REPORT CRPL-5-1

ISSUED JANUARY 24, 1947

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
CENTRAL RADIO PROPAGATION LABORATORY
WASHINGTON, D. C.

INTERIM REPORT ON THE MEASUREMENT OF ATMOSPHERIC NOISE LEVEL

BY H. A. THOMAS AND H. V. COTTONY

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I. SUMMARY

The original equipment developed by one of the authors for measuring atmospheric noise on a world-wide basis is briefly described.

At an early stage in the observational program it was realised that at many locations the noise level fell considerably below one microvolt per meter at certain times of the day and that therefore, owing to the limited sensitivity of the original equipment, measurement was not always possible.

In this report the theoretical and experimental work which has been undertaken to improve the sensitivity of the original equipment is described. The improved equipment employs a high input impedance wide band preamplifier situated at the base of the antenna and connected to a receiver by a coaxial line; calibration is effected by inserting a voltage directly into the antenna system.

Provisional tests indicate that the sensitivity of the improved equipment is adequate for the measurement of noise level down to 0.05 microvolt per meter. The possibility of error in measurement due to changes in the parameters of the system has also been greatly reduced.

The improved system offers a practical means of increasing the sensitivity of the original equipment with a minimum of alteration.

II. INTRODUCTION

To compute the transmitter power required for satisfactory radio communication between two distant points it is necessary first to determine the optimum frequency corresponding to the particular time of transmission and the particular transmission path. When this optimum frequency for minimum ionospheric attenuation has been determined it is then necessary to know the minimum field intensity necessary to give a specified degree of intelligibility at that particular frequency and in the locality of the receiver. The chief factor limiting the minimum permissible value of field intensity for any grade of reception is the prevailing background radio noise level.

Investigation of the mechanism of radio wave propagation has provided means of predicting with reasonable accuracy the average field intensities obtainable from distant transmitters, and in order to improve the reliability of forecasting numerous ionospheric measuring stations have now been set up on a routine basis at a considerable number of locations.

The complementary problem of assessing radio noise level has on the contrary received scant attention. The limited nature of the available data has long been appreciated and efforts to improve knowledge of the world distribution of noise level are now being made.

As a first step the British Radio Research Board recommended in May 1943, that a survey of existing information and data on atmospheric noise level over the frequency range 1 - 30 Mc/s. be undertaken. While this critical survey of all the available published literature on the subject was being prepared, it was suggested that, concurrently, quantitative knowledge on atmospheric radio noise levels in the high-frequency radio communication bands be obtained for immediate application by developing a quantitative, but simple method of measurement for use at existing receiving stations by the operating personnel. It was considered at that time that the inauguration of a scheme of world-wide measurement by standardised equipment would not only meet the then pressing war-time needs but would also pave the way for a more comprehensive study of the science of atmospheric noise at all radio frequencies.

Such a scheme was proposed by one of the authors* and its implementation was directed by the Combined Communications Board in Washington, D.C., during the period April, 1944 - March, 1945. Eighteen stations were installed, all utilising identical equipment, and the data obtained have for the past eighteen months been collected and analysed at three centralising laboratories - the Central Radio Propagation Laboratory, Washington, D.C., U.S.A., the National Physical Laboratory, Teddington, England, and the Australian Radio Propagation Laboratory, Sydney, Australia. The factors governing the design of this original equipment, together with a brief description, are given in Sections III and IV.

It was soon realised that the measured noise level at many locations was considerably lower than had at first been thought likely and consequently that the sensitivity of the original equipment was inadequate. Effort has recently been made to develop a suitable means of modifying the existing equipment to give adequate sensitivity and this report is concerned primarily with describing the manner in which such improvement has been obtained.

III. GENERAL PRINCIPLE OF METHOD OF MEASUREMENT

The field intensity of an interfering noise cannot be specified in terms of any single parameter. Measurement can be made of the r.m.s., average, or peak value, or of the fractional time during which the disturbance exceeds some previously assigned value.

For practical purposes, measurement of any of these quantities alone serves no very useful purpose, since it is not the absolute value of any of these parameters which is required but rather the minimum value of the superimposed signal field intensity which will give a specified degree of intelligibility.

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For this reason it is now recognized that the most useful method of expressing noise is in terms of the minimum field intensity which will give a certain degree of intelligibility with a specified type of transmission.

Noise can be measured either by

(i) use of receiving equipment of known characteristics terminating in an output meter designed to register some particular amplitude characteristic of the noise which can be related to its interfering effect on signal reception,

or (ii) use of uncalibrated receiving equipment identical with that used in the particular type of communication service of interest, together with means of superimposing an artificial signal simulating an actual signal, the artificial signal being adjusted until a pre-specified degree of intelligibility is obtained.

In order that the readings given by an output meter shall indicate as nearly as possible the interfering effect on signal reception careful attention must be given to the circuit design so that subjective factors are fully taken into account. Considerable diversity of opinion exists at present as to the most appropriate constants for the circuit associated with the output meter [2,3,4,5] and until considerably more work has been done, it would be unwise to accept any particular circuit. The chief advantage claimed for the use of equipment involving a noise meter is that it dispenses with the services of an operator and permits the utilisation of automatic recording equipment. However, at the present stage of development, continuous monitoring is necessary if interfering signals are to be avoided and the equipment cannot, therefore, be left unattended.

The second method, which already has been used to a large extent, is strictly not a method of measuring noise at all, but rather a method of measuring directly the minimum field intensity required for a predetermined degree of intelligibility for a specific type of service. The distinction is a fine one, however, since the first method does not of itself provide data of immediate applicability.

The great merit of the second method is that full account is taken of all subjective factors and the measurement gives directly a value of minimum field intensity which is immediately applicable to practical calculations.

It was decided in 1944 by a special sub-committee of the Wave Propagation Committee of the Combined Communications Board that the non-availability of a fully developed method of measuring the absolute value of noise and the availability of relatively simple means of manual measurement justified the adoption of the second method for immediate application.

Accordingly, comprehensive tests were made at the Sterling station of the Central Radio Propagation Laboratory to ascertain what accuracy could be obtained with such a simple subjective method. A standard communication receiver of known band width was set up, associated with a vertical antenna and coaxial feeder; an artificial signal automatically keyed at suitable speed was introduced and its intensity adjusted until a predetermined degree of readability was attained. The noise level was defined as "the field intensity of a C.W. signal which, when keyed at ten words per minute and superimposed on the noise field, gives 95% intelligibility with a receiver of 10 kc/s band width, a word being considered as consisting of five letters".

In the tests conducted with twelve typical U.S. Signal Corps operators the effects of variations of the parameters on the system were studied. The details of these tests were reported in a C.C.B. report [6], and are summarised below.

A. Capabilities and Instruction of Operators.

The operators made available for the tests were of very varying abilities. Their respective reading speeds were first obtained and are shown in Table 1.

TABLE I

Percentage Reading Capability of Each Operator

Speed in words per minute	OPERATOR 1	2	3	4	5	6	7	8	9	10	11	12
5	100	100	100	100	100	100	100	100	100	100	60	100
10	100	90	97	87	100	100	100	100	100	100	20	100
15	100	87	95	80	100	99	93	89	100	95	0	100
20	93	82	87	75	100	91	70	70	100	30	0	100
30	30	30	40	30	96	40	30	30	40	30	0	98

It is seen that operators 5 and 12 were both capable of reading 30 words a minute with practically no error whereas operator 11 could not read 5 words a minute accurately. The varying abilities of the operators were, therefore, eminently suitable for the tests.

The normal procedure was explained and practice given to familiarize each operator with the equipment. After a very short training period, each man was able to operate the equipment satisfactorily. The difference in character between "smooth" or fluctuation noise and "crash" or impulsive noise was explained and instruction given as to how best to obtain a measure of the magnitude of both types.

With fluctuation noise, each operator was instructed to raise slowly the level of the artificial signal, after having first selected a channel free from interference, until he estimated that he would receive 50 per cent of the Morse characters. Then he was instructed to raise the level further until he estimated that he could read 95 per cent of the characters. The mean of these two readings was recorded as the measured value.

With impulsive noise, the operators were instructed to raise the level slowly, asking themselves continually whether they could read the groups which occurred during a "crash". When they had just reached a level giving 95 per cent intelligibility in the presence of "crashes" they were to record that value.

This procedure was found to be readily understood and to give consistent results.

B. Effect of Variation of Beat Frequency.

Tests were made with operators 1, 9, 10, and 12 to ascertain whether the measured value was dependent on the choice of beat frequency. Each operator in turn was blindfolded and the procedure for fluctuation noise adopted, the beat frequency being varied in each test. No difference in the measure could be observed over the frequency range 250-1700 c.p.s. Below 250 and above 1700 c.p.s. a higher artificial signal level was required to give the estimated intelligibility. The procedure was repeated with actual measurements of intelligibility, each operator being required to copy the groups for two minutes at each beat frequency. No difference in intelligibility at a given artificial signal level could be detected over the frequency band 250-1700 c.p.s.

Since the normal range which would be used by an operator lies between 500 and 1500 c.p.s. it was concluded that the beat frequency selected is of no importance to the accuracy of the measurements.

C. Effect of Variation of Receiver Gain

The receiver was adjusted to give a fluctuation noise output and the artificial signal was introduced. The gain was adjusted to give a medium telephone strength and for various signal inputs the intelligibility was measured by observing the character errors over a period of two minutes. The procedure was repeated for five gain settings ranging from a barely audible signal to one which was

uncomfortably loud (requiring the telephone to be partially removed from the ear). The results showed that the possible error which may be introduced by gain-setting variations between different operators is about ± 12% (1 db) if the range is confined to what is practicable. For exceptionally loud or extremely weak signals the possible variation may amount to ± 25% (2 db). If the telephones are removed entirely from the ear or a loud speaker used, a higher artificial signal level is necessary because extraneous acoustic noise is introduced. It is important therefore to insist that the telephones be worn properly.

D. Errors arising from Differences in the Individual Characteristics of Operators.

The characteristics of each operator were studied carefully with both fluctuation and impulsive types of noise. In all these tests the operators were blindfolded so that there was no possibility of their observing the signal generator attenuator settings.

(1). Fluctuation Noise.

A constant fluctuation noise level was set up and each operator in turn was required to copy two minutes of message at 10 words a minute for various levels of artificial signal. The percentage intelligibility was thus obtained for each signal level. This was repeated three times, and mean values obtained.

Each operator in turn was then requested without copying the characters to assess the two levels of 50 and 95 per cent. This was repeated twenty times and the range of observations or "scatter" noted: this scatter was marked on each intelligibility characteristic. A typical characteristic (for Operator.9) is shown in Fig. 1.

From these tests the maximum errors were computed and are given in Table 2.

TABLE 2

Errors in Measurement of Fluctuation Noise

Operator	"Scatter" or range of variation in estimation of signal level. (decibels)	Mean difference between estimated and measured 95% signal level. (decibels)	Maximum error in measurement of noise level (decibels)
1	± 0.6	- 4.1	- 4.7
2	± 1.2	- 3.7	- 4.9
3	± 1.3	- 2.9	- 4.2
4	± 0.9	+ 0.6	+ 1.5
5	± 0.5	- 2.1	- 2.6
6	± 1.1	- 1.2	- 2.3
7	± 0.7	- 3.3	- 4.0
8	± 0.9	- 2.4	- 3.3
9	± 0.6	- 2.3	- 2.9
10	± 1.0	- 0.3	- 1.3
12	± 0.8	+ 0.3	+ 1.6

It is seen that this method of assessing 95% intelligibility gives in most cases a field intensity which may be between 55% and 70% of the true value (3 to 5 db less), although in some cases the error is of opposite sign but small in magnitude.

(2) Impulsive Noise

For impulsive noise it is not possible to set up a standard noise input and recourse must be made to statistical methods of assessing the probable accuracy. It must always be remembered that the quantity being measured is not constant and that some at least of the observed variations may be real.

In the first place each operator was required to copy the Morse characters for two minutes at 10 words a minute for various levels of artificial signal in the presence of the noise field.

Each operator in turn was then requested to raise the artificial signal level slowly until he estimated that he could just read the message (95%) through the "crashes". The degree of consistency which attached to this estimate and the range obtained with twenty such estimates is shown in Table 3.

TABLE 3

Errors in Measurement of Impulsive Noise

Operator	"Scatter" or range of variation in estimation of signal level (decibels)	Mean difference between estimated and measured 95% signal level. (decibels)	Maximum error in measurement of noise level (decibels)
1	± 1.3	- 2.4	- 3.7
2	± 1.6	- 1.5	- 3.1
3	± 1.2	- 1.4	- 2.6
4	± 1.2	- 1.5	- 2.7
5	± 1.0	- 1.7	- 2.7
6	± 0.7	- 1.4	- 2.1
7	± 0.7	- 2.5	- 3.2
8	± 1.0	- 1.0	- 2.0
9	± 1.5	- 5.5	- 7.0
10	± 1.0	- 2.5	- 3.5
12	± 1.7	0.0	± 1.7

It is seen that, as before, the value given is likely to be between 70% and 90% of the true value (1 to 3 db low), and that, allowing for the range of variation in the estimation of the 95 % level, a maximum error of 55% (7 db) was possible in the case of one operator, but for the other ten it would not have exceeded 3.7 db.

In this method of assessing 95% intelligibility the artificial signal level is raised slowly until the message is just readable through the noise. The level might be estimated by either dropping down to the 95% level or swinging on either side of it. The differences in the measured value which might be obtained by adoption of either of these alternative procedures was examined by tests on operators 9 and 10. The results are shown in Table 4.

TABLE 4

Assessment of 95% Level by Three Different Methods

Operator	Assessment by		
	Raising Level	Lowering Level	Swinging Level
10	16	16	18
	18	18	16
	14	17	16
	15	16	16
	16	16	17
9	12	13	13
	15	15	15
	14	14	14
	15	16	16
	16	16	18

The table shows that there is no significant difference between any of the various methods of arriving at an estimate of 95% intelligibility.

E. Effect of Keying Speed

If the speed at which the tape is run be increased from 10 to 20 words a minute the measured value is higher by about 12 to 25% (1 to 2 decibels). Table 5 shows the results obtained on Operators 9 and 10.

TABLE 5

Effect of Variation in Speed of Artificial Signal

Operator	Words per Minute	
	10	20
9	23.2	24.1
	22.6	24.2
	22.3	23.8
	20.8	23.8
	21.4	25.6
10	24.2	24.2
	23.2	25.1
	23.2	25.3
	23.4	24.2
	24.0	25.3

The speed can, in practice, readily be maintained within the range 8 to 12 words a minute, in which case the error would be negligible.

