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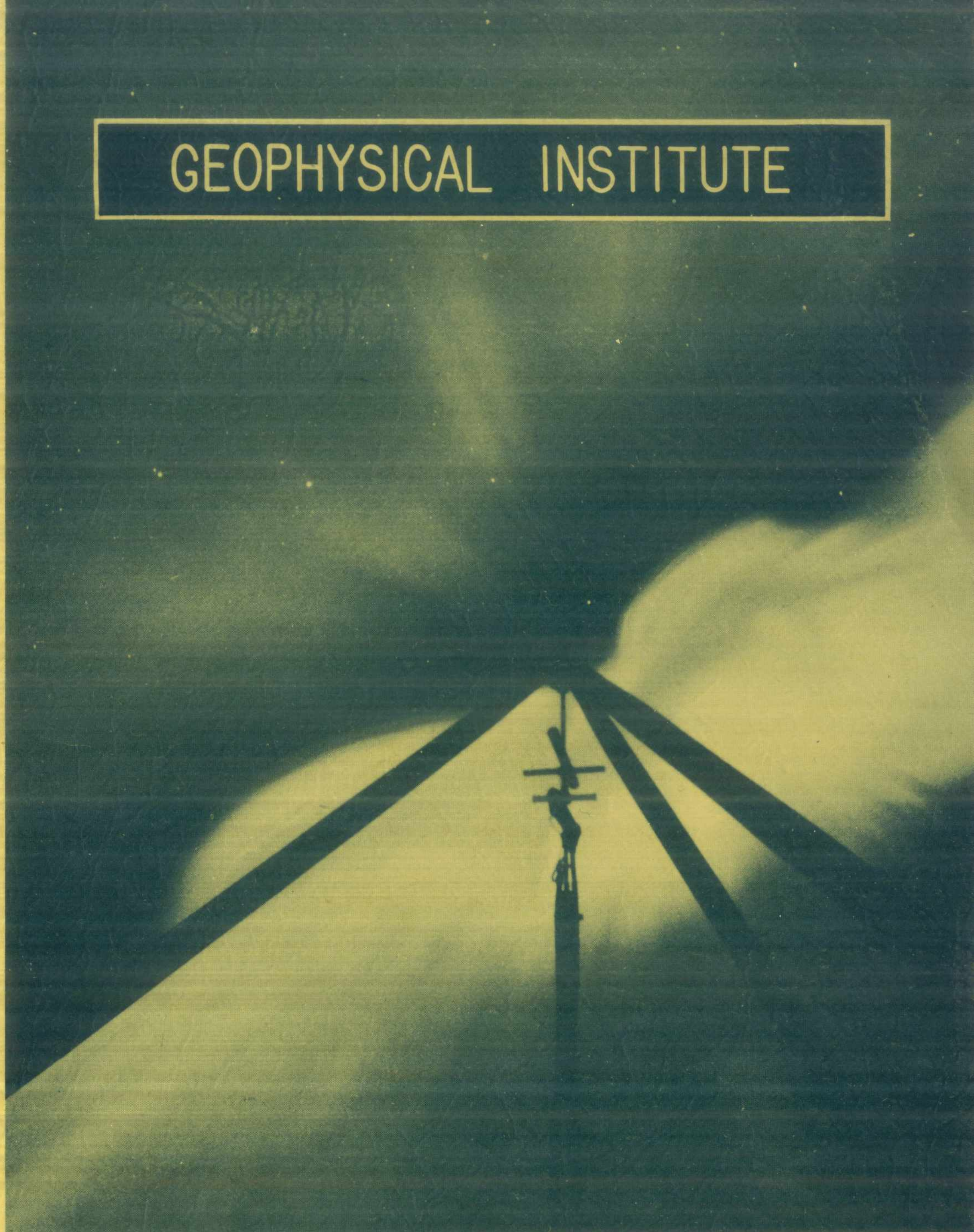

RADIO PROPERTIES OF THE AURORAL IONOSPHERE

Supplement to

FINAL REPORT (PHASE 1)

1 February 1960

Air Force Contract No. 30(635)-2887

Project No. 5535 - Task 45774

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

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RADIO PROPERTIES OF THE AURORAL IONOSPHERE

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by

G. C. Reid and E. Stiltner

Design and Use of a Phase-Sweep Interferometer for the Study of Radio Star Scintillations in the Auroral Zone.

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Director

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ABSTRACT

The usefulness of the phase-sweep technique in interferometers designed to record radio star signals is discussed. Interferometers of this type have been built for use at frequencies of 223 and 456 Mcs., and their electronic design is explained in some detail.

The report also includes a discussion of the automatic data processing system which has been designed to operate in conjunction with the interferometers in the analysis of the amplitude scintillation of radio stars.

Introduction

The phase-switch interferometer, as described in a previous report[1], has some disadvantages which prevent simple analysis of the resulting data. For example, the amplitude information is presented as a series of samples, one sample at each maximum of the quasi-sinusoidal trace. The information between the maxima and crossovers contains a complex minture of angular and amplitude information, and is of little value for precise scaling.

The phase-sweep interferometer, to be described in this report, was developed to obtain equipment which would give continuous amplitude information in a form that would be simple to use for numerical analysis.

The system is derived from the phase-sweeping equipment used by Hanbury Brown, Palmer and Thompson[2]. Since the basic interferometer principles are used, the total power system will be reviewed, and the equations modified for the case of phase-sweeping.

Total Power Interferometer

Let two antennas be situated a distance D apart, as shown in Fig. 1. Signals from a distant source arriving at the antennas will have parallel paths, so that the signal travelling the longer path will have a phase differential relative to the other of

$$\Delta = \frac{2\pi \mu D \sin \theta}{\lambda} \qquad (1)$$

where μ = index of refraction of air

D = separation of the antennas

θ = angle of arrival of the signal relative to a normal to the antenna baseline

λ = operating wavelength.

After the signals have been added together at the center of the antenna system, the amplitude of the resultant signal, E_o, is given by

$$E_o^2 \propto E_1^2 \ (1 + \cos \Delta) \qquad (2)$$

where E_1 is the signal at either antenna.

Thus the signal appearing at the recorder of the total power interferometer is given by (2) plus receiver noise. For the study of radio star scintillation in the VHF and UHF frequency bands, the receiver noise is of the order of 50 times the magnitude of the signal.

Phase-Sweep Interferometer

Modifying the total power equations to take account of phase-sweeping consists of adding a continuously rotating phase shift ω to the signal from one antenna, where ω is an angular frequency large compared to the time rate of change of Δ.

The signal appearing at the center of the antenna system after vector addition becomes

$$E_o^2 \propto E_1^2 \left[1 + \cos (\omega t + \Delta)\right] \qquad (3)$$

By feeding this signal into an amplifier which is sensitive only to the phase-sweeping frequency ω , an output proportional to $E_1^2 \cos(\omega t + \Delta)$ is obtained, where Δ is now a quasi-constant phase-shift. This signal can be rectified and fed to a recorder to give a continuous recording of the amplitude of the incoming signal.

<u>223 Mcs. Equipment</u>

The equipment which has been developed to perform the action described above is given in functional block diagram form in Fig. 2 for the 223 Mcs. channel.

The radio star signal from the antennas is fed to 223 Mcs. low-noise preamplifiers and mixed with the local oscillator signal to obtain the first IF frequency of 32 Mcs. The 32 Mcs, signals are fed to second conversion mixer stages which obtain their local oscillator signals from two separate crystal-controlled oscillators with a frequency in the neighborhood of 9 Mcs. To obtain the phase-sweeping action, the two local oscillator signals are separated in frequency by the desired phase-sweeping frequency, chosen to be 142.7 cps. in this equipment. The circuitry associated with the local oscillators will be described in detail later.

The outputs from the mixers, at 23 Mcs., are added in a resistive pad and amplified in an IF amplifier.

The output of the IF amplifier is demodulated and fed to an audio amplifier which is sharply tuned to 142.7 cps. The output of the audio amplifier is rectified and fed through a time-constant network and thence to a DC amplifier which drives the recorder.

This completes the circuitry suggested by the previous equations, but the question of signal-to-noise ratio has not been considered. An examination of the system described above reveals that the bandwidth of the audio amplifier is one of the major factors in the overall system signal-to-noise ratio. As this bandwidth is decreased, the overall signal-to-noise will continue to increase until two limiting factors appear.

The first of these is the stability of the phase-sweeping frequency which is determined by the difference of the two second conversion local oscillator frequencies. With no control, this difference would be expected to vary to some extent, depending on such factors as crystal drive and aging, and ambient temperature. This would imply that the audio amplifier pass-band must be wide enough to encompass the expected drifts in the phase-sweeping frequency. This difficulty has been overcome by stabilizing the difference frequency with a phase-lock circuit as shown, and the audio amplifier bandwidth can be decreased until the second, and ultimate, limiting factor arises: that of attenuation of high frequency components in the scintillation of the signal being observed.

The phase-lock circuit operates as follows. The two local oscillator signals are heterodyned together to obtain their difference frequency. A phase-sensitive detector is used to compare this beat frequency with a reference frequency derived from a tuning-fork. The output of the phase-sensitive detector is a DC signal whose magnitude depends on the relative phase difference of the two input signals. This DC signal is fed to a reactance circuit across one crystal to change its frequency by a small amount if necessary. Thus a system is obtained which will maintain the crystal frequency difference, or phase-sweeping frequency, constant as determined by an external reference frequency.

By using the phase-lock control on the phase-sweeping frequency, an audio amplifier bandwidth of 6 cps. is feasible and easily obtained with reliabel circuitry. The high frequency attenuation of a 6 cps. passband is negligible for most conditions since normal operation of the recorders is such that a frequency much above 1 cps. cannot be resolved.

Circuit description - The end-hut equipment, consisting of RF amplifiers, local oscillators, and IF preamplifiers, has been described in a previous report[1], and will be omitted here. The IF signals are brought into the center building and fed to splitting amplifiers. The circuit for these units is given in Fig. 3 and consists of a resistive splitting pad, either end feeding an isolating grounded-grid amplifier which is followed by a pentode stage of amplification. One output of the two splitting amplifiers in either channel goes to the phase-switch equipment, and one to the phase-sweep equipment. The splitting amplifiers, with excellent isolation between outputs, were incorporated to allow continuous uninterrupted operation of one equipment while the other was shut down, allowing a continuous record to be obtained.

Mixers - The 32 to 23 Mcs. converters are of two types: one has a free-running (uncontrolled frequency) local oscillator, and the other has a controlled frequency local oscillator.

The free-running mixer (Fig. 4) consists of a single stage of RF amplification at 32 Mcs., a mixer stage and a crystal oscillator at 9 Mcs. The oscillator section uses an International Crystal Company model FO-6 printed circuit chassis for simplicity. A small variable capacitor is connected across the crystal to allow manual adjustment of the phase-sweeping frequency to the point where the automatic control will operate.

The controlled frequency mixer circuit (Fig. 5) is similar to that of the above unit, with the variable capacitor being replaced by a reactance circuit, consisting of a special silicon junction diode fed by a DC amplifier.

Phase-lock control unit - The function of this circuit (Fig. 6) is to accept the two 9 Mcs. signals from the mixers, heterodyne them without cross-coupling to obtain the audio difference frequency, compare this audio frequency with a reference frequency and generate a DC correction voltage if necessary. The correction voltage is applied to the reactance circuit in the controlled frequency mixer to maintain the phase-sweeping frequency to the value set by the reference signal.

The circuit operation is as follows: The two 9 Mcs. signals are amplified in grounded-grid amplifiers to obtain isolation and then heterodyned in a pentagrid mixer tube. The resulting audio frequency output is fed through a low-pass filter to obtain the fundamental frequency and then through a split-load phase inverter to the phase-sensitive detector. The reference frequency is likewise amplified and fed to the phase-sensitive detector as a reference signal. The DC output of the phase-sensitive detector is integrated in a one-half second RC network and fed to the reactance circuit in the controlled frequency mixer.

IF amplifier - The 23 Mcs. second IF signal is further amplified in a four-stage amplifier (Fig. 7) consisting of two remote-cutoff pentodes for gain control, and two sharp-cutoff pentodes for power gain. The amplified signal is demodulated and fed to the audio amplifier as an audio signal.

Tuned audio amplifier (Fig. 8) - The audio signal from the IF amplifier is amplified in a one-pentode stage, filtered in a high-Q circuit to remove the receiver noise, and the resulting 142.7 cps. signal is further amplified in another pentode stage. The output of the last pentode is rectified and fed to the DC amplifier as a DC signal.

DC amplifier (Fig. 9) - The DC signal from the audio amplifier is integrated in a variable time-constant network and amplified in a recorder drive amplifier. This amplifier is designed to present an output impedance to the recorder which is close to its critical damping resistance, allowing signal frequencies of the order of one cycle per second to be recorded at full amplitude.

Auxiliary equipment - The tuning-fork oscillator (Fig. 10) and the time-base circuit (Fig. 11) are used to supply the reference frequency of 142.7 cps. to the phase-lock control unit. The tuning-fork operates at 1 kcs., and this frequency is divided by 7 in the phantastron circuit of the time-base unit to obtain the 142.7 cps. reference frequency. The 1 kcs. signal is available from the time-base unit for operating the 223 Mcs. phase-switch interferometer.

456 Mcs. Phase-Sweep Equipment

The equipment for the 456 Mcs. channel uses the same circuitry as described above with a slight change in various frequencies to avoid interaction. The 456 Mcs. phase-sweep frequencies are:

second local oscillator: 9.225 Mcs.
second IF frequency: 22.775 Mcs.
phase-sweeping frequency: 137.5 cps.

Digitizing Equipment

The output of the phase-sweep interferometer is a DC signal whose magnitude is always proportional to the magnitude of the incoming phase-coherent signal. This type of signal lends itself very readily to automatic scaling in the form of digitization. Consequently a program was initiated which has resulted in the installation of simple, but adequate, digitization equipment.

The basic procedure is that the output signal from the phase-sweep interferometer is sampled periodically by a digital voltmeter. The voltmeter in turn drives an IBM model 523 card punch so that a value is punched on an IBM card corresponding to the output signal of the equipment.

The actual equipment is shown in block diagram form in Fig. 12. The phase-sweep voltages from both the 223 and 456 Mcs. channels are fed to two digital voltmeters at ten-second intervals. The digital voltmeters balance on the signal and set up contacts for the model 523 punch. As soon as both voltmeters have balanced, the punch is commanded to punch by the balance detector, shown in Fig. 13. The punch samples the voltmeter switches and punches the values read by the voltmeters into a card, resulting in one card for every data sample, or once every ten seconds for the present operation.

Identification is also required on each card. The desired identification includes the following:

project code

code number

equipment

source

year

month

day

hour

RF input (star signal or calibrating resistance signal).

voltmeter range

The first six items can be gang-punched from one card to another by the machine by using a pre-punched lead card. The rest of the items are considered to be varying often enough for it to be desirable to have them controlled directly. The day and hour digits are generated by manual 12-position rotary switches at a control panel.

During operation the antennas are periodically turned off the source so that the noise level can be measured. These noise readings are subsequently subtracted from the on-star readings to obtain the true signal from the star. The on- or off- source signals, consisting of an 11-punch for off-star and a 12-punch for on-star, are obtained from two relays driven in parallel with the antenna switching relays. The need for a voltmeter ranging mark comes from the fact that the voltmeter calls for operation at input signals between 0 and 0.999 volts. If a larger signal is fed in, the voltmeter will automatically range upward, with the result that a voltage of 1.32 volts, for example, would appear in the IBM card as 0.132 volts. Most of the runs are made with a mean star level of the order of 0.3 volts, but in this range, large positive scintillations can give signals in excess of 0.999 volts, so that a check is essential. The voltmeter range contacts are wired to produce an 11-punch for any range except the 0.1 volt range, which is indicated by a 12-punch.

Calculation of Mean Power Fluctuation

The mean fractional power fluctuation, $\overline{\Delta P}/\overline{P}$, for any selected period of time, can be expressed as

$$\frac{\overline{\Delta P}}{P} = \frac{1}{N\overline{R}} \sum_{i=1}^{N} \left|\overline{R} - R_i\right| \tag{4}$$

where R_i are the individual data readings, N in number, and $\overline{R}$ is the mean level for the period.

In terms of the data punched on the cards, this can be written as

$$\frac{\overline{\Delta P}}{P} = \frac{\sum_{i=1}^{N} \left| \frac{1}{N} \sum_{i=1}^{N} \left(R_i - \frac{1}{n} \sum_{j=1}^{N} r_j\right) - \left(R_i - \frac{1}{n} \sum_{j=1}^{N} r_j\right) \right|}{\sum_{i=1}^{N} \left(R_i - \frac{1}{n} \sum_{j=1}^{N} r_j\right)} \tag{5}$$

where R_i = individual on-star readings,

N = number of on-star readings,

r_j = individual off-star data readings,

n = number of off-star readings.

A program has been set up for the University of Alaska's IBM 602A calculator which will automatically evaluate $\overline{\Delta P}/\overline{P}$ for a given group of cards. The operation of the program is as follows. The noise cards belonging to the group are run through the calculator with both lead and follow-up master cards. The lead card clears the machine and sets it up for the following detail cards, which are read and their values summed. A count is also made of the total number of cards. When the follow-up master card enters the machine, the noise mean is evaluated and punched into this card.

The next step is to remove the two master cards from the noise details and put them with the on-star cards so that the card which has the noise mean leads the group and the other master card follows up. During this pass through the machine, the noise mean is read off the first card and subtracted from all the data values in the detail cards. This difference is punched into each detail card and is also accumulated along with a card count until the follow-up card enters the machine. At this time the mean of the star level is evaluated and punched into the follow-up card.

The third and final part of the operation is to interchange master cards and put the cards through the machine again. This time, the lead master card will contain the star mean, which is subtracted from each of the star values calculated on the previous pass. The absolute values of the differences are accumulated along with a card count. When the follow-up master card enters the machine, the mean of the sum of the differences is obtained, and is in turn divided by the mean star level to obtain the value of $(\overline{\Delta P}/\ \overline{P})$ for the group of cards.

Along with the operation of counting the number of detail cards, a consecutive numbering is punched into them. This allows the cards to be counted for the investigation of probability distributions similar to the examples given in a previous report[3], and then re-sorted into time sequence for sequential studies.

The final appearance of the data cards is as follows after the calculation of $(\overline{\Delta P}/\ \overline{P})$:

Columns	Data
1, 2, 3	Project identification
4	Code number (2)
5	Source (Cassiopeia = 1, Cygnus = 2, Taurus = 3, Virgo = 4)
6	Equipment (Phase-switch = 1, phase-sweep = 2, phase-track = 3)
7, 8, 9, 10	Year and month
11, 12, 13, 14	Day and hour
21	RF input (223 Mcs.) (on- or off-star)
22	Voltmeter range (223 Mcs.)
23, 24, 25	223 Mcs. data
27, 28, 29	Consecutive number
31, 32, 33	Star signal amplitude
37, 38, 39	Consecutive number
41, 42, 43	Deviations of star signal from mean star signal
51	RF input (456 Mcs.) (on- or off-star)
52	Voltmeter range (456 Mcs.)

Columns	Data
53, 54, 55	456 Mcs. data
57, 58, 59	Consecutive number
61, 62, 63	Star signal amplitude
67, 68, 69	Consecutive number
76	Calculator control punch

The master cards used as leaders during the first run (coded 0010) will appear as follows after calculation:

1, 2, 3	Project identification
4	Code number
5	Source
6	Equipment
7 through 14	Year, month, day, hour
27, 28, 29	Number of on-star cards (223 Mcs.)
31, 32, 33	Mean of star level (223 Mcs.)
57, 58, 59	Number of on-star cards (456 Mcs.)
61, 62, 63	Mean of star level (456 Mcs.)
78	Calculator control punch

The master cards used as follow-up masters during the first run (coded 0011) will appear as follows after the calculation:

Columns	Data
1, 2, 3	Project identification
4	Code number
5	Source
6	Equipment

Columns	Data
7 through 14	Year, month, day, hour
27, 28, 29	Number of off-star cards
31, 32, 33	Mean of receiver noise level
37, 38, 39	Number of on-star cards
41, 42, 43	Deviation index ($\overline{\Delta P}/\overline{P}$)
76, 78	Calculator control punches.

Acknowledgements

The authors of this report wish to acknowledge the fact that the initial development of the phase-sweep interferometer was carried out under the leadership of Dr. C. G. Little, and with the assistance of other members of the staff of the Geophysical Institute, notable Mr. R. P. Merritt.

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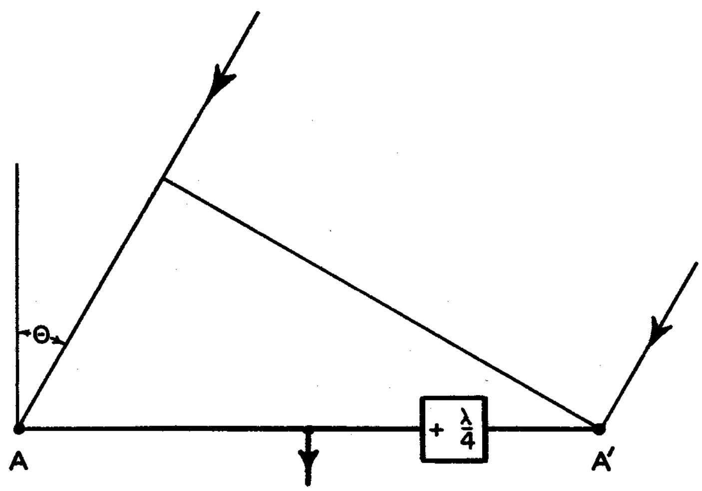
(1) Radio Properties of the Auroral Ionosphere, Final Report (Phase I) (February 1959).

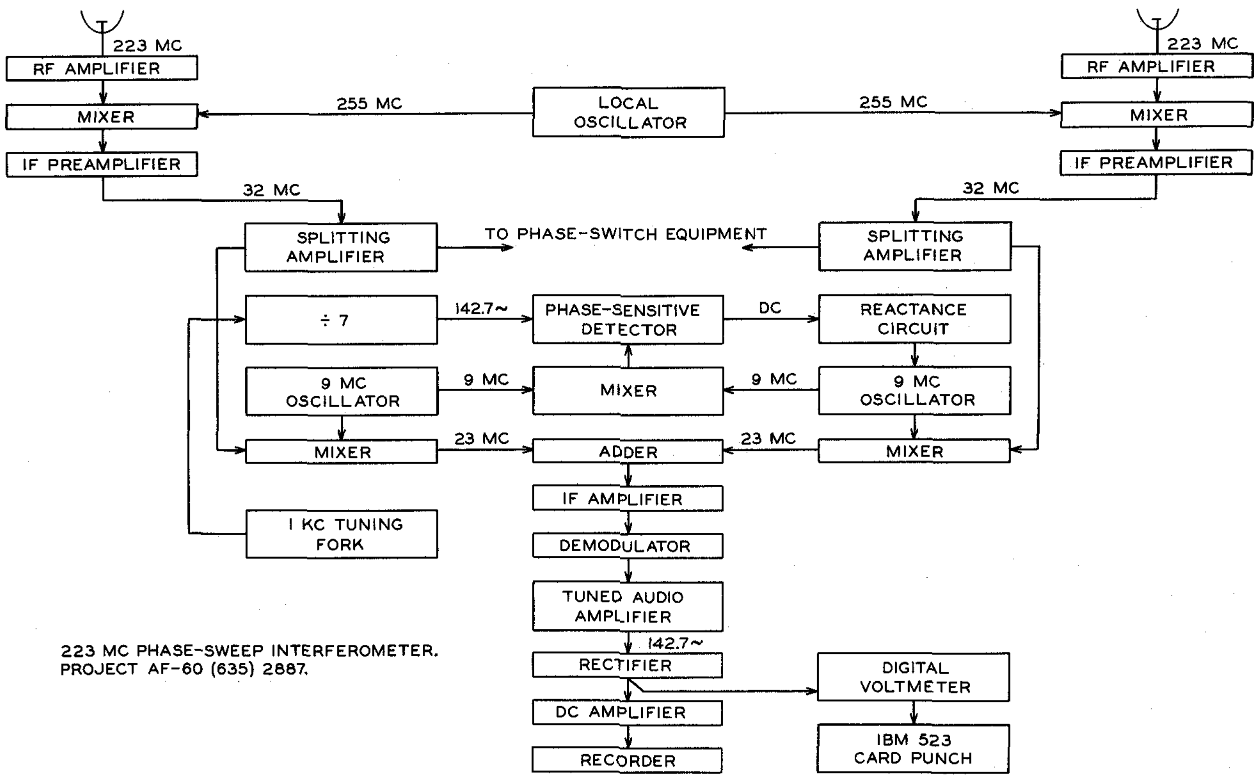
(2) Hanbury Brown, R., Palmer, H. P., Thompson, A. R.: Phil. Mag. 46, 857 (1955).

(3) Radio Properties of the Auroral Ionosphere, Quarterly Progress Report No. 10 (Sept. 1958 - Nov. 1958).



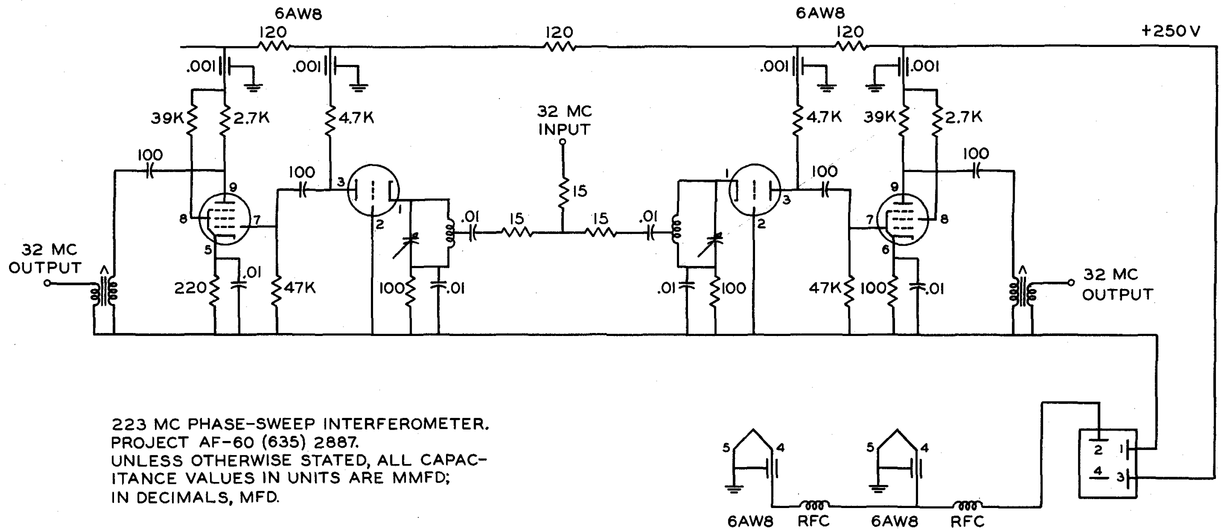
RAY PATHS FOR TOTAL POWER INTERFEROMETER

Fig. 1



PHASE-SWEEP EQUIPMENT BLOCK DIAGRAM

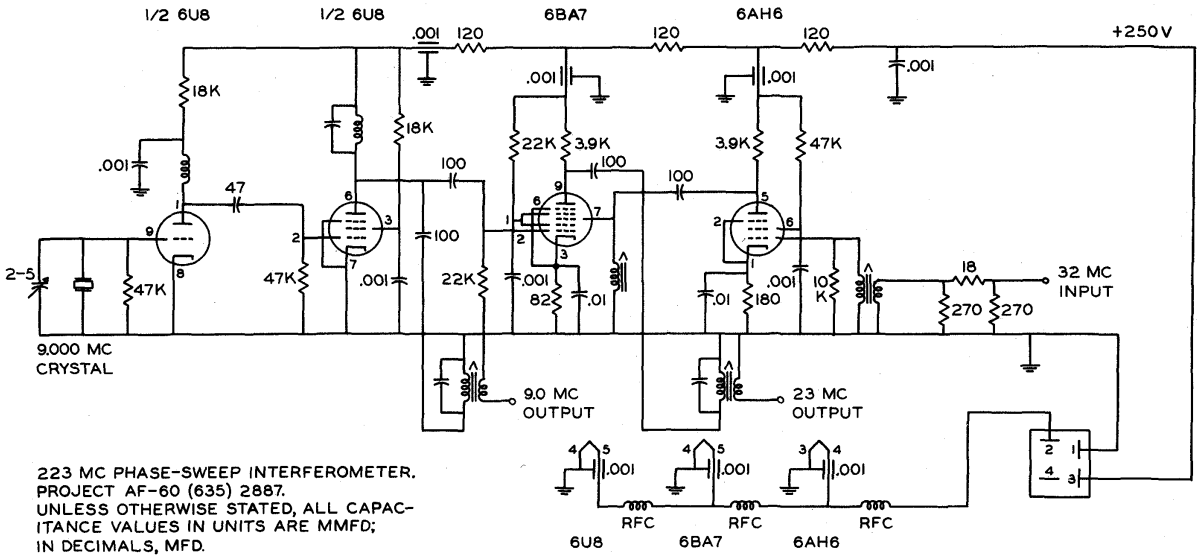
Fig. 2



223 MC PHASE-SWEEP INTERFEROMETER.
PROJECT AF-60 (635) 2887.
UNLESS OTHERWISE STATED, ALL CAPACITANCE VALUES IN UNITS ARE MMFD; IN DECIMALS, MFD.

SPLITTING AMPLIFIER

Fig. 3



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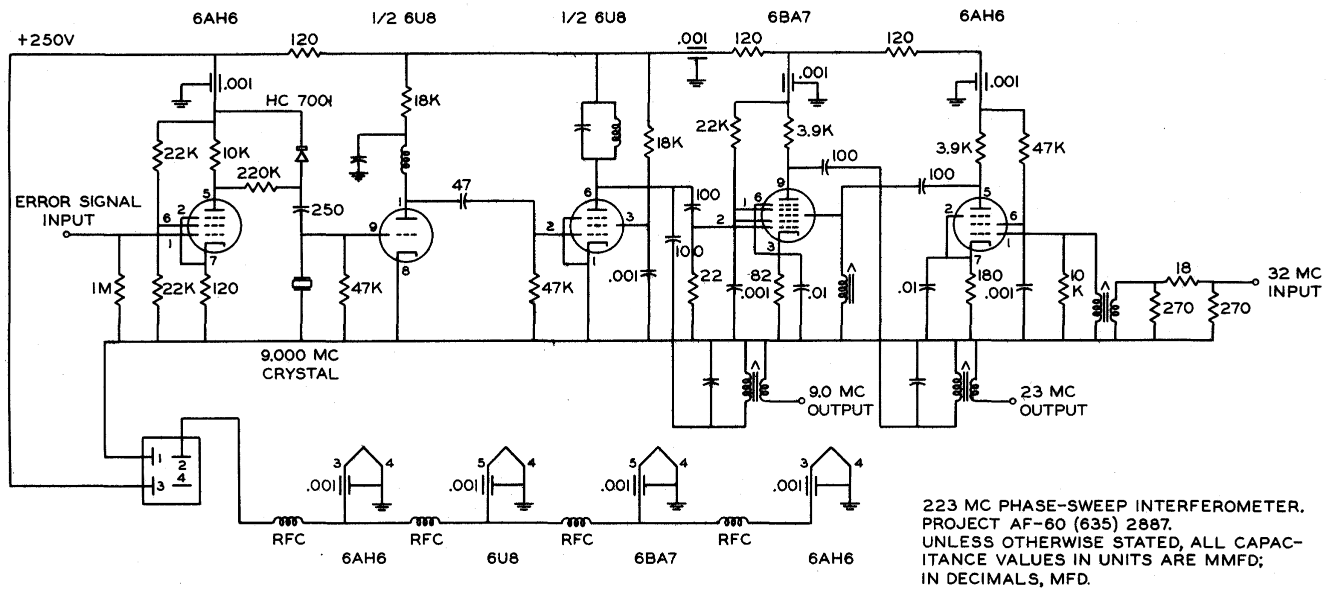
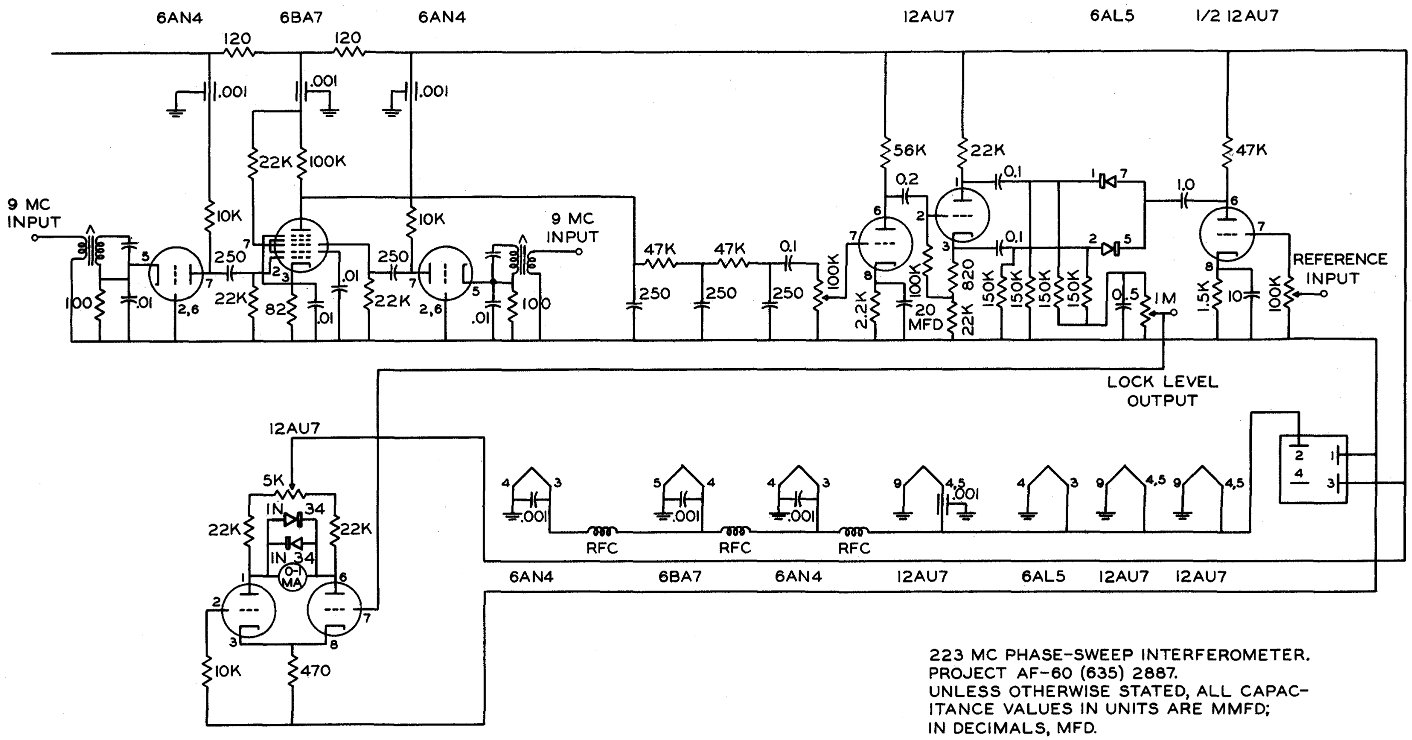
FREE-RUNNING MIXER CHASSIS

Fig. 4



CONTROLLED FREQUENCY MIXER CHASSIS

Fig. 5



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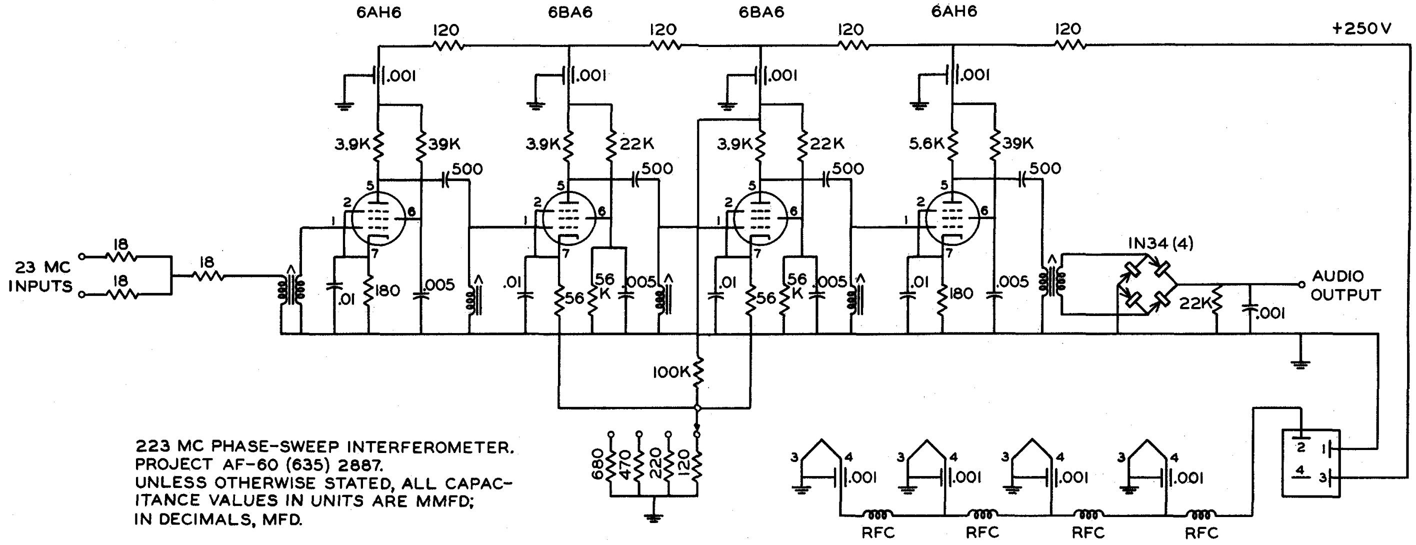
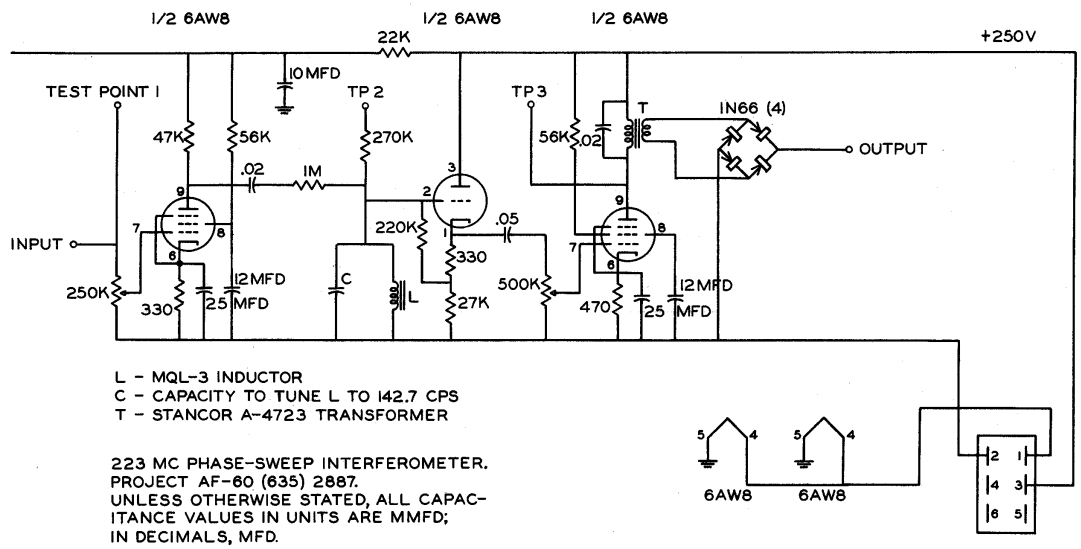
PHASE LOCK CHASSIS

Fig. 6



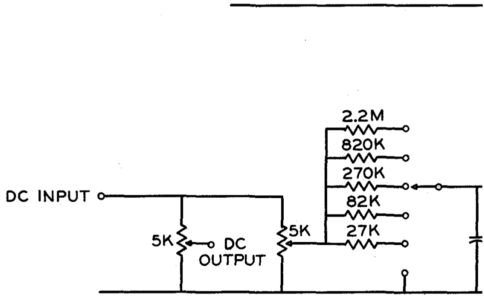
23 MC IF AMPLIFIER

Fig. 7



TUNED AUDIO AMPLIFIER

Fig. 8



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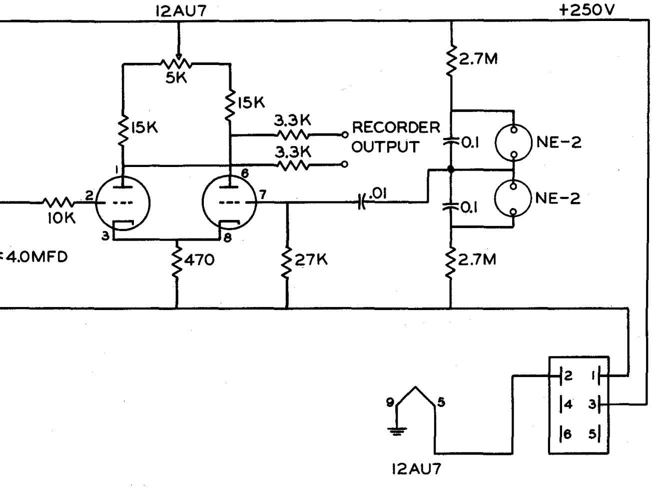
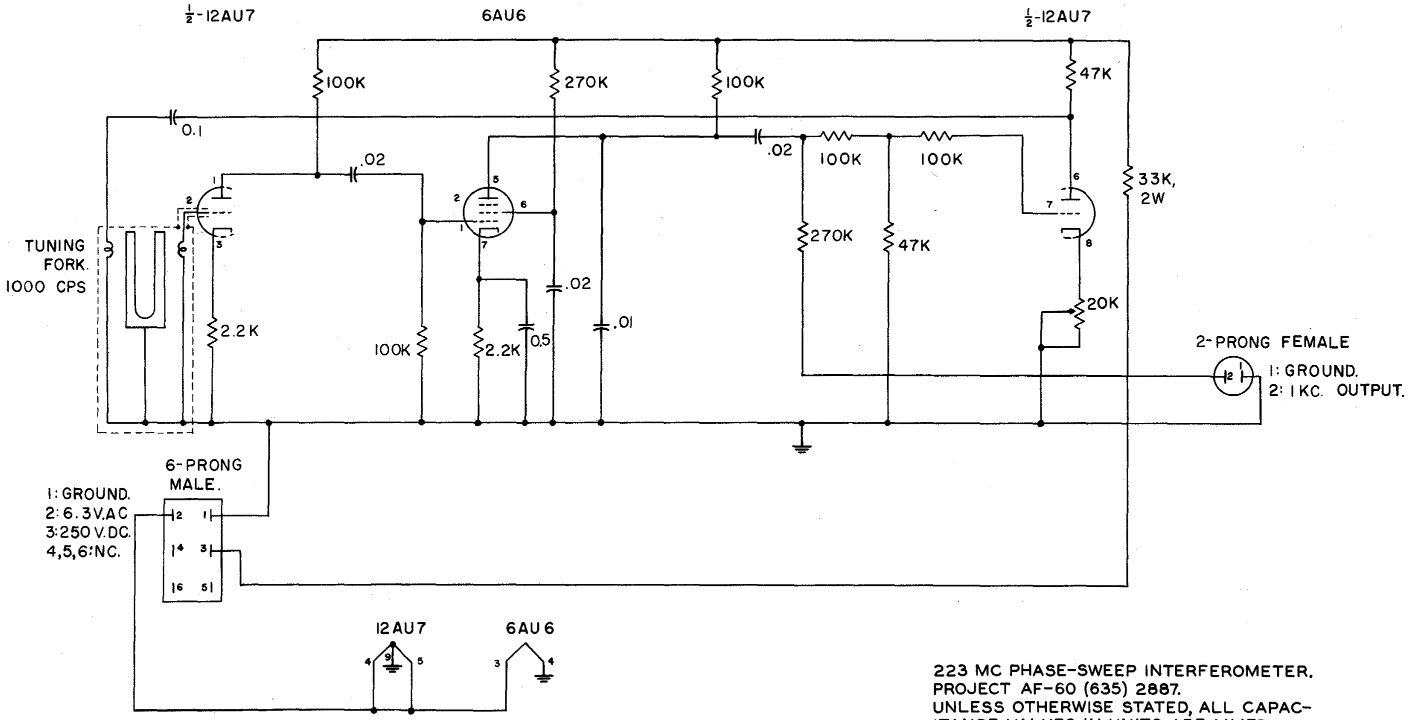


DC AMPLIFIER

Fig. 9



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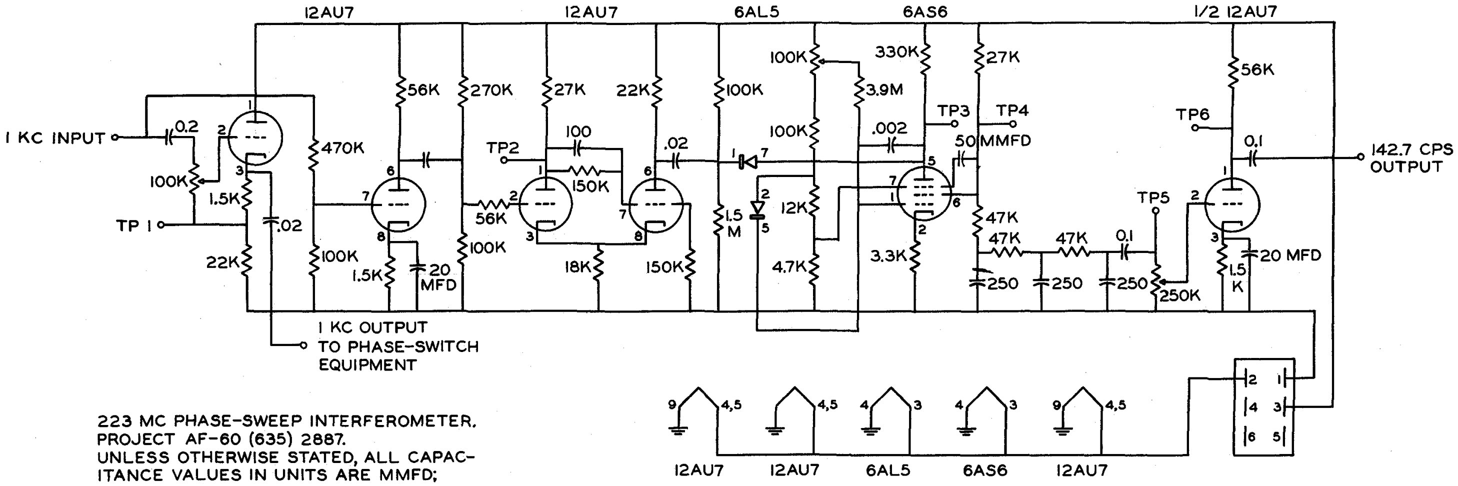
TUNING-FORK OSCILLATOR.

Fig. 10



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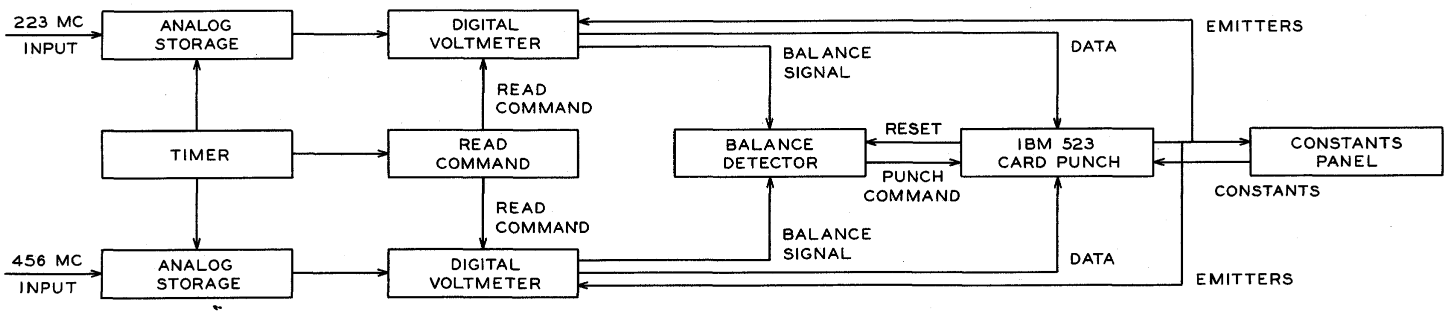
REFERENCE FREQUENCY GENERATOR

Fig. 11



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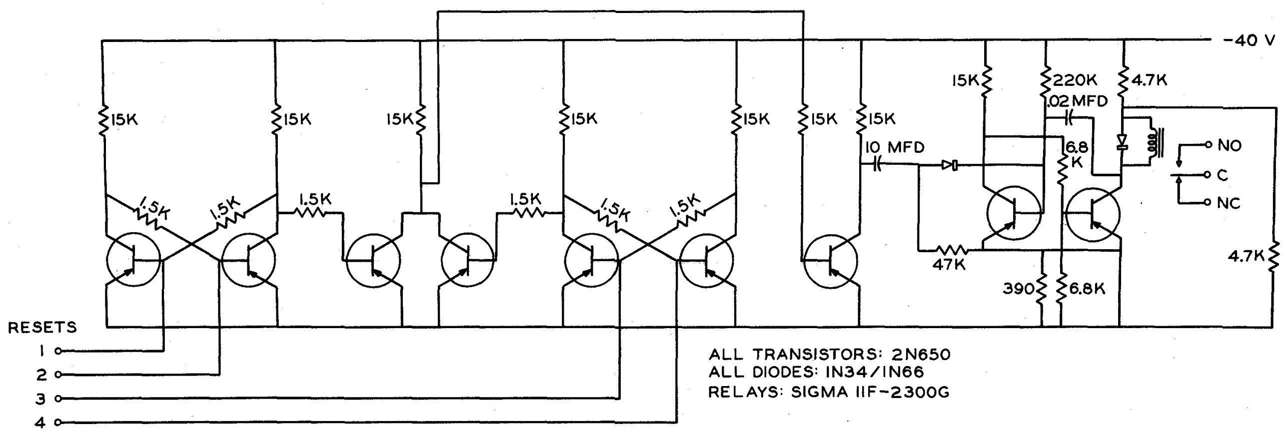
DIGITIZING EQUIPMENT BLOCK DIAGRAM

Fig. 12



COINCIDENCE DETECTOR

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Fig. 13