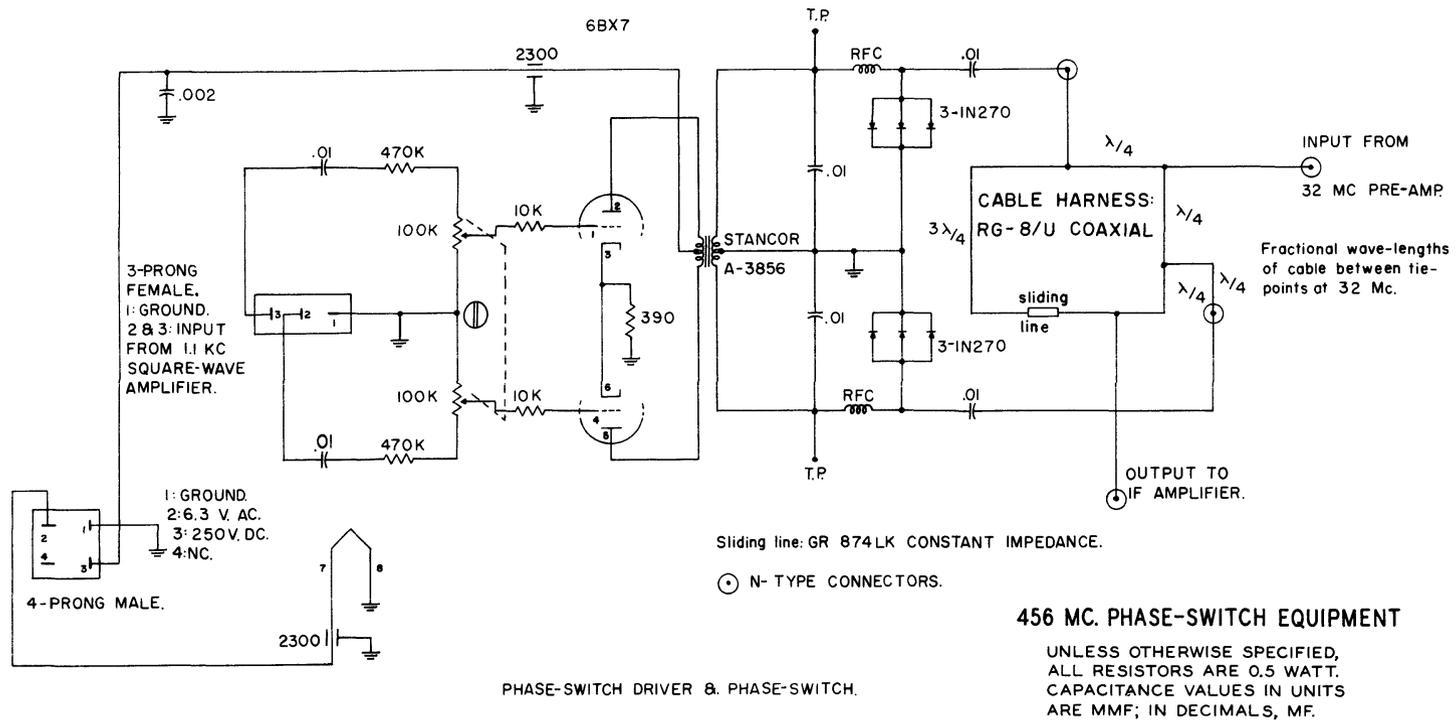


Fig. 3-17

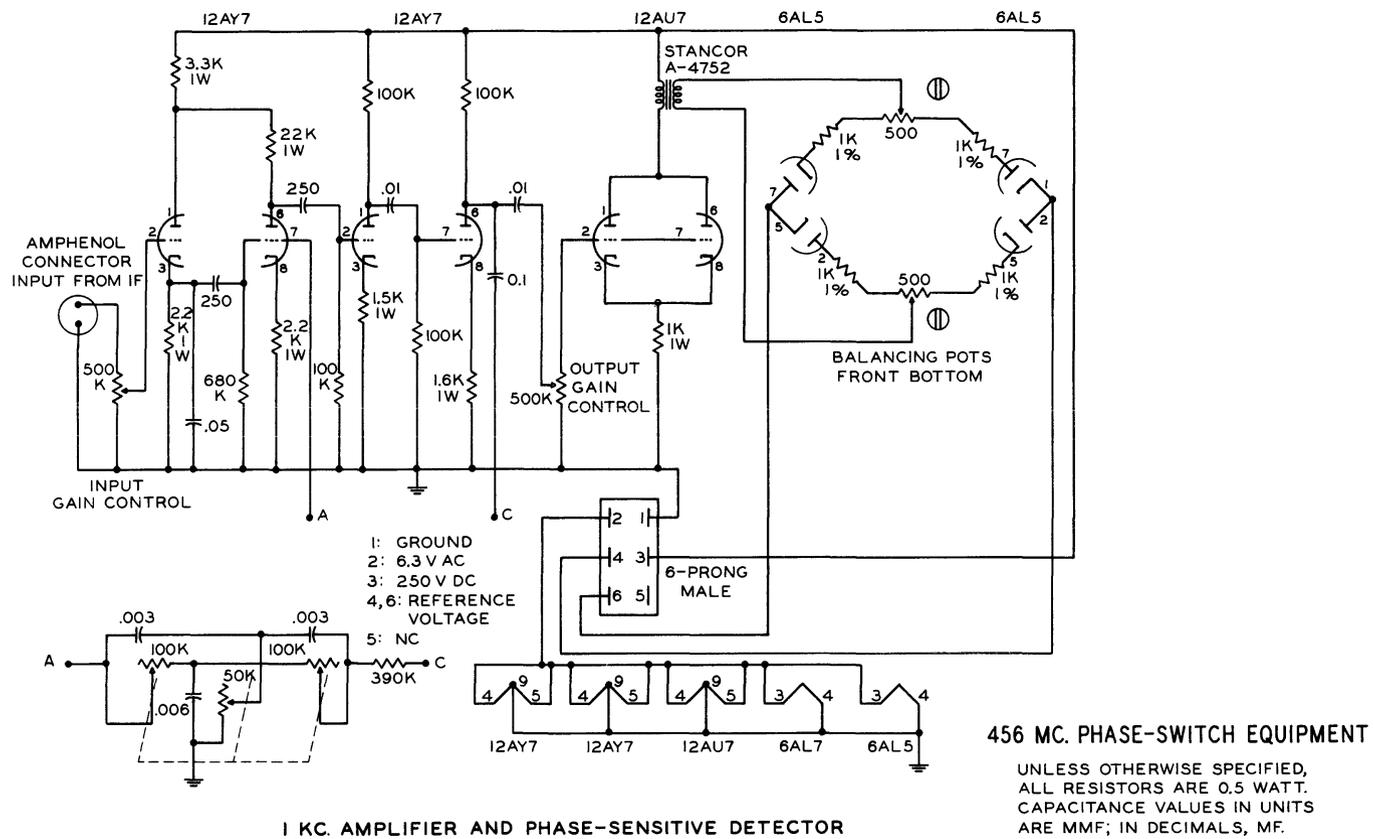
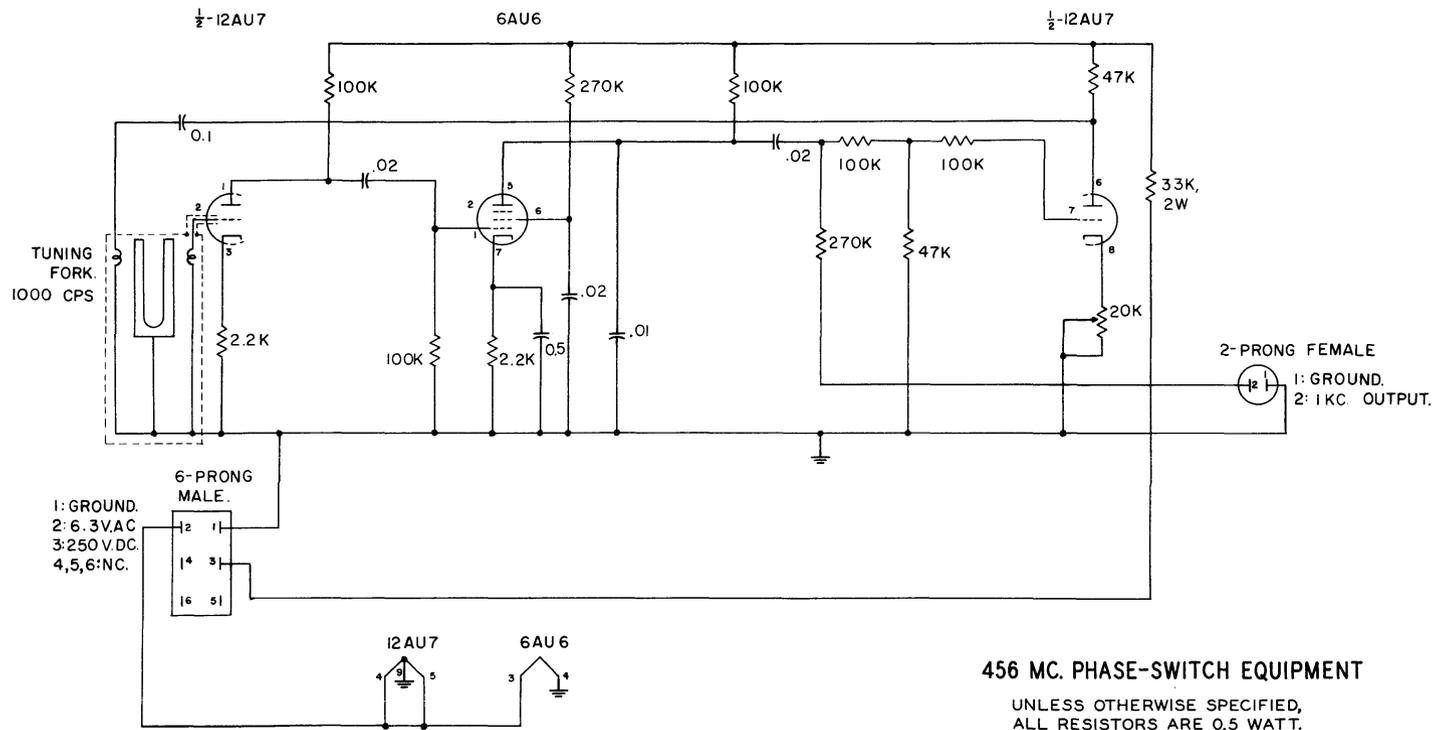


Fig. 3-19



TUNING-FORK OSCILLATOR.

Fig. 3-20

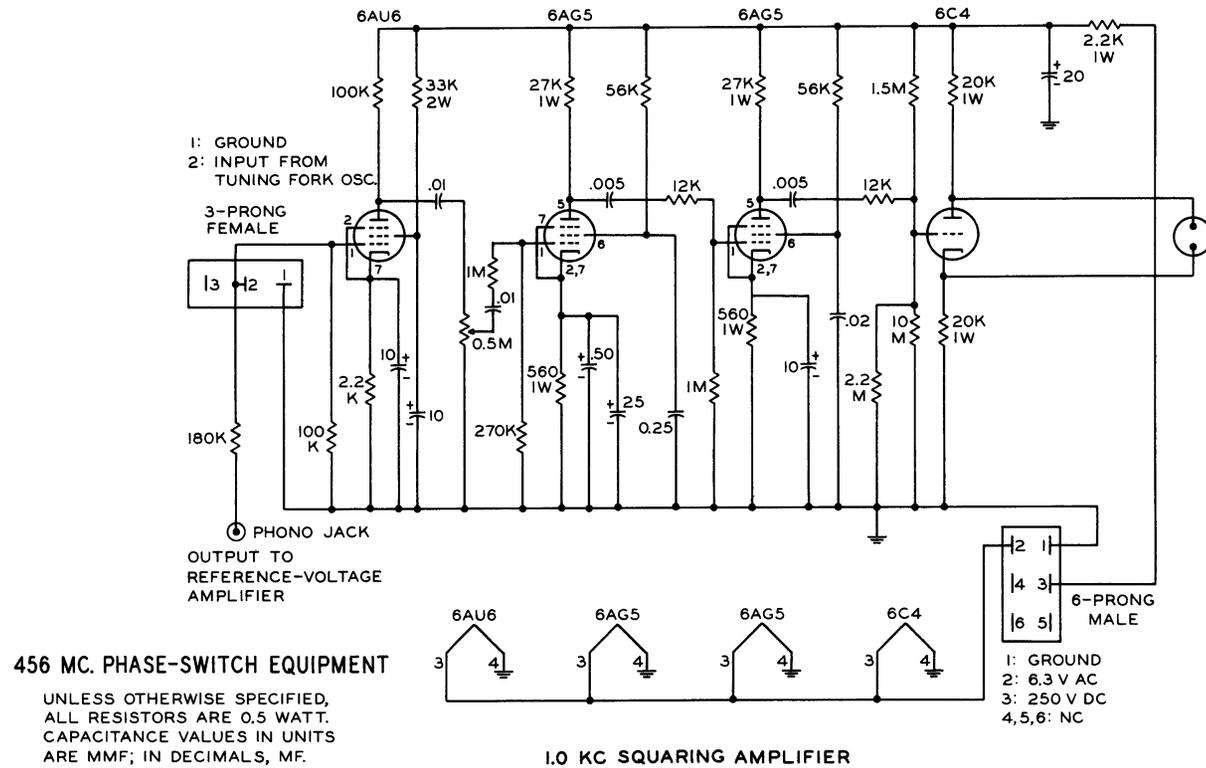


Fig. 3-21

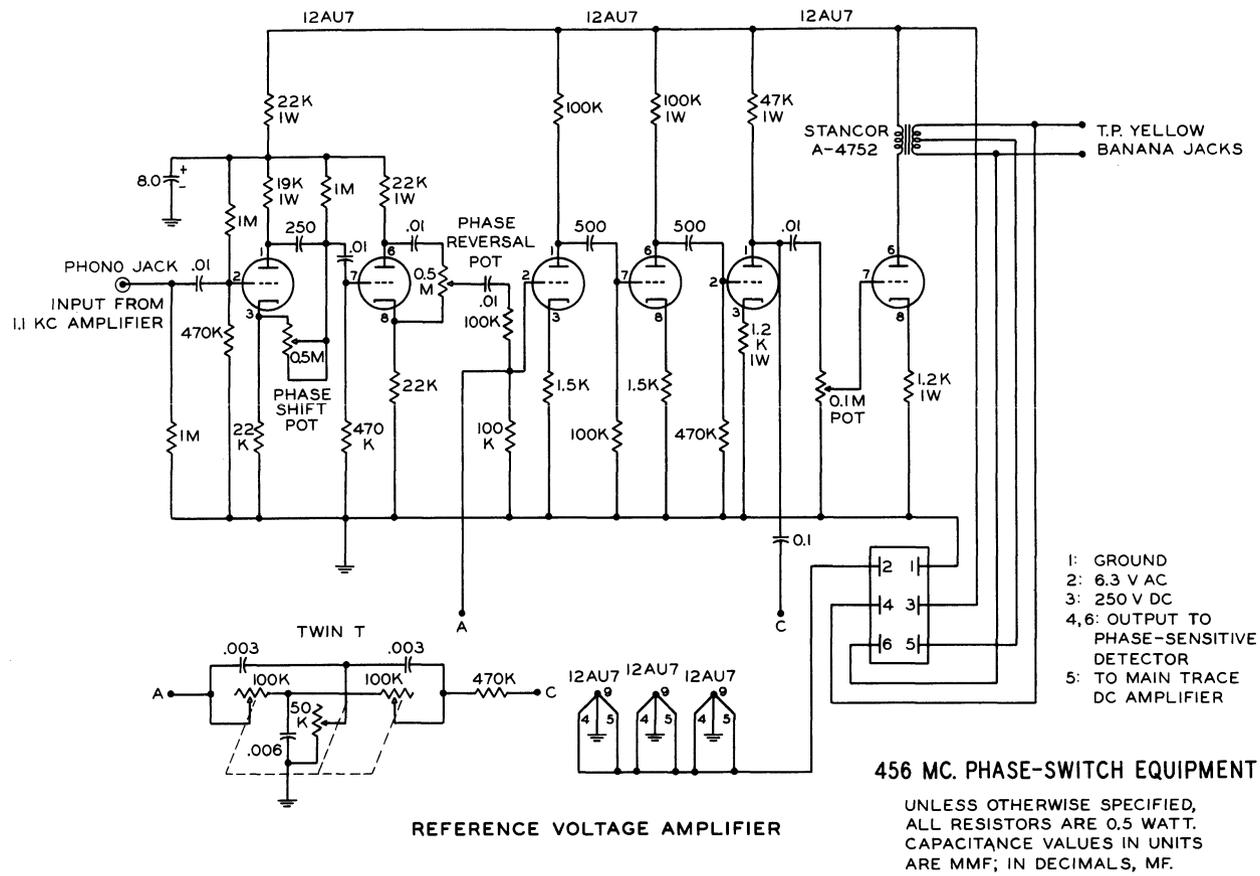
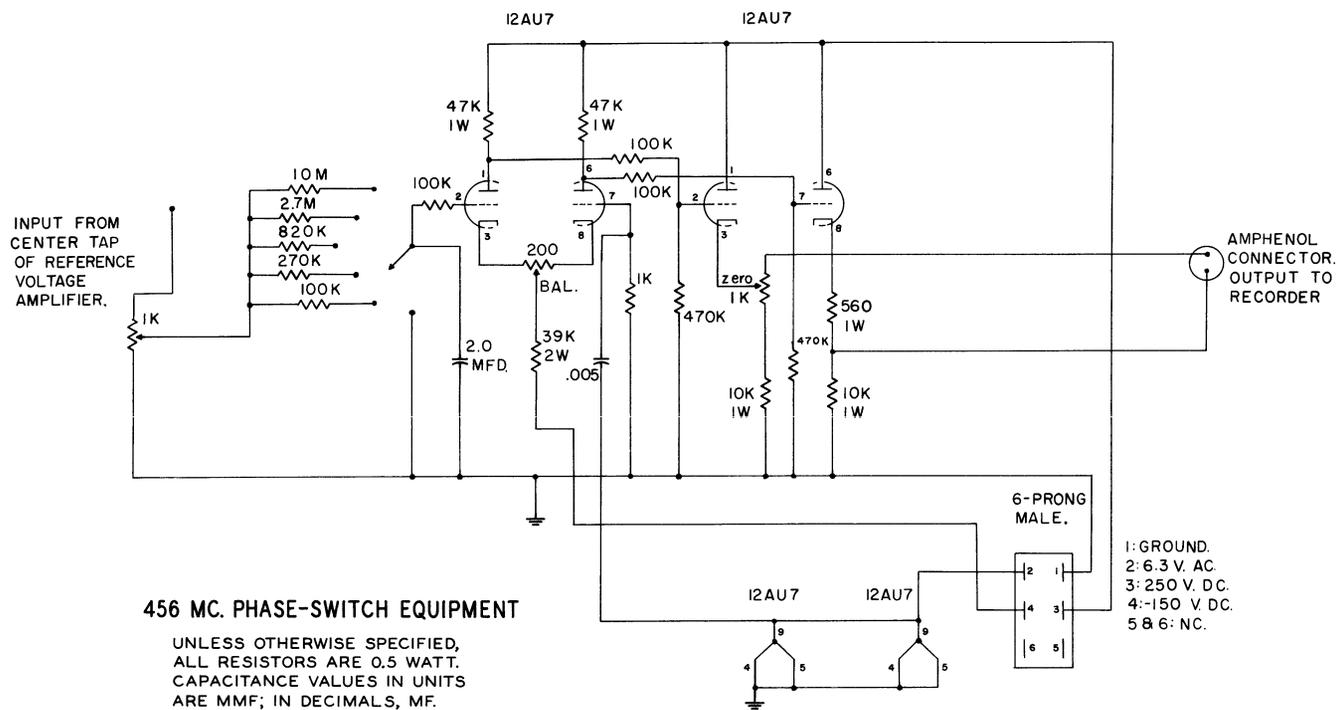
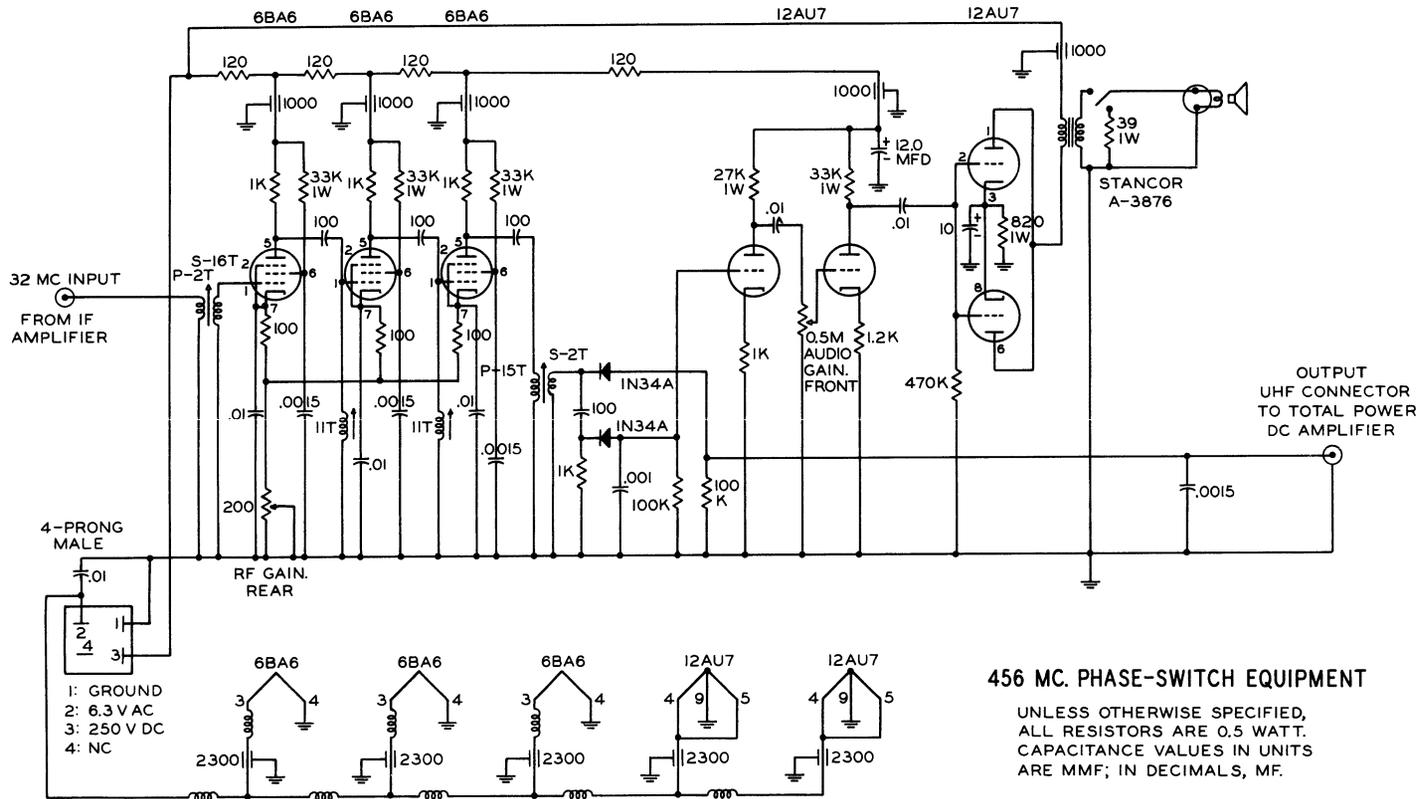


Fig. 3-22



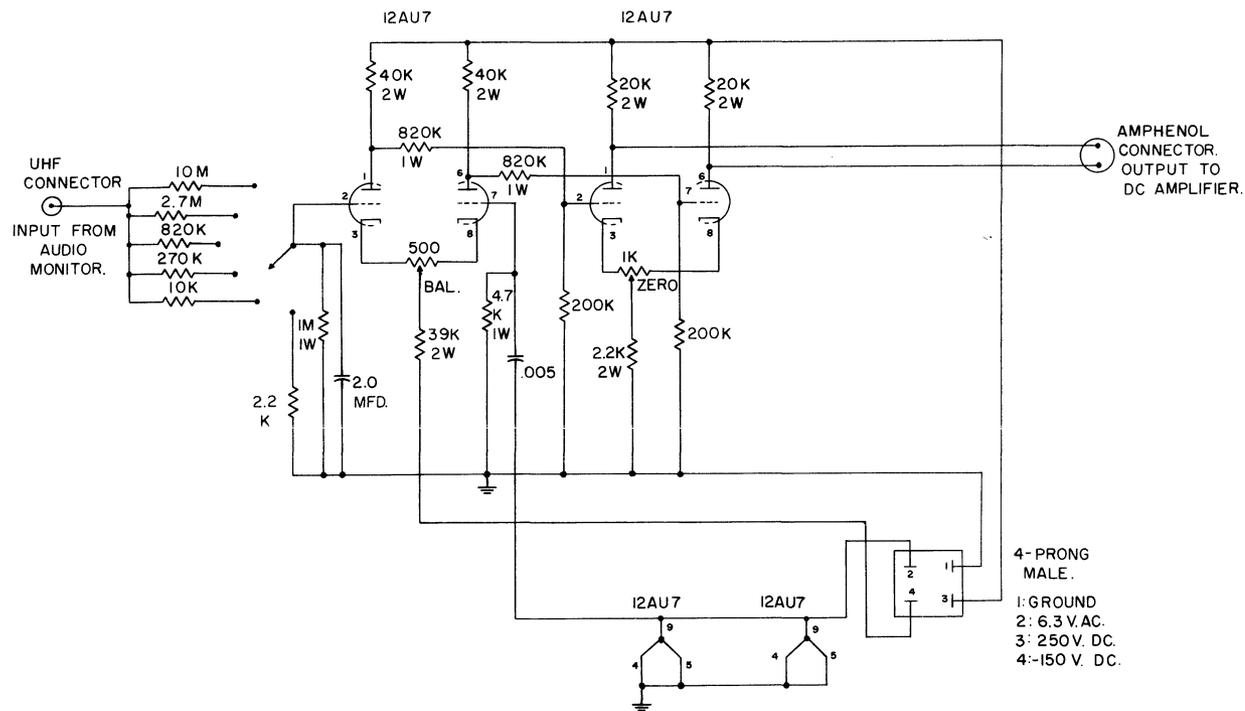
DC AMPLIFIER FOR MAIN TRACE.

Fig. 3-23



AUDIO MONITOR

Fig. 3-24



456 MC. PHASE-SWITCH EQUIPMENT

UNLESS OTHERWISE SPECIFIED,
ALL RESISTORS ARE 0.5 WATT.
CAPACITANCE VALUES IN UNITS
ARE MMF; IN DECIMALS, MF.

DC AMPLIFIER FOR TOTAL POWER TRACE.

Fig. 3-25



UHF CONNECTOR
TO ANTENNA
223 MC

NOTE:

L-1 WOUND ON 3/8" CERAMIC FORM
L-2 AND L-3 WOUND ON 1/4" CERAMIC FORM
T WOUND 3/16" CERAMIC FORM

223 MC. PHASE-SWITCH EQUIPMENT

UNLESS OTHERWISE SPECIFIED,
ALL RESISTORS ARE 0.5 WATT.
CAPACITANCE VALUES IN UNITS
ARE MMF; IN DECIMALS, MF.

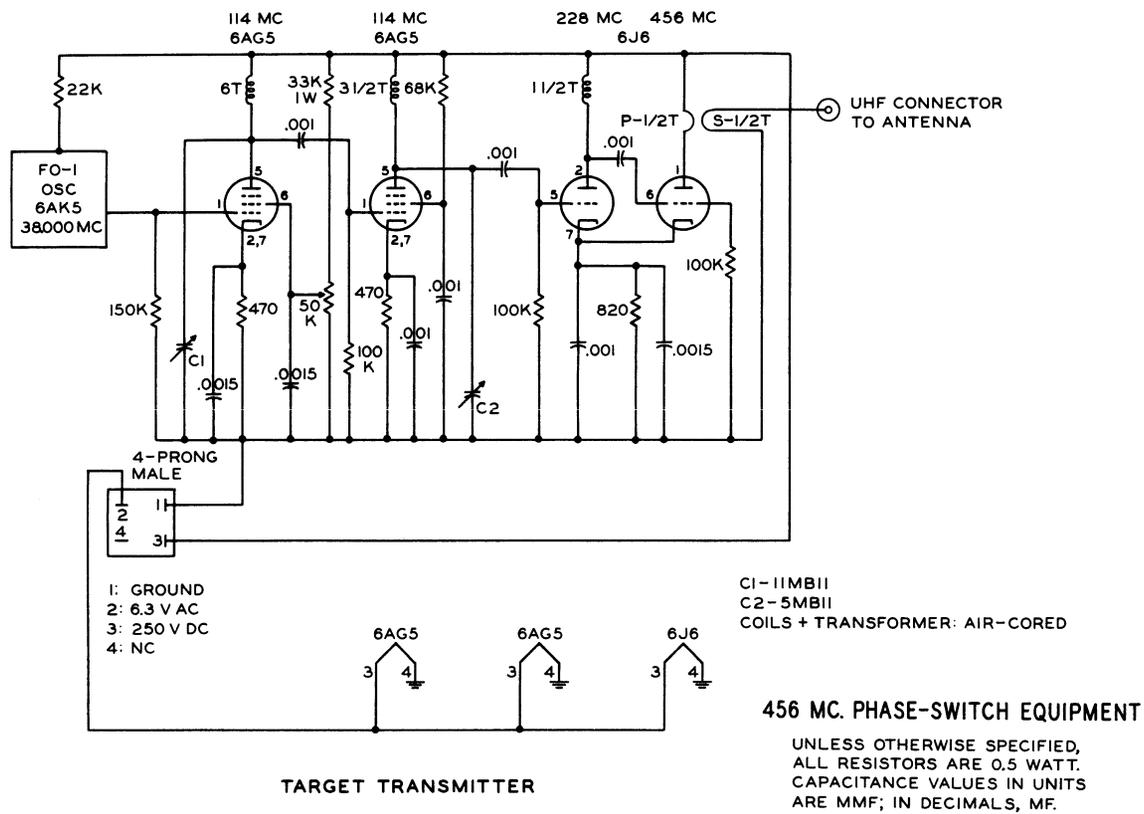
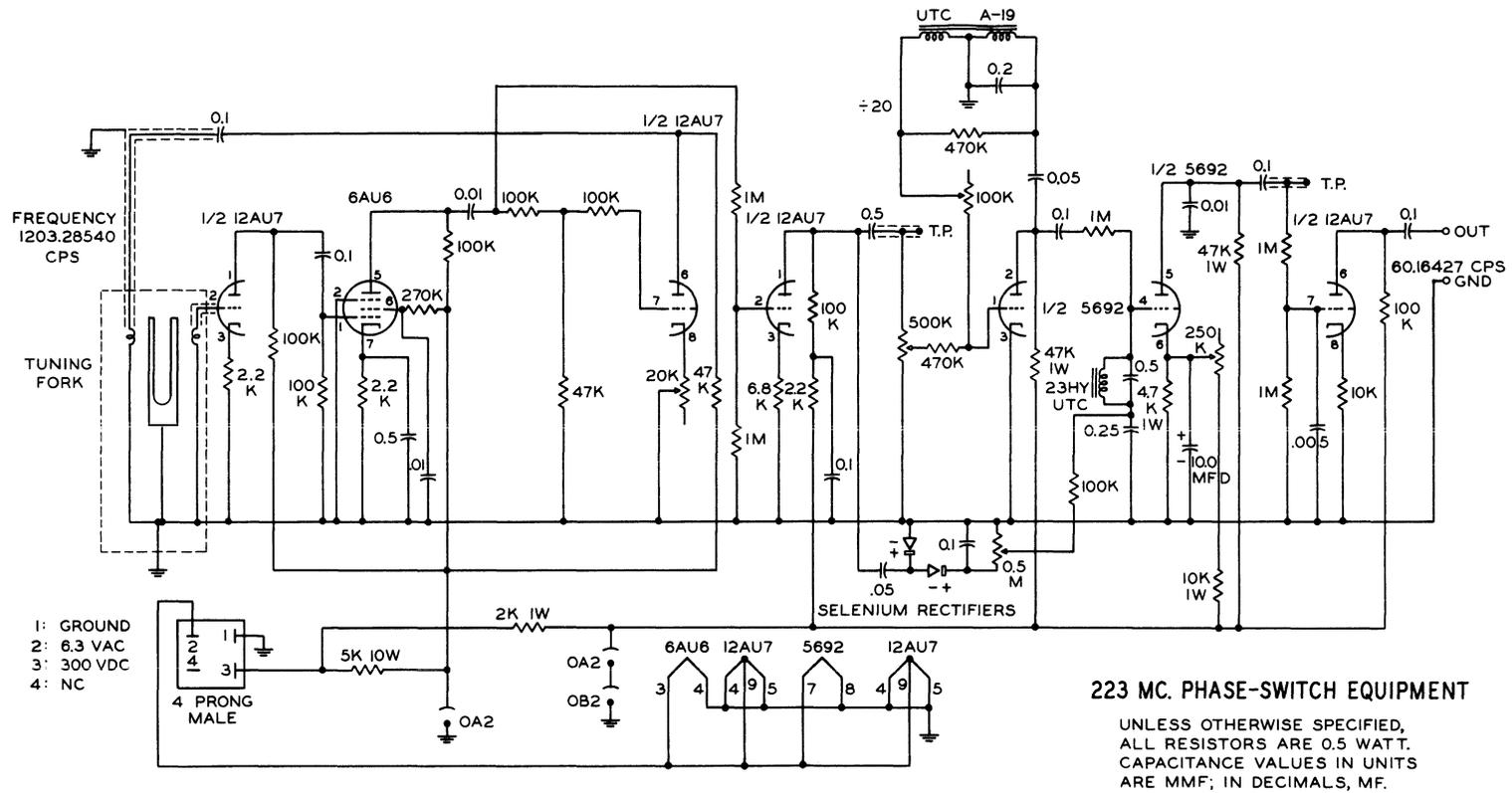
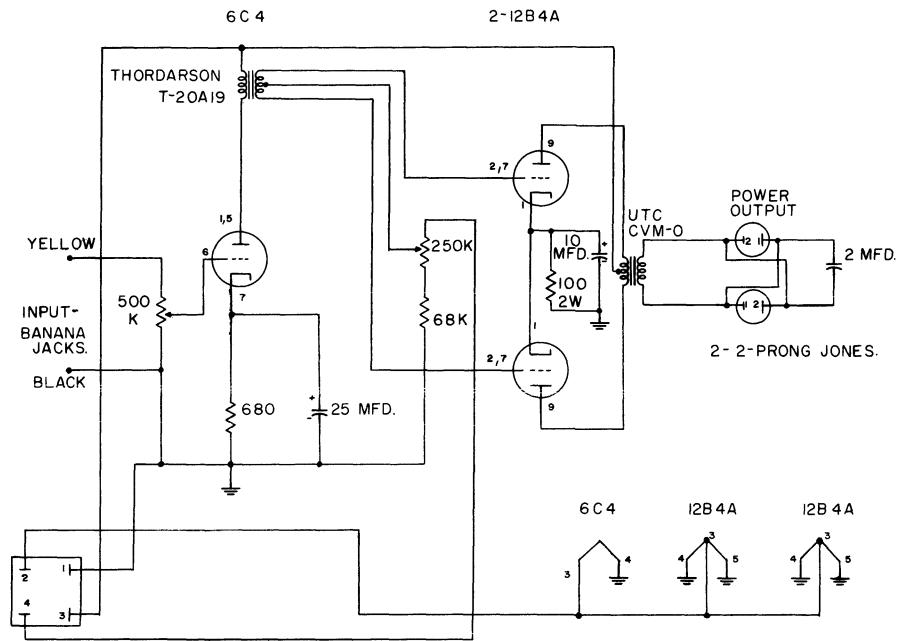


Fig. 3-27.



TUNING FORK OSCILLATOR FOR SIDEREAL CLOCK

Fig. 3-29



4- PRONG MALE
 1: GROUND.
 2: 6.3V A.C.
 3: 250 V D.C.
 4: -150 V D.C.

223 MC. PHASE-SWITCH EQUIPMENT

UNLESS OTHERWISE SPECIFIED,
 ALL RESISTORS ARE 0.5 WATT.
 CAPACITANCE VALUES IN UNITS
 ARE MMF; IN DECIMALS, MF.

SIDEREAL FREQUENCY POWER AMPLIFIER.

Fig. 3-30