F. Summary of all Sources of Error

To get a fuller picture of the probable consistency of measurement with a number of different observers a test was made on bad impulsive noise (local storms in vicinity). In this test, operators 9, 10 and 12 were required in turn to make an estimate of 95 % intelligibility by the normal method as rapidly as possible and at the same time to vary the frequency setting of the receiver over the band 2.4 - 2.9 Mc/s. A plot of 100 such measurements taken over a period of 90 minutes is shown in Fig. 2 from which it is seen that all observations lie within ± 5 decibels of the mean value. The standard deviation is 2.14 decibels and the probable error of any individual reading is ± 1.43 decibels.

The magnitude of all the possible errors which may occur in making a measurement are summarized in tabular form: .

TABLE 6

Summary of all Sources of Error in Measurement

Maximum Value of Errors in Decibels which may arise due to

Variation of band width of receiver	Variation of beat frequency over range 250-1700 c.p.s.	Variation of receiver gain	Speed variation over range 8-12 words a minute	Differences between individual operators judgment on fluctuation noise	Differences between individual operators judgment on impulsive noise
1	0	1	0	+ 1.5 to - 5.0	+ 2 to - 4

If the conditions are such as to make all the errors cumulative (which is unlikely) the maximum range of error would be + 4 to - 7 decibels about the correct value.

IV. DESCRIPTION OF ORIGINAL EQUIPMENT

Comprehensive tests made in England [7] had previously shown that for reliable measurement a vertical omnidirectional antenna system should be located on a level piece of ground not nearer than 100 feet from any hut, hedge, railing or tree, and well clear of other antennas, power lines, or other structures. Consequently, a 200-foot feeder line was provided so that the receiver could be placed in a suitable building remote from the actual measuring antenna.

A 20-foot vertical rod self supporting antenna was arranged with a buried earth system consisting of eight 40-foot lengths of copper wire arranged radially 3 - 6 inches below the ground. The antenna and receiver circuit is shown in Fig. 3. The terminating resistors were inserted to prevent standing waves on the lines. The antenna resonated at 10.5 Mc/s, and the voltage applied to the receiver for unit field strength is shown in Fig. 4. The multiplying factor necessary to convert signal generator voltage into field strength is shown in Fig. 5. Calibration at three different locations, (Washington, D.C., U.S.A., Panama, and Belem, Brazil) was made and found to be consistent.

The sensitivity of the equipment is limited by receiver noise and since the antenna is untuned, the minimum value of the noise field which can be measured with this type of equipment varies with frequency; the measured sensitivity is shown in Table 7.

TABLE 7

Frequency	Minimum Measurable Field	
	Microvolts/M	db below µv/m
2.5	0.8	2
5	0.56	7
10	0.32	27
15	0.18	11
20	0.10	11

Equipment of this type was set up at eighteen locations throughout the world and has been in continuous use for the routine measurement of noise every hour on 2.5, 5, 10, 15 and 20 Mc/s for nearly two years.

V. LIMITATION OF ORIGINAL EQUIPMENT

At an early stage in the observational program it was realized that at many locations during a considerable part of the day the noise level fell to values considerably below 1 microvolt per meter and that owing to the limited sensitivity of the original equipment, measurement was not always possible. At the instigation of the Central Radio Propagation Laboratory, it was decided to initiate an investigation into the possibility of modifying the existing equipment to give improved sensitivity.

The first method which was investigated involved the elimination of the antenna loading resistor and the tuning-out of the antenna reactance by the insertion of fixed inductors at the base of antenna for each measuring frequency. This method was examined very carefully by one of the authors [8]; it was found that, although improved sensitivity could be obtained, calibration of the equipment was critically dependent not only upon many parameters in the system but also on frequency. Since, in practice, measurement may take place over a frequency band of about 1 Mc/s it is essential that the calibration shall remain constant over each such band.

Attempt was made, therefore, to overcome this objection by adjusting the parameters of the system to give a calibration as independent of frequency variation as possible over the measuring frequency ranges. Although some improvement can be achieved by adjusting the length of the coaxial cable and suitably loading the receiver, the general conclusion was reached that it would be very difficult in practice to obtain satisfactory performance since there are far too many possibilities of variation in the parameters of the system. It was considered most desirable, therefore, to investigate alternative means of increasing sensitivity with, at the same time, a high degree of calibration constancy.

VI. DESIGN PRINCIPLES OF IMPROVED EQUIPMENT

A. Introduction

One of the authors [9] proposed modification of the original system to improve the sensitivity by adoption of an untuned high impedance preamplifier installed at the base of the antenna and connected to the distant receiver by a matched coaxial transmission line. By adopting such a preamplifier the mismatch in the antenna circuit inevitably associated with the original system can be ameliorated - use of a high impedance preamplifier allows the grid of the first tube to receive practically the full no-load e.m.f. of the antenna. Another important advantage of such a system is that, since the antenna impedance is always very high, variation in ground constants and ground resistance has negligible effect on the calibration constant of the equipment.

Before consideration was given to the circuit of the preamplifier the design of the first stage was studied, since the noise therein will impose an upper limit to sensitivity irrespective of the nature of the circuits which follow it.

B. First State of Preamplifier

The first stage needs to be reasonably efficient over the frequency band 2-20 Mc/s with good stability and the lowest possible noise level. Use of a triode, at least in the first stage is, therefore, indicated since pentodes are intrinsically more noisy than triodes, due to the presence of partition fluctuations in current. The use of a triode in radio frequency circuits, however, presents a problem of Miller effect; the grid to plate capacitance is effectively increased by a factor equal to $(A + 1)$, in which A is the voltage gain in the stage.

To illustrate the problem, consider the use of a 6AC7 connected as a triode; the input capacity is equal to 11 μμf of which the major part (say 7 μμf) is grid to plate capacitance.

With a transconductance of 12,000 micromhos and a load impedance of 600 ohms, a stage gain of seven or eight can be realized. Under these conditions the Miller phenomenon would increase the effective input capacitance from 11 to over 60 micromicrofarads. This effectively precludes the use of a triode in the second stage of the pre-amplifier.

It does not, however, preclude its use in the first stage, since it is possible to obtain appreciable amplification even with this high value of input capacitance. However, the rather wide variations in input capacitance plus variations in transconductance between different tubes of the same type and even the same make, make possible wide variations in input capacitance with each tube replacement. This would result in proportionate variations in calibrating constant of the apparatus. To prevent this the "Wallman circuit" shown in Feb.6 was proposed. This circuit consists of a grounded cathode triode amplifier tube, the output of which is fed into a grounded-grid amplifier tube. The voltage amplification of the first tube is, theoretically, equal to unity, and, therefore, Miller effect only increases the input capacitance to a value equal to twice the grid-cathode capacitance. The second tube provides full amplification.

It can be shown that the contribution of the second tube to the noise output of the stage is negligible. A Wallman circuit could also be used in the second stage, if it were found necessary to keep the noise of that stage to a minimum; actually, it was found possible to obtain sufficiently high gain from the first stage so that the tube noise contributed by the second stage was dominated by the amplified noise of the first even though the second stage employed a pentode tube.

A suitable tube having a high mutual conductance and low noise resistance is the 6AC7.

The ratio $$\frac{V_2}{V_1} = S_m \cdot \frac{1}{S_m} \cdot S_m Z$$

$$= S_m \cdot Z$$

since the input impedance of a grounded-grid triode is $\frac{1}{S_m}$.

If Sm, the mutual conductance of a 6AC7 be taken as 12. x 10-3 and Z, the impedance of the coupling unit assumed to have unity gain at all frequencies be taken as 700 ohms then $\frac{V_2}{V_1} = 8.4$

The input capacitance of a 6AC7 stage is $C_{GK} + C_{GA}(1 + A) = 18\ \mu\mu F$

in which C_{GK} = grid-cathode capacitance = 4 μμF

C_{GA} = grid-plate capacitance = 7 μμF

and A = stage gain

$= \frac{S_m}{S_m} = 1$ if the grounded-grid triode is also a 6AC7.

Allowing for the tube socket this input capacitance is about 20 μμF.

The noise produced by the first stage can be computed in the following manner. Referring to Figure 7.

$Y_i = jY + Gi$ = input admittance of input circuit across grid

$i_{TA}^2 = 4kTG_i df$ = thermal agitation noise equivalent current

$i_G^2 = 4kT5G_T df$ = induced grid noise equivalent current

$i_{KA}^2 = 4kTR_{eq} S_m^2 df$ = shot noise equivalent current in which

G_i = total conductance presented to input terminals of tube

G_T = transit-time damping conductance

$= 0.13\ f^2$ micro-ohms if f is in Mc/s.

S_m = mutual conductance of tube

R_{eq} = equivalent shot noise resistance of tube (about 200 ohms for 6AC7)

T = absolute temperature

k = Boltzmann's constant

df = band width in cycles per second

Z_A = plate load impedance

For a band width of 10 kc/s these equations may be reduced to

$$i_{TA}^2 = 1.58 \times 10^{16} G_i \qquad (1)$$

$$i_G^2 = 7.9 \times 10^{16} G_T \qquad (2)$$

$$i_{KA}^2 = 1.58 \times 10^{16} R_{eq} \, S_m^2 \qquad (3)$$

For the 6AC7 stage $Z_A = \frac{1}{S_m} = 83$ ohms

$R_{eq} = 200$ ohms

and $S_m = 12 \times 10^3$

giving a shot noise voltage at the plate of the first tube of 0.176 micro-volt.

The equivalent shot noise voltage on the grid of the 6AC7 is, therefore,

$$\frac{0.16}{\text{stage gain}} = 0.176 \ \mu v.$$

The value of i_G at 20 Mc/s is 0.0002 micro-amp and, therefore, induced grid noise will be unimportant unless the input impedance is greater than 1000 ohms.

Noise due to thermal agitation is 0.0126 $\sqrt{R_i}$ micro-volts, if $R_i = \frac{1}{G_i}$ is the effective resistance component of the input circuit; it will not become important compared with shot noise unless the resistance is greater than 400 ohms; with a resonant input circuit in which $R_i = Q_w L$ noise due to thermal agitation may become the predominant factor.

C. Antenna Coupling

For preliminary analysis it was assumed that shot noise limited the sensitivity of the first stage and that for the circuit shown in Figure 6 this limiting voltage was 0.17 micro-volt.

It was then necessary to ascertain the magnitude of the voltage which could be applied to this stage by the antenna system. The pick-up factor $\frac{E_A}{E_F}$ for a vertical antenna, E_A being the equivalent e.m.f. in the antenna circuit and E_F the field intensity is plotted in Figure 8 for various lengths in feet, assuming vertical polarization and infinite ground conductivity. It is at once noticed that increasing the height above 25 feet leads to reduction of pick-up at the higher frequencies; it would appear that a height of 25 feet is an optimum value.

If the antenna is connected directly to the grid of the 6AC7 tube of input capacitance 20 μμf the voltage applied to this tube for a field strength of one microvolt per meter is as shown in Fig.9; in computing this voltage the known constants for a 20 ft. antenna have been taken - for the proposed 25 ft. antenna, slight differences would naturally be introduced. The figure also shows the performance which would be obtained if the input capacitance of the tube were intentionally increased. It is seen that by increasing the input capacitance to between 30 and 50 μμf a much more constant sensitivity frequency characteristic can be obtained. A further advantage of increasing this capacitance is that change of tube capacitance will have only a secondary effect on sensitivity.

With direct connection it is seen that a sensitivity of between .08 and .01 microvolt per meter (22 to 40 decibels below one microvolt per meter) over the frequency range 2 to 20 Mc/s can be achieved very simply without resonance at any frequency. The impedance of the antenna circuit is always reactive and always quite large, so that small variations in antenna resistance become unimportant.

Consideration was then given to methods of stepping-up the voltage applied to the preamplifier without introducing noise. Both parallel- and tapped-tuned input circuits were considered and comparison made between the characteristic obtainable with such circuits and that obtainable with direct connection. It was soon observed that, although some additional gain could be achieved by using special input circuits, the peakiness of the characteristic with frequency was such as to outweigh the advantages. It was decided, therefore, to use direct connection.

D. Method of Feeding the Line and Receiver

The best method of feeding and at the same time matching the transmission line and receiver is to utilize a cathode-follower circuit as shown in Fig. 10.

For correct termination to prevent standing waves R_{SH} and the receiver impedance in parallel must equal Z_o, and for maximum transfer of power to the receiver R_S should be as high as possible. R_S cannot be eliminated entirely, however, since a D.C. path must be provided.

Reasonable variation in Z_R will have a small effect on the net terminating impedance and will almost certainly not give rise to significant standing waves.

The ratio E_R/V_3 will equal

$$\frac{S_m}{S_m + \frac{R_3 + Z_o}{R_3 Z_o}}$$

$S_m = 9 \times 10^{-3}$ for a 6AC7 connected as a pentode.

Therefore if R_3 be taken as 200 ohms, the ratio E_R/V_3 will be 0.32

E. Wide-band Amplifier

The noise on the grid of the preamplifier cannot be made less than 0.17 microvolt and the noise at the input of an AR88 receiver is known to be about 0.15 microvolt; consequently, since there is a loss in the cathode follower, it is necessary to provide one stage of amplification to raise the level of the preamplifier noise to a value such that it predominates over the receiver noise. Analysis of the noise figure of a system consisting of two networks A and B in cascade shows that the noise figure N_{AB} of the system as a whole is given by the expression (10)

$$N_{AB} = N_A + \frac{N_B - 1}{G_A} \quad - - - - (4)$$

in which

N_A = noise figure of network A (Preamplifier)

N_B = noise figure of network B (Receiver)

G_A = gain of network A (Preamplifier)

In other words, for minimum noise figure for the system, the gain of the preamplifier should be high if the noise figure of the receiver N_B is much larger than unity. The noise figure of the receiver used (RCA AR88) is approximately 2.5 at low frequencies, but after the padding resistor R_{SH} is added it becomes approximately 7; the gain of the preamplifier may be made fairly constant and approximately equal to 10.

The noise contributed by the cathode follower may be neglected and the equivalent noise of the AR88 receiver expressed at the grid of the first preamplifier stage is about 0.01 microvolt; the total equivalent noise on the grid from all sources should, therefore, not exceed 0.2 microvolt.

F. General Assembly and Calibration

Linking together the various components independently considered in the preceding sections, the essential circuit of the preamplifier required to be located at the base of the antenna is as shown in Fig.11.

It would seem desirable to provide all the signal gain in one unit, so raising the signal level about ten times before application to the feeder; by this means unwanted induced effects will be minimized. This necessitates an A.C. power supply lead and power pack at the base of the antenna.

To render the equipment less susceptible to changes in tube capacitance due to replacements of the 6AC7 preamplifier stage, it seemed desirable to sacrifice a little sensitivity and shunt the input circuit with a capacitance of about 20 uuF; this will also tend to reduce noise.

It would be most unwise to trust the permanance of the calibration over extended time periods and it is considered essential to insert the calibrating voltage from the signal generator directly into the antenna circuit. This circuit is now truly a series circuit and the calibrating voltage is an exact measure of the antenna voltage since the impedance is always high and there are no stray parallel paths.

This can be accomplished quite easily as shown in Fig. 11; the signal-generator feeder must be terminated with a load of 70 ohms and if a resistive load is used in the cathode circuit of the first tube the calibration volts will be substantially independent of frequency. With this arrangement the antenna constants will play a negligible part in the calibration and can be assumed the same for all equipments.

VII. DEVELOPMENT OF IMPROVED EQUIPMENT

Considerable effort was made to select the best combination of tubes in the Wallman circuit to give the lowest tube noise. Tube types 6AK5, 6J4 and 6AC7 were all tried and it was found that the 6J4 gave the best results from the standpoint of minimum tube noise. Unfortunately, however, this tube has a short life and it was considered that for practical reasons of reliability, life and cost, use of 6AC7 tubes was preferable. The noise level of this tube is approximately 25% (2 decibels) higher than that of the 6J4 but it offered an important practical advantage in that it could be used in all sockets and that it is more generally available.

Using 6AC7 tubes connected as triodes in a Wallman circuit, a series of experiments were made to determine the best operating condition to give minimum noise; it was found that minimum bias and high cathode current were required. Unfortunately, this condition also implies nonlinear operation and, as shown later, to reduce cross-modulation effects, it is of high importance to maintain linear operation as far as possible. A compromise value of one volt bias and 85 volts plate voltage produced tube noise very nearly equal to the minimum value and yet maintained operation on a linear portion of the tube characteristics.

The noise voltage for 16 Kc/s band width (that of an AR88 receiver in the "broad" condition) referred to the grid of the first tube was found to be 0.17 microvolt. Using the same tube in a pentode circuit a noise voltage of about 0.24 microvolts was obtained. Since a voltage gain of seven to eight was secured in the first (triode) stage the contribution of the second (pentode) stage increased by noise contribution of the preamplifier by only 6%.

Theoretical considerations show that further reduction of circuit noise, to the extent of 30%, can be obtained by parallel operation of two tubes in the input stage. Experimental tests confirmed these conclusions, although the improvement was more nearly equal to 20%. Because the use of parallel tubes in the input circuit involved the addition of another tube, and because of the possibility that the second tube in the Wallman circuit would also need to be parallelled, it was decided that use of parallel tubes in the input stage was undesirable.

Development of the wide-band amplifier followed conventional lines; a number of different combinations of the parameters $L_1, L_2, L_3, L_4, R_6, R_7, R_{11}$ and R_{12} (See Fig.12) were tried and the best overall performance was obtained with the following values:

$L_1 = 6.5\ \mu H$

$L_2 = 5.0\ \mu H$

$L_3 = 6.5\ \mu H$

$L_4 = 5.0\ \mu H$

$R_6 = 15000$ ohms

$R_7 = 680$ ohms

$R_{11} = 15000$ ohms

$R_{12} = 600$ ohms

The constancy of gain with frequency variation achieved by this amplifier is shown in Fig. 17.

The cathode-follower load consists of the resistor R_{14} equal to 200 ohms in parallel with the line of surge impedance 70 ohms.

The range of the signal generator voltage is 1 microvolt to 100 millivolts; the first circuit tube noise is about 0.2 microvolt. It is desirable, therefore, that at minimum setting of signal generator input the voltage delivered across the resistor R_{21} shall be slightly less than the tube noise referred to the grid. Values of $R_{21} = 4$ ohms and $R_{22} = 65$ ohms were selected to give a satisfactory range of measurement.

The impedance of the preamplifier looking into the cathode circuit of the first tube is very nearly $\frac{1}{G_m}$ or 80 ohms. Since this impedance is connected across a 4 ohm resistor, variations in this impedance will not appreciably affect the accuracy of calibration.

VIII. GENERAL DESCRIPTION OF IMPROVED EQUIPMENT

The various components of the improved equipment are shown in Fig. 13 and are listed below:

A. Antenna and preamplifier
B.C. and D. Automatic transmitter for keying the signal generator
E. Signal generator
F. Receiver
G. Receiver input matching unit (110 ohms in parallel with receiver).
H. Signal generator matching unit (70 ohms in parallel with line to give correct 35 ohm load to generator)
J. Distribution base and switches
K. Receiver coaxial 70 ohm radio frequency cable (200 feet)
L. Calibration generator 70 ohm radio frequency cable (200 feet)
M. Supply lead to preamplifier (200 feet)

The mechanical arrangement of the antenna and preamplifier is shown in Fig. 14 and top and bottom views in Figs. 15 and 16 respectively. The unit consists of a 25 foot vertical steel antenna mast A_1 bolted to the antenna base insulator assembly A_2. This base is supported by a housing A_3 comprising three units - cover, base, and support - which, when the housing is bolted securely, provides a support for the antenna and at the same time a weatherproof cover for the preamplifier A_4. Contact is made between the antenna and preamplifier by the assembly A_5.

To prevent condensation on the electrical components a small heater is provided to maintain an interval temperature 20-30° F above the ambient temperature.

IX. PERFORMANCE OF IMPROVED EQUIPMENT

Pending the manufacture of a considerable number of equipments for distribution to the existing noise measuring station preliminary tests have been made on a prototype preamplifier constructed at the National Bureau of Standards.

In this prototype equipment built specifically for test purposes the components are not exactly identical with those which will be used in the equipment for distribution; in particular, the input circuit differs somewhat from that which will apply to the final sets. For this reason the performance given in this section will not apply strictly to the final equipment, but the differences will not be such as to affect the essential conclusions drawn from the experimental work on the prototype.

A. Gain of Preamplifier

The preamplifier was set up with an AR88 receiver connected across the output; the measured gain is shown in Fig. 17 from which it is seen that over the frequency range 1-20 Mc/S the variation does not exceed ± 15%.

B. Sensitivity of Preamplifier

Since the lower level of atmospheric radio noise which can be measured by the equipment is limited by the circuit and tube noise of the preamplifier, the latter is a very important quantity. It was measured at a number of frequencies and its values are shown in Fig. 18.

The value of the circuit and tube noise, as used in this discussion, is the voltage of a single frequency which when applied to the grid of the first tube produces the same voltage indication in the output of the second detector of the receiver as does the circuit noise itself, at the same gain setting. In making the measurement, a single frequency voltage was applied to the grid of the first preamplifier tube and its value was adjusted until the output indication was ten times that due to noise of the preamplifier alone. The preamplifier noise was then, by definition, equal to one tenth of the calibrating signal. The linearity of detection was verified and found to be satisfactory over the range of measurement.

It should be noted that the noise voltage is a function of bandwidth; it is, in fact, proportional to the square root of the bandwidth. The value determined in this series of measurements corresponds to the bandwidth of an AR88 receiver in the "broad" position where the effective bandwidth is 16 kc/sec. It is sometimes convenient to express tube noise in terms of a resistor which would give equal thermal voltage at room temperature, thus eliminating the bandwidth. The value of such a resistor for the tube used in this circuit would range from 100 ohms at 1 Mc/s to 750 ohms at 20 Mc/s. This value may be compared with that given by W. A. Harris [11] who cites a value of 200 ohms for a 6AC7 tube when used as a triode.

C. Calibration Constant of Preamplifier

The preamplifier calibration constant is defined as the factor which has to be applied to convert the applied signal generator voltage to equivalent voltage supplied to the grid of the first tube. For the manufactured equipment it should, theoretically, be 4/69 or 0.058. In the tests on the prototype a 50 ohm cable only was available and the values of R_{21} and R_{22} (see Fig. 12) were accordingly 4 and 47 ohms respectively; the theoretical value of the constant is, therefore, 4/50 or 0.08.

The value of this constant was measured at frequencies between 1 and 20 Mc/s, and the values are shown in Figure 19. It can be seen that the calibration constant of the prototype model varies with frequency due undoubtedly to inductance in the 4 ohm resistor. It is expected that in the production models this inductance effect will be negligible.

D. Cross Modulation Effects

Because the preamplifier is untuned, all signals at frequencies from below 1 Mc/s to over 20 Mc/s will be amplified and passed through the amplifier uniformly. Since no tube characteristics are linear, some degree of cross modulation will inevitably be introduced.

Cross modulation may manifest itself in two different ways; in one, two reasonably powerful signals may beat against each other so producing two cross modulation products at frequencies equal to the difference and sum of the frequencies of the signals. If the cross-modulation characteristics of the preamplifier were pronounced the effect would be to increase appreciably the congestion of the radio spectrum making it more difficult to find unoccupied frequency bands in which to make a measurement of atmospheric noise. The other way in which cross modulation may be significant is as follows; with the receiver tuned to some particular frequency the measure of noise over the acceptance band of the receiver may be affected by cross modulation products of noise at other frequencies.

The importance of the first effect can be found only by long experience in the field and will depend upon the prevalent field intensities existing at particular sites. It is possible, however

to make some laboratory measurements giving at least an indication of the possible magnitude of such cross modulation effects. In Figure 20 are presented the results of a simple test in which two voltages differing in frequency by the frequency to which the receiver is tuned were injected into the input circuit; the value of the output is plotted for varying signal voltages. It can be seen that the product of the two signals in microvolts must exceed 50,000 before the cross modulation product appears above the noise level of the system.

To measure the effect of noise cross modulation a noise diode was used, the test circuit being shown in Figure 21; the output of the noise diode was connected to an untuned preamplifier which increased the noise output to the fairly high level of about 20 microvolts for the bandwidth of the receiver. The output from this amplifier was fed into a band rejection filter passing with negligible attenuation all frequencies except the one band at 2.5 mc/sec. at which frequency attenuation of over 300 times in voltage occurred. The output from the band-rejection filter was in turn fed into the preamplifier and receiver.

The results of this test are shown in Figure 22. It can be seen that the noise level at 2.5 mc. is approximately .01 of the level at other frequencies. This can be accepted as a proof that cross modulation products do not give rise to an output greater than .01 of the maximum atmospheric noise received anywhere in the frequency spectrum. Consequently it may be inferred that if the difference between the minimum and the maximum atmospheric noise intensity over the spectrum is not greater than 100:1, no errors should be encountered in measuring accurately the noise level at any frequency.

E. Performance of Complete Equipment

The tests described in the preceding section were all made on the preamplifier alone; the performance of the complete equipment under field conditions cannot be determined until the final equipment is available. Owing to time limitation and lack of exact replicas of the radio-frequency cables which will be used it is not yet possible to give an exact statement of performance, but it has been found possible to give a reasonable indication of the probable performance by setting up the equipment in the field under conditions which simulated reasonably well the actual conditions which will ultimately exist.

The prototype model of the preamplifier was set up and connected to an exact replica of the antenna; the capacitance of the antenna lead from the antenna base to the input of the preamplifier was 92 μμF, whereas in the production models it will be much less; the impedance of the receiver coaxial cable was 70 ohms, but the impedance of the calibrating generator cable was only 50 ohms. Otherwise, the rest of the equipment was identical with that which will be provided in the production models.

1. Calibration Constant of Preamplifier Including Voltage Generator Cable.

The first test made was made with a test signal-generator connected across the input of the preamplifier in place of the antenna; the output from the receiver was indicated by a meter in the diode circuit. The test generator was adjusted to give a constant input of 1 millivolt and then the calibrating generator was adjusted to give the same output both being observed by indication on the diode meter. The value of the calibrating generator voltage required in decibels above one microvolt per meter is plotted in Figure 23. The observations show some evidence that the 50 ohm line transmitting the calibrating signal was not properly matched at the load (preamplifier)end.

2. Calibration Constant of Equipment

The calibration constant of the complete equipment is defined as the factor which when applied to the actual signal generator voltage as read on the attenuator gives at any frequency the actual corresponding field strength in microvolts per meter.

To obtain this the antenna was connected and local fields generated; an indication in the diode meter was obtained and then this same diode current was obtained by injection of the calibrating signal generator voltage. The field was simultaneously measured by an R.C.A. Field Intensity Measuring Equipment Model No. 308A.

The result obtained is shown in curve A of Fig. 24 and for comparison the theoretical constant is shown in curve B; the latter having been computed by using the measured constants of a 20 foot, instead of the actual 25 foot antenna; close agreement is not, therefore, to be expected.

3. Sensitivity of Equipment

To determine the sensitivity of the equipment the antenna was disconnected and the noise level of the system measured in terms of the calibrating generator voltage; this is shown in curve C of Figure 26. Applying the calibration constant shown in curve A the minimum field intensity which can be measured by the system is computed and is shown in Curve D.

It can be seen that a minimum field intensity of .05 to .018 microvolt/meter (26 to 35 decibels below one microvolt per meter) can be measured if the limiting factor is circuit and tube noise.

In the production models in which the capacitance shunted across the preamplifier input should be appreciably less than that existing in the prototype model, the sensitivity should be increased, particularly at the high-frequency end of the measuring range.

X. CONCLUSION

A. The improved system has a number of advantages over other possible alternatives, mostly of a practical character. It requires a minimum of additional equipment which can readily be adapted to the existing apparatus and it does not call for any new procedures on the part of the operating personnel and it is not likely to get out of adjustment. A particularly valuable improvement is the injection of the calibrating signal at very nearly the point of antenna input; in this way errors of calibration are minimized.

B. The only disadvantage of the improved system is the possibility of cross modulation effects introduced by use of a wide-band preamplifier. As pointed out previously such effects may interfere with operation in two ways; firstly, the spectrum may be congested by the addition of cross modulation products appearing as interfering signals, and secondly, errors in the measurement of a minimum noise may occur when such a minimum coexists with strong atmospheric noise at other portions of the spectrum.

The first possible disadvantage can only be determined by extensive field experience; preliminary field tests have failed to show it to be of particular significance. The second possibility, of the noise cross modulating with itself, appears to have been settled satisfactorily provided the minimum noise voltage is not less than about .01 of the prevalent noise over the frequency range of the preamplifier.

C. The improved system is capable of measuring atmospheric noise over a range of .05 to 5000 microvolts/meter (-25 to + 75 decibels above one microvolt per meter), at all frequencies within the band 2.5 to 20 Mc/s.

D. The calibration is independent of frequency over any one of the five measuring ranges.

E. The improved system appears to be quite stable as far as calibration and gain are concerned.

'F It is believed that the improved system offers a practical means of increasing the sensitivity of the original equipment with a minimum of alteration.

XI. ACKNOWLEDGEMENTS

Acknowledgement is expressed to Mr. R. Bateman for many suggestions and comments on the equipment and methods of testing. Acknowledgement is also due to Mr. F. P. Viezbicke who was responsible for the bulk of the mechanical details and layout.

BIBLIOGRAPHY

(1) Radio Research Board Special Report by H. A. Thomas and R. E. Burgess, British Stationery Office.

(2) C. V. Aggers, D. E. Foster and C. S. Young "Instrument and Methods of Measuring Radio Noise", Elect. Eng. 1940 V 59 178-192.

(3) C. M. Burrill "An Evaluation of Radio Noise Meter Performance in Terms of Listening Experience" Proc. Inst. Radio Engrs.N.Y. 1942 V30 473-478.

(4) C. M. Burrill "Progress in the Development of Instruments for Measuring Radio Noise" Proc. Inst. Radio Engrs. N.Y. 1941 V 29 433-442.

(5) British Standards Institution "The Characteristics and Performance of Apparatus for the Measurement of Radio Interference" B.S.S. 1937 No. 727.

(6) C.C.B. Report CX/WP 19/6 22 June 1944

(7) BBC Report "An Approximate Method of Field Strength Measurement in the Band 2-8 Mc/s and Its Application to Measurement of Noise Interference". G. I. Ross.

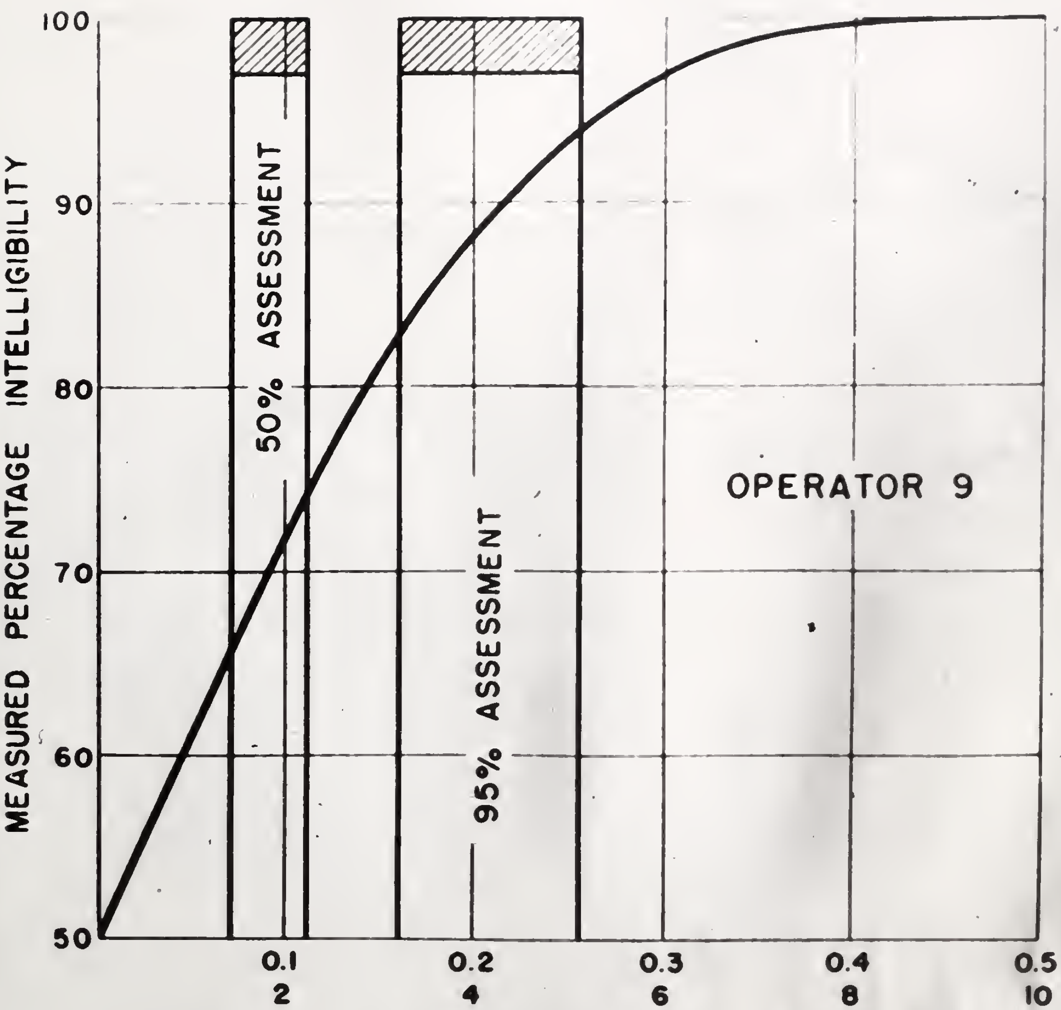
(8) Report to C.R.P.L. No. 1 by Dr. H.A. Thomas, May 1946.

(9) Report to C.R.P.L. No. 2 by Dr. H. A. Thomas, July 1946.

(10) Noise Figures of Radio Receivers - by H.T. Friis (Bell Telephone Laboratories) Proceedings Institute of Radio Engineers Vol. 32 No. 17 - July 1946, page 419 ff.

(11) Fluctuations in Space-Charge-Limited Currents at Moderately High Frequencies - Part V - Fluctuations in Vacuum Tube Amplifiers and Input Systems - by W. A. Harris, R.C.A. Mfg. Co. R.C.A. Review Vol. 5 No. 4 April 1941 p. 505 ff.

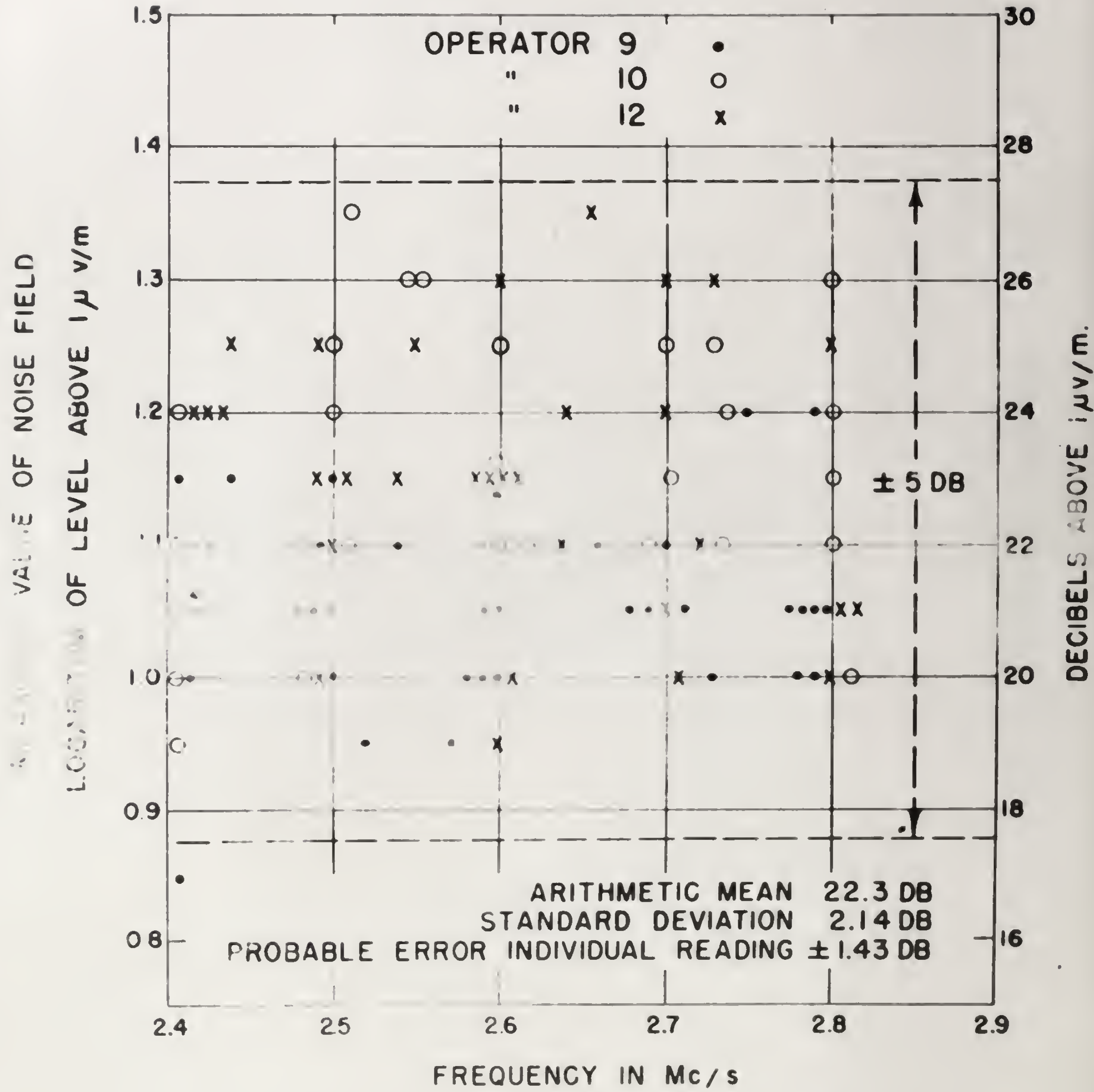
December 20, 1946.



RELATIVE SIGNAL VOLTAGE LEVEL EXPRESSED AS LOGARITHM OF VOLTAGE AND (BELOW) IN DECIBELS

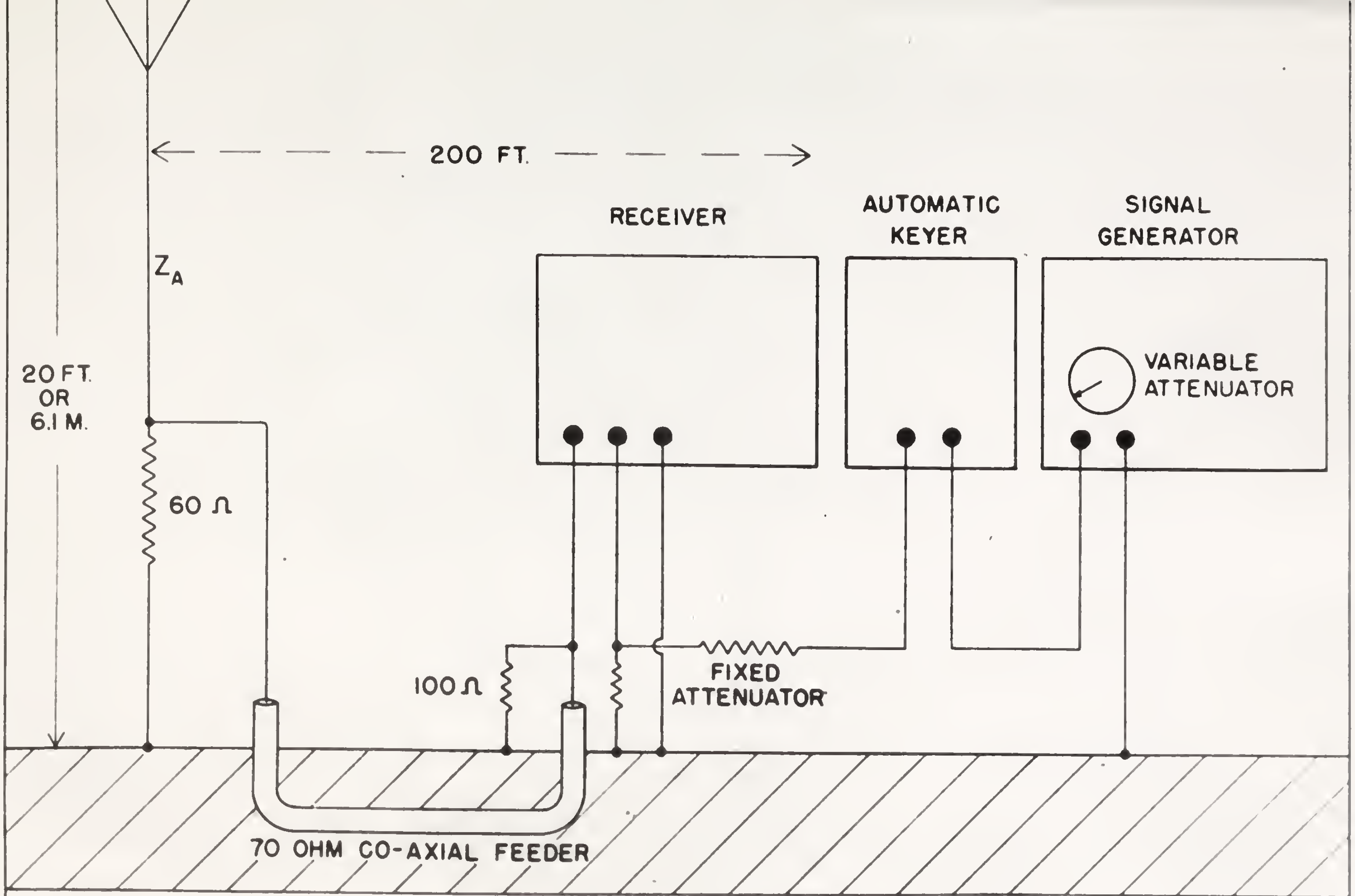
TYPICAL INTELLIGIBILITY CHARACTERISTIC

Fig. 1.



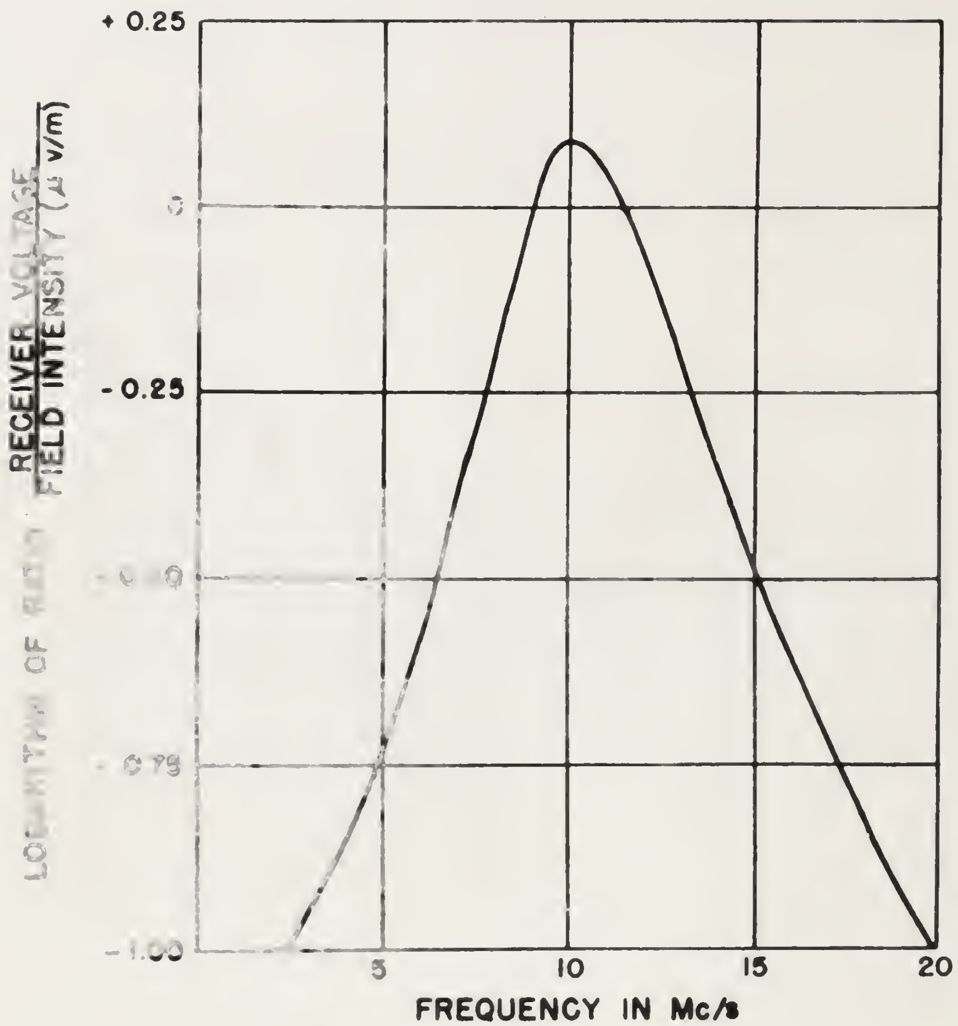
PLOT OF 100 OBSERVATIONS OVER A FREQUENCY BAND

Fig. 2.



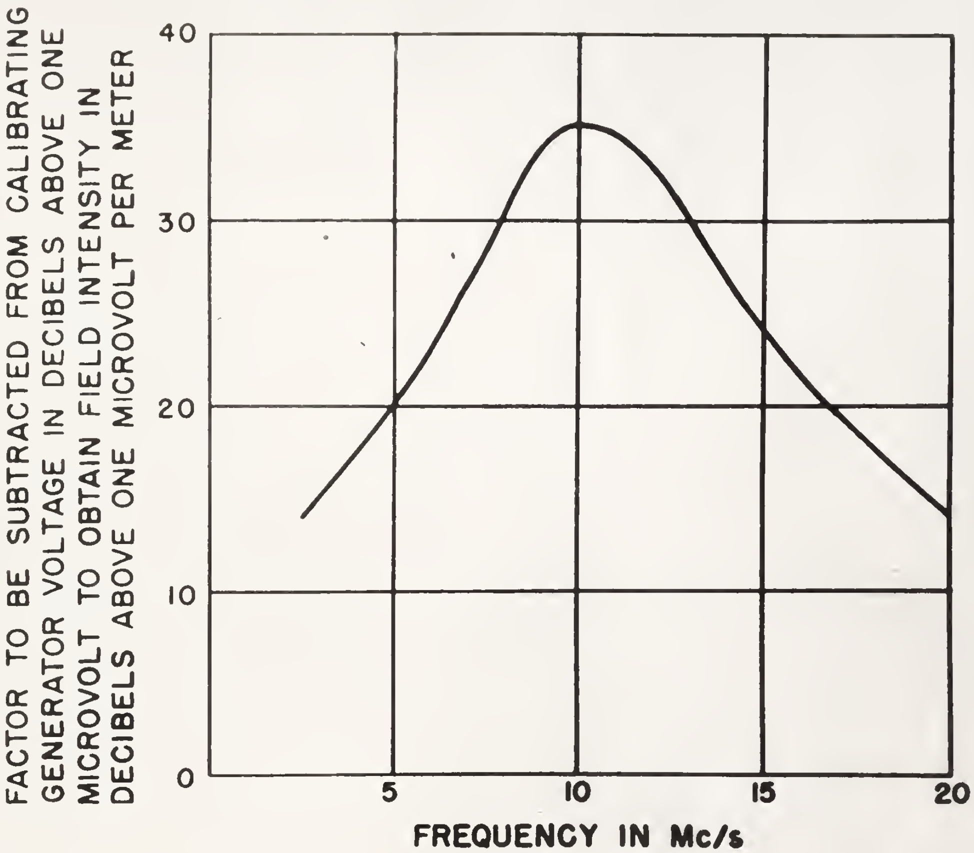
CIRCUIT OF ORIGINAL EQUIPMENT

FIG. 3



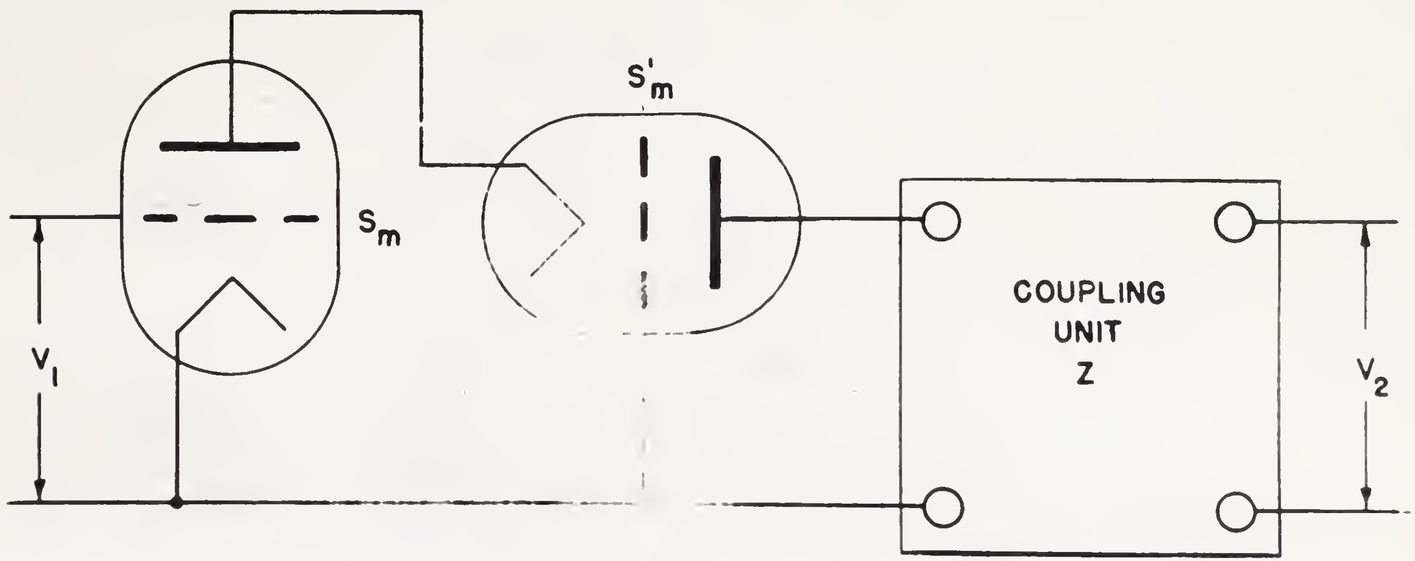
RATIO $\frac{\text{RECEIVER VOLTS}}{\text{FIELD INTENSITY}}$ FOR ORIGINAL EQUIPMENT

Fig. 4.



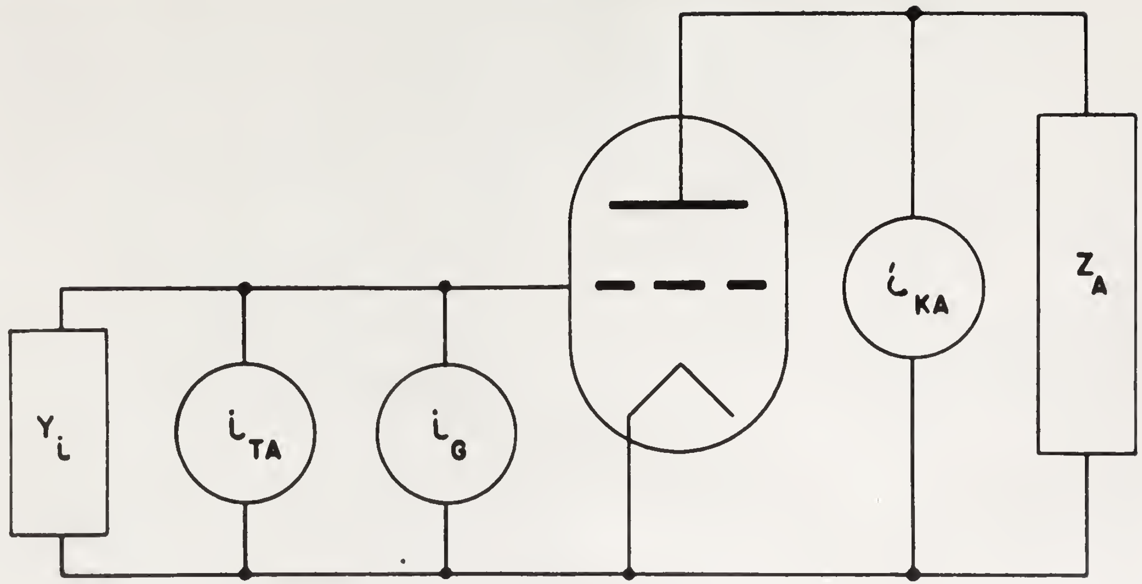
CALIBRATION CONSTANT OF ORIGINAL EQUIPMENT

Fig. 5.



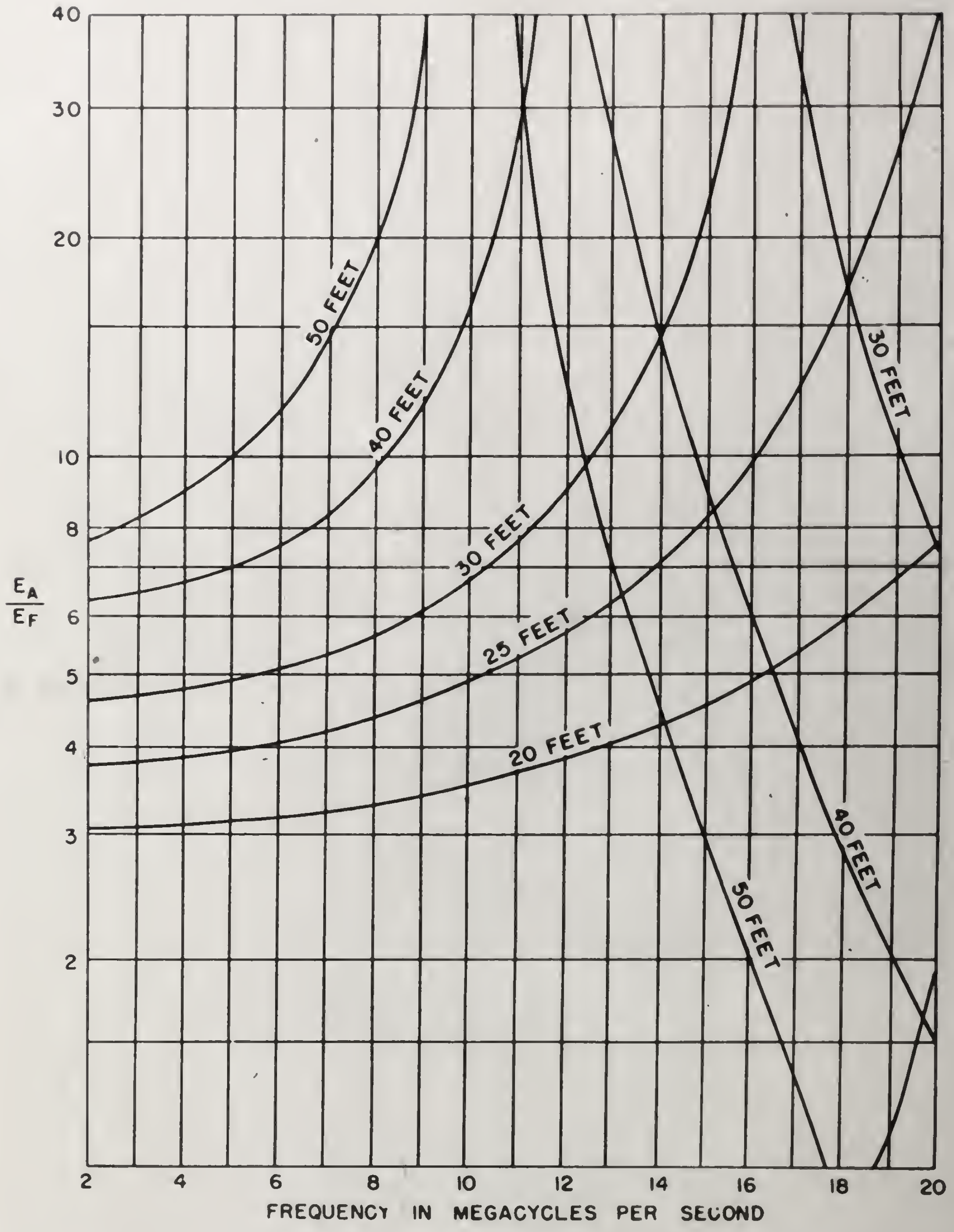
FIRST STAGE OF PREAMPLIFIER

Fig. 6



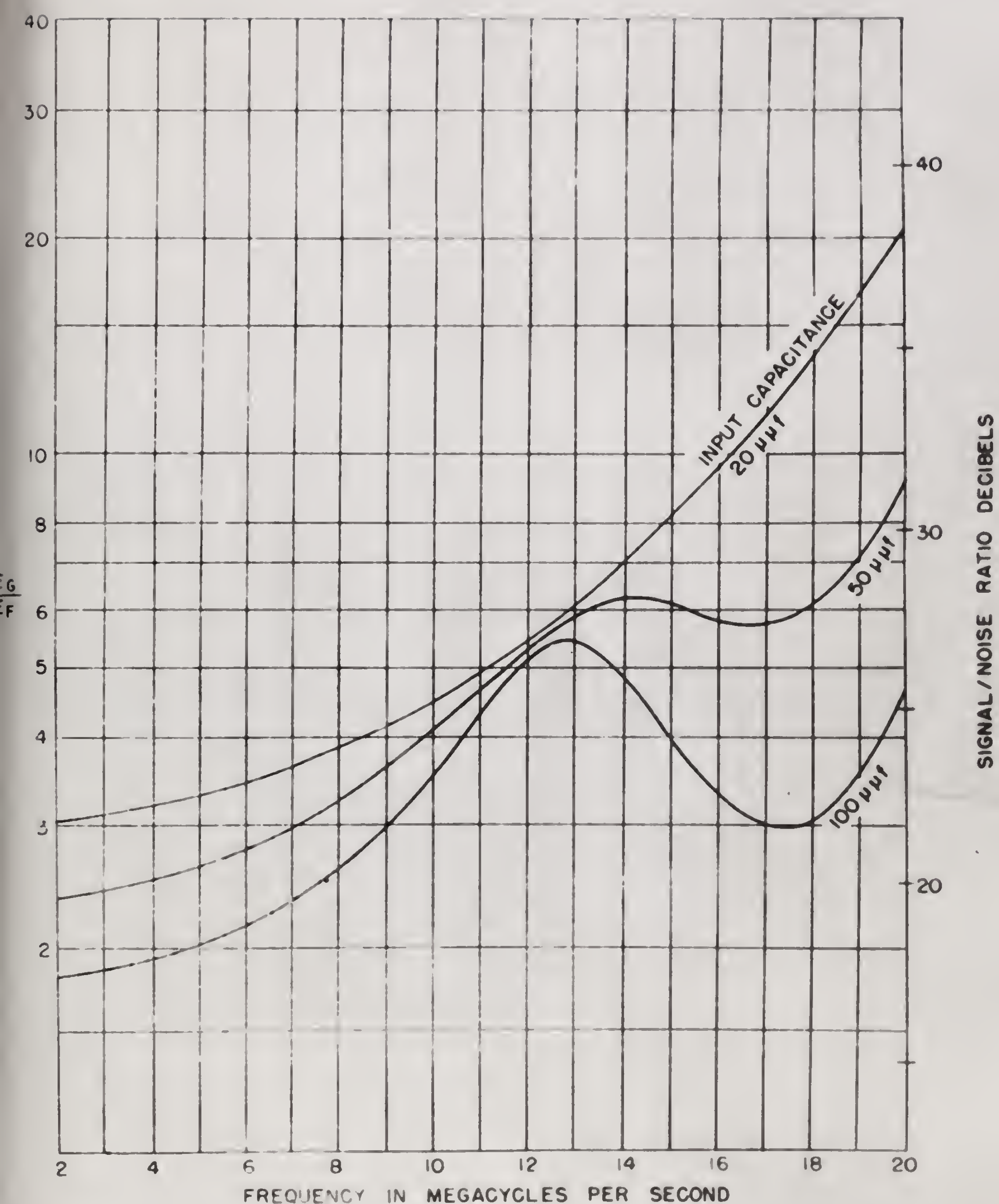
EQUIVALENT NOISE CIRCUIT OF TUBE

Fig. 7



PICK-UP FACTOR OF ANTENNA

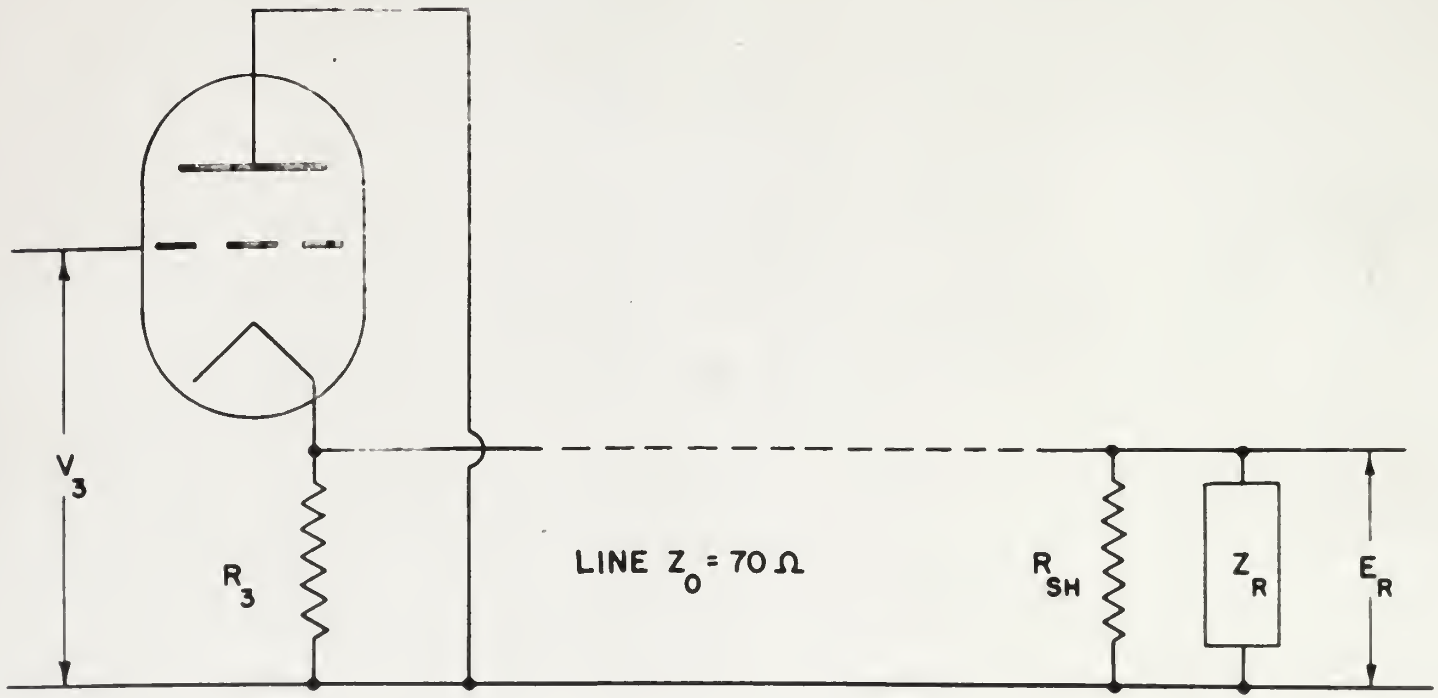
Fig. 8.



MICROVOLTS APPLIED TO GRID OF PREAMPLIFIER FOR 1μv/m FIELD INTENSITY

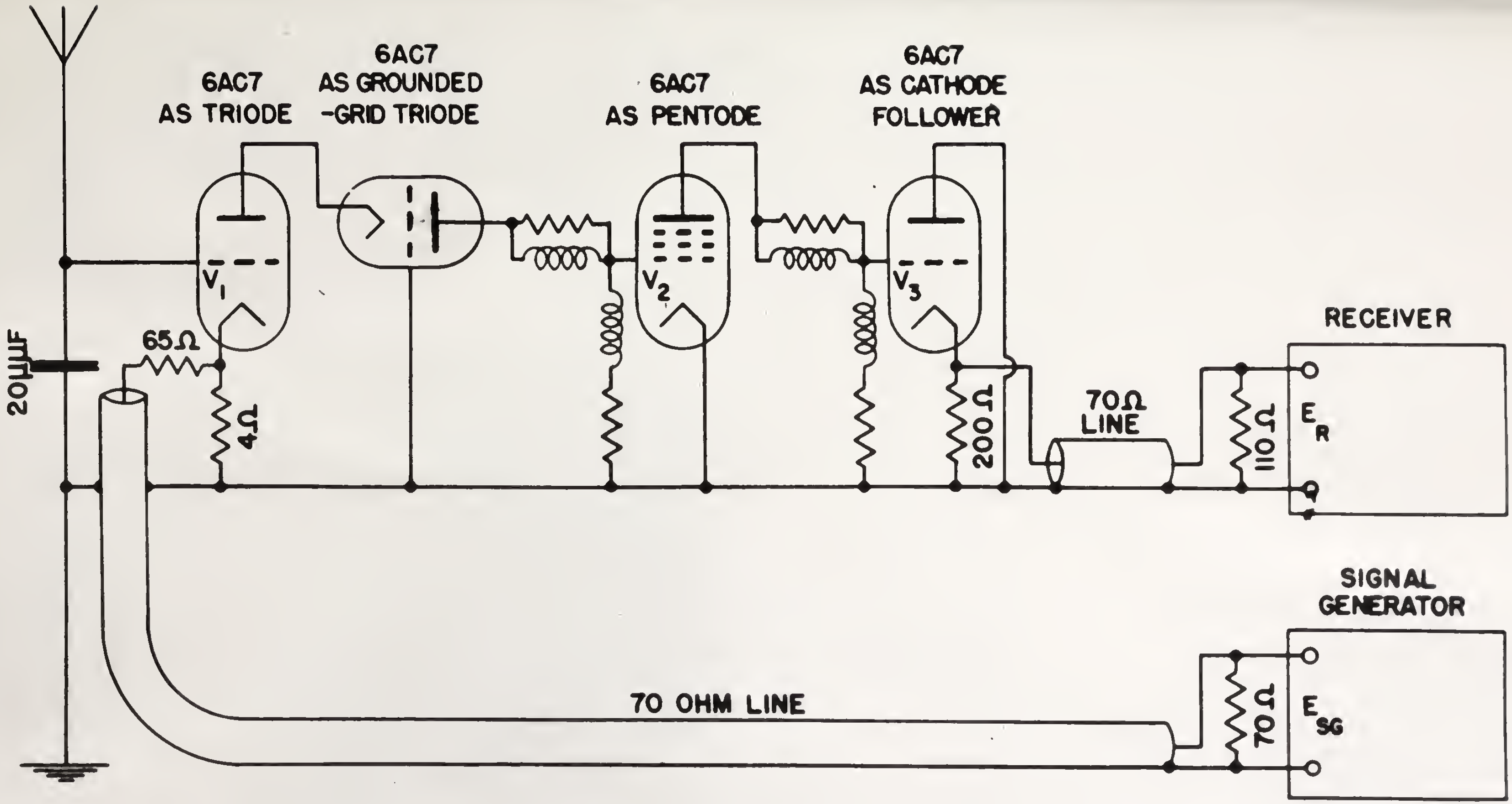
DIRECT CONNECTION

Fig 9



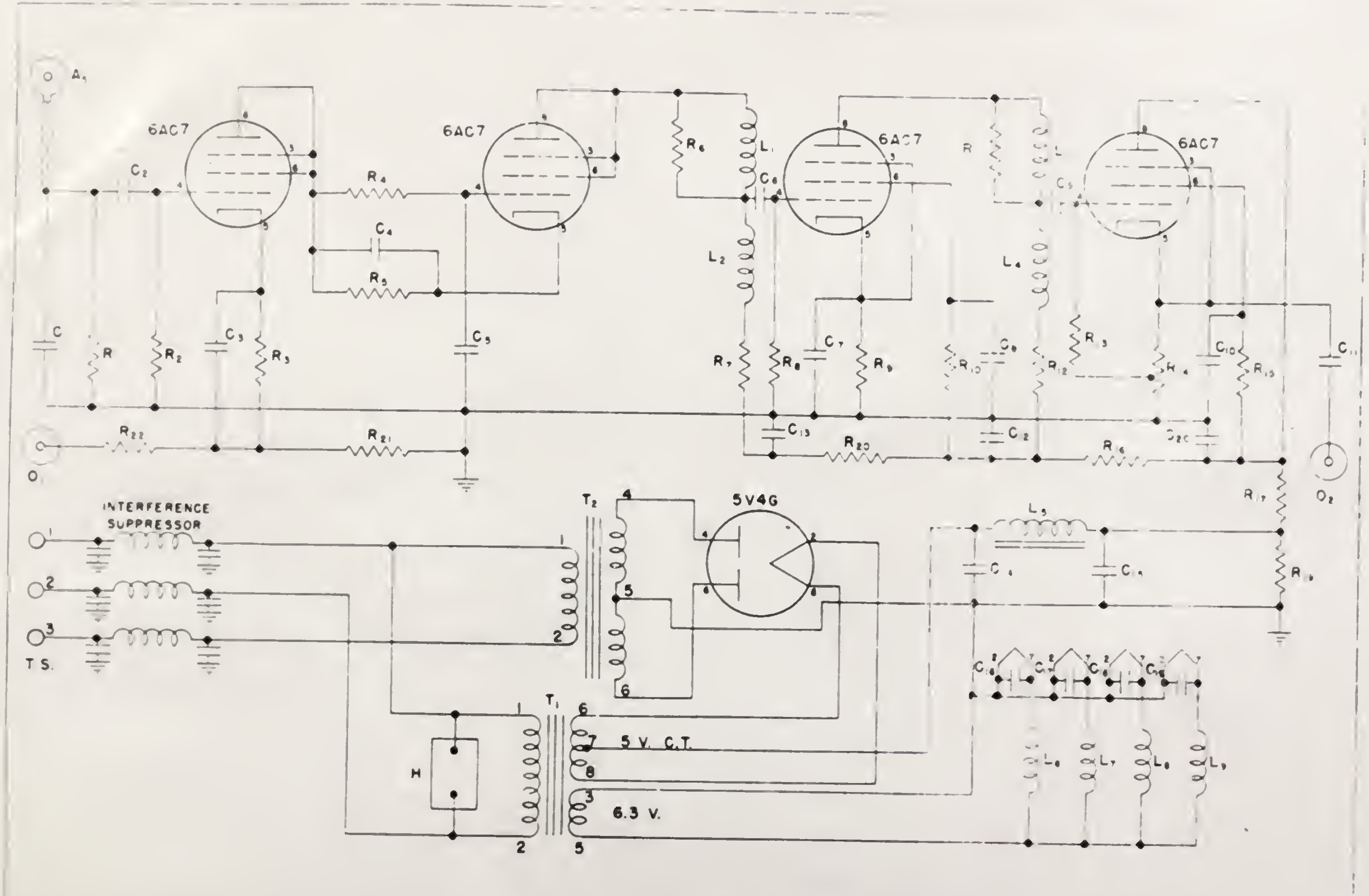
CIRCUIT OF CATHODE FOLLOWER

Fig. 10

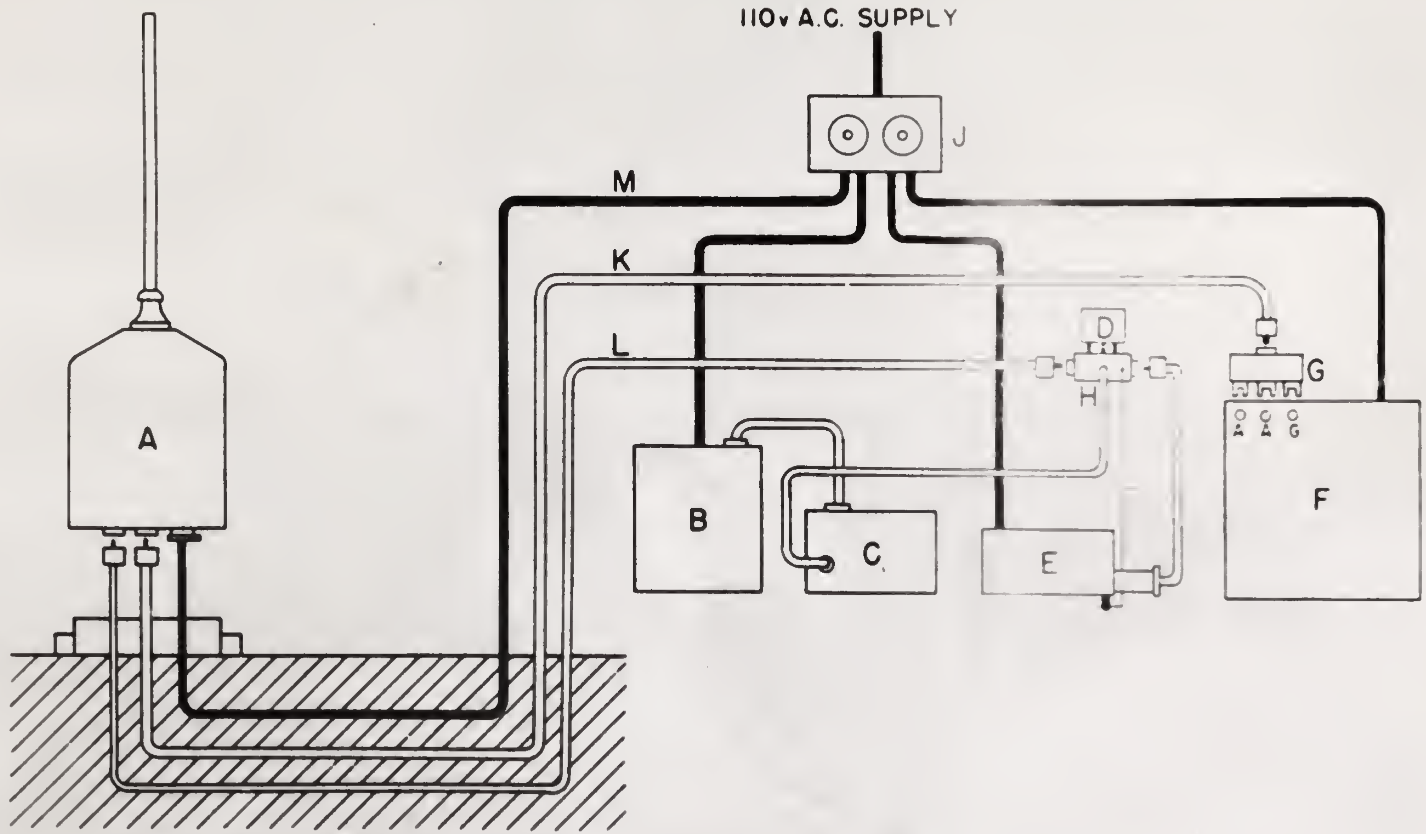


BASIC CIRCUIT OF PREAMPLIFIER SYSTEM

Fig.11

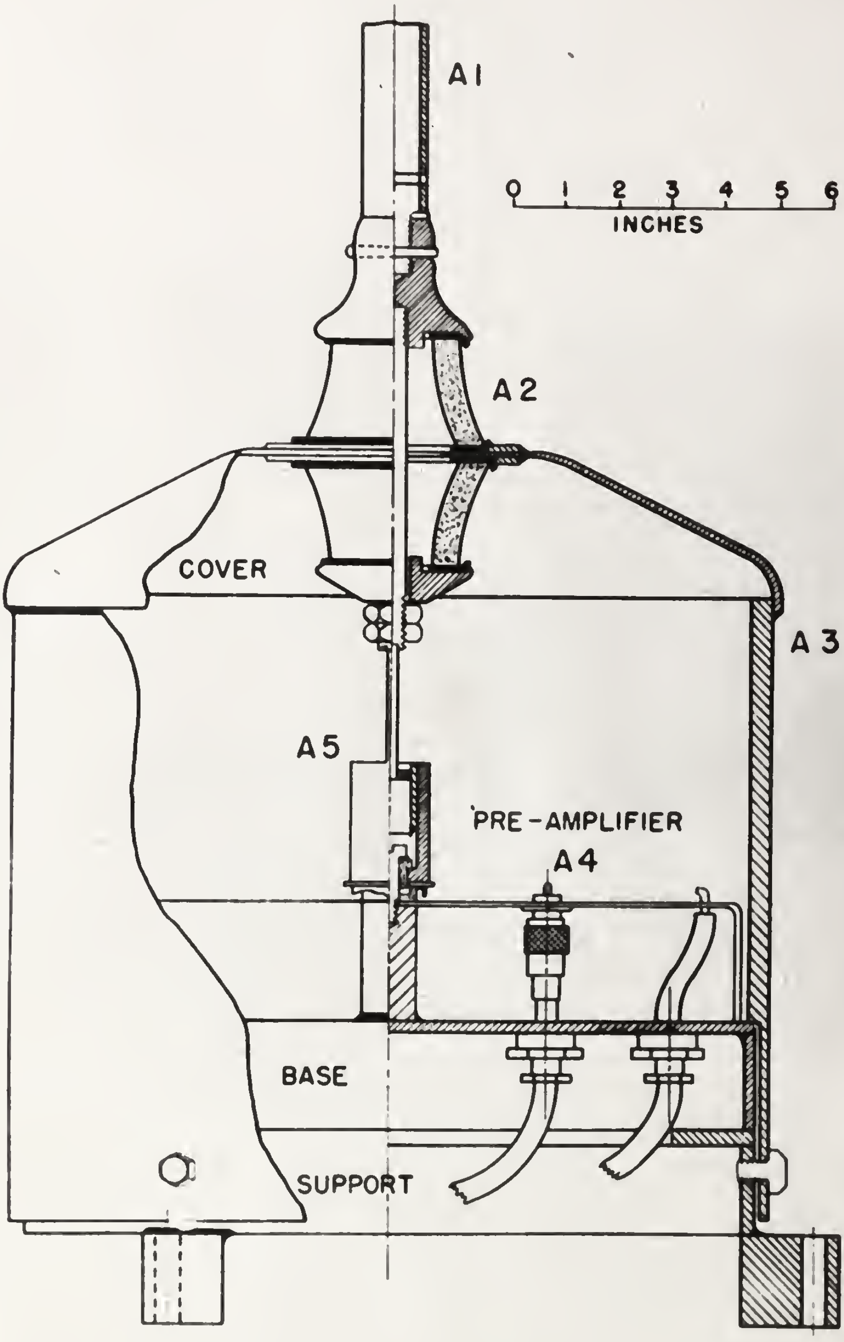


CIRCUIT DIAGRAM OF PREAMPLIFIER
Fig. 12



BLOCK DIAGRAM OF IMPROVED EQUIPMENT

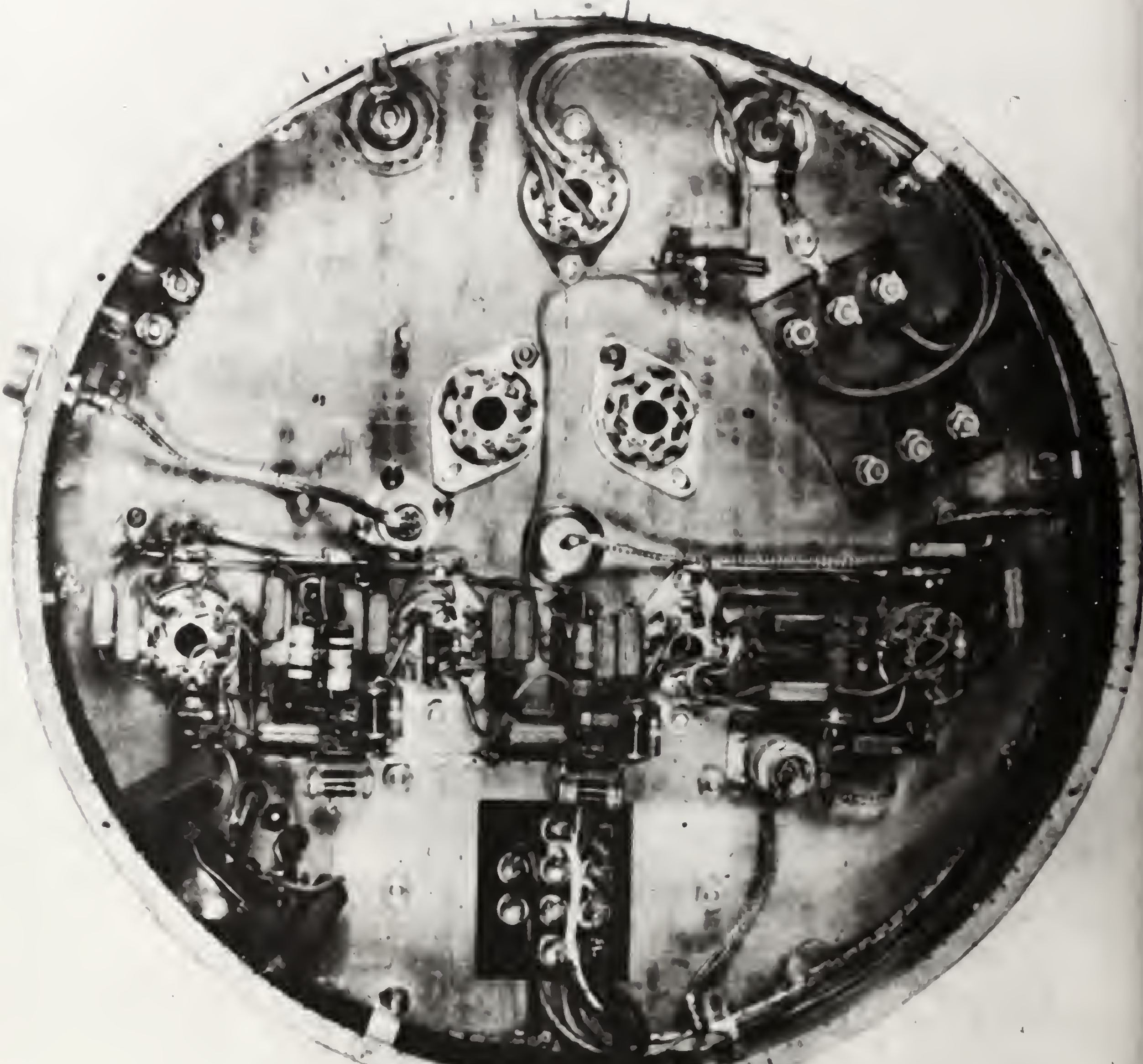
Fig. 13



GENERAL ARRANGEMENT OF ANTENNA AND PREAMPLIFIER

Fig. 14

TOP VIEW OF PREAMPLIFIER
Fig 15.



BOTTOM VIEW OF PREAMPLIFIER
Fig. 16.

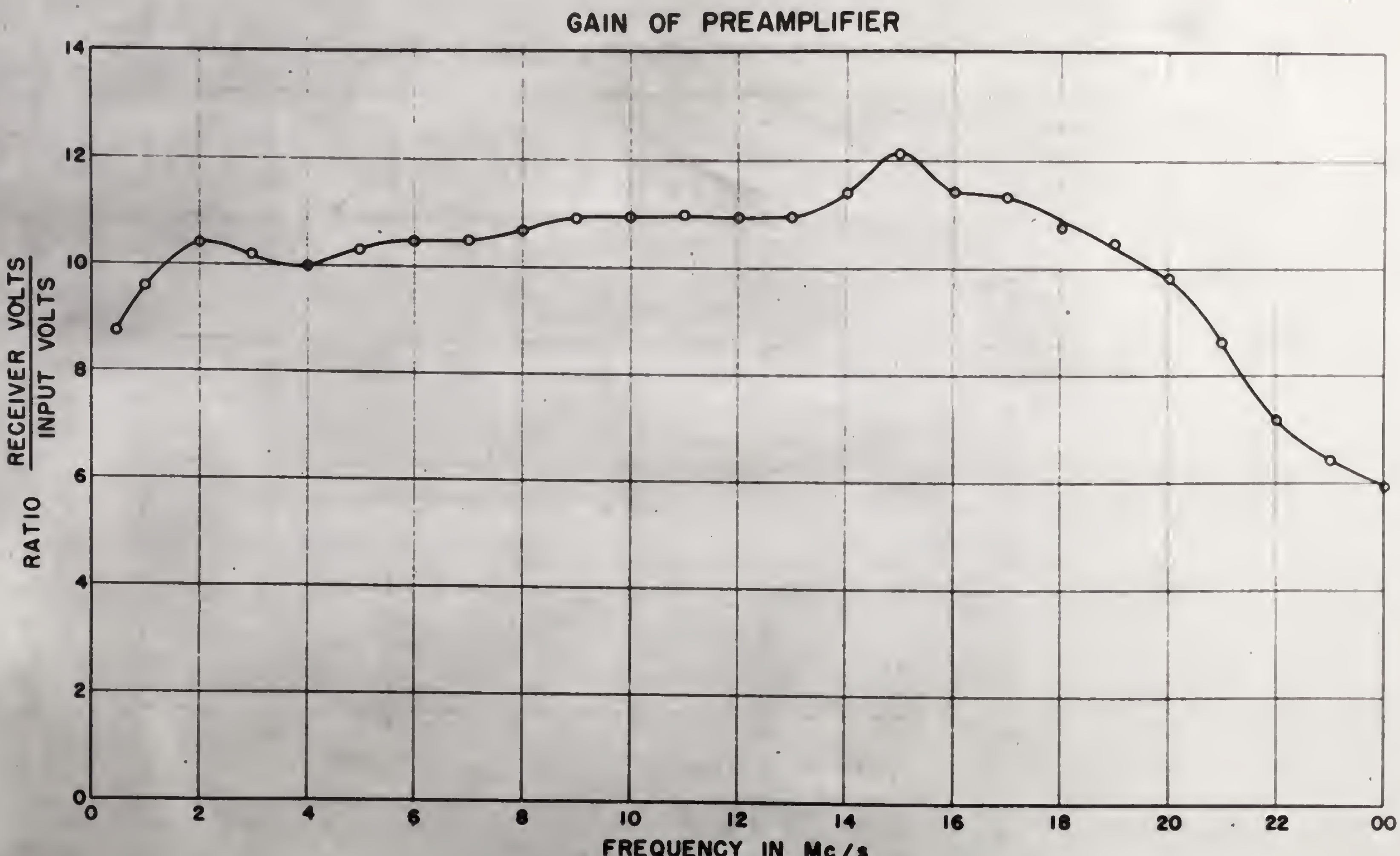

GAIN OF PREAMPLIFIER
RATIO RECEIVER VOLTS / INPUT VOLTS
0
2
4
6
8
10
12
14
16
18
20
22
00
FREQUENCY IN Mc/s

Fig. 17

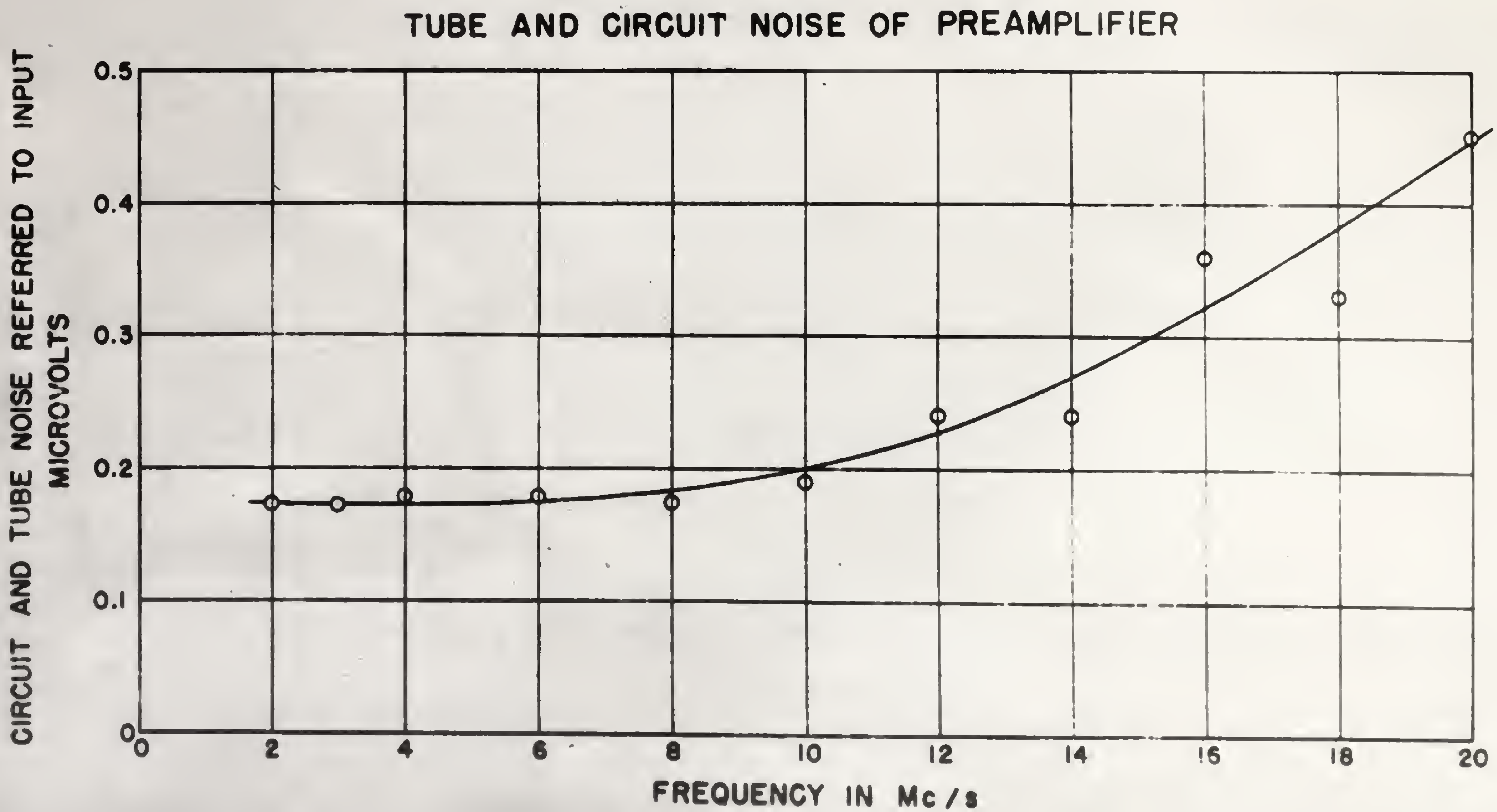
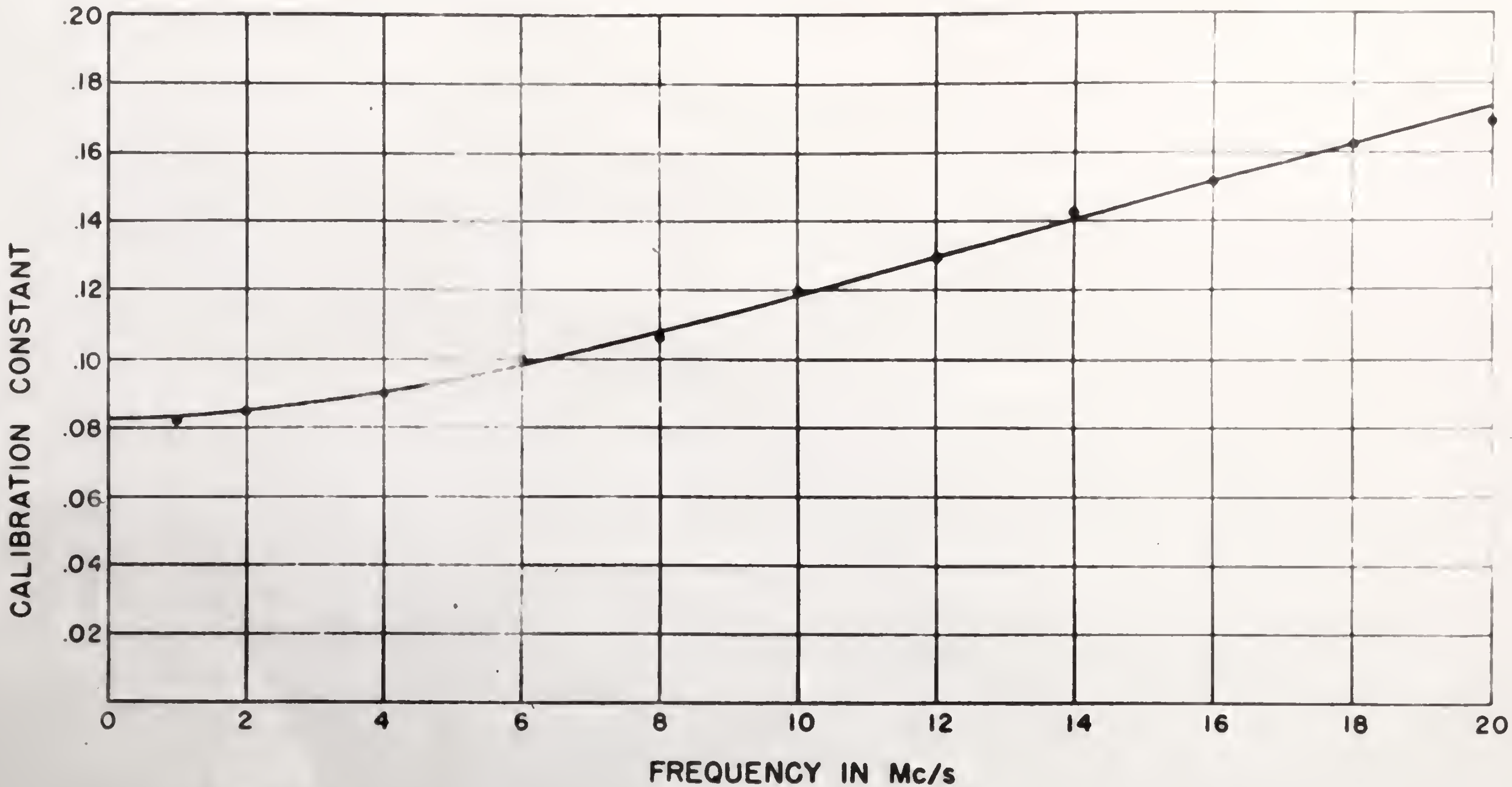

TUBE AND CIRCUIT NOISE OF PREAMPLIFIER
CIRCUIT AND TUBE NOISE REFERRED TO INPUT MICROVOLTS
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
12
14
16
18
20
FREQUENCY IN Mc/s

Fig. 18.



CALIBRATION CONSTANT OF PREAMPLIFIER

Fig. 19

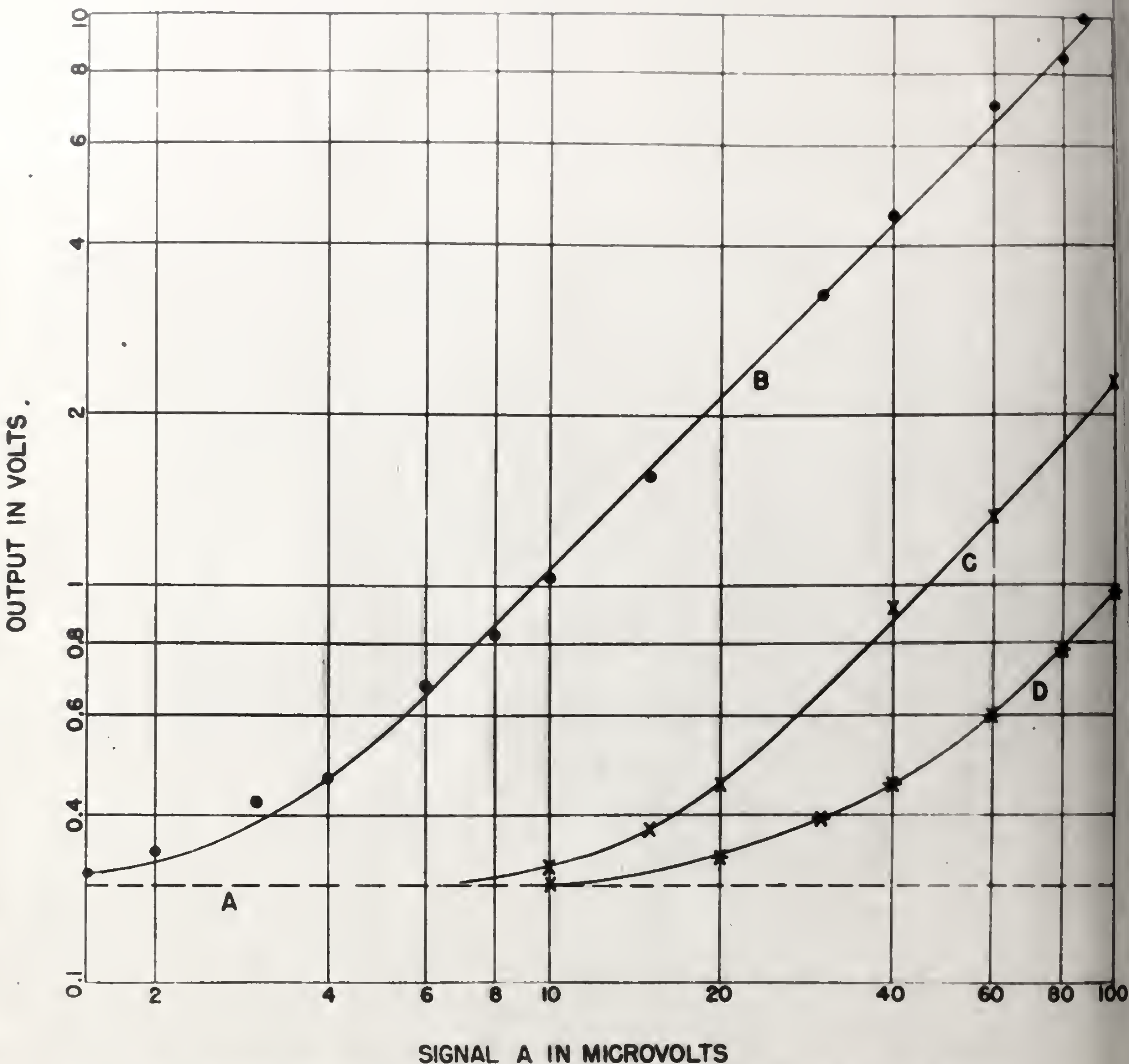


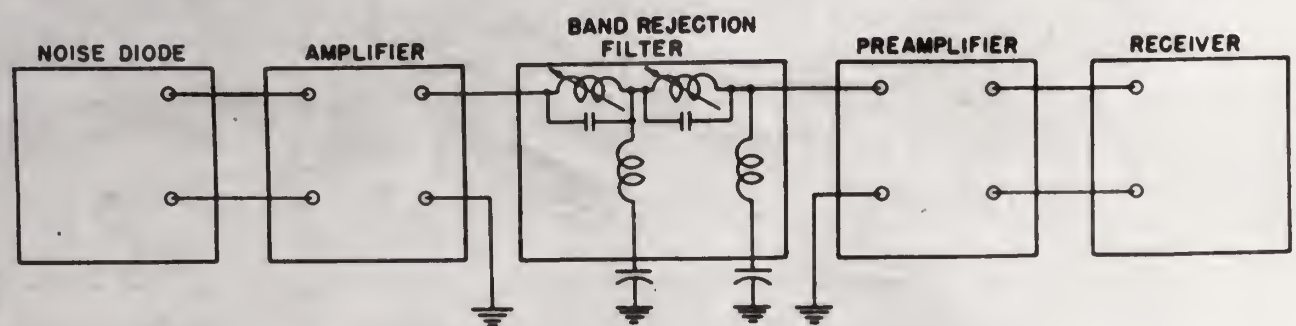
Fig. 20 CROSSMODULATION OF TWO SIGNALS BY PREAMPLIFIER

A.- NOISE LEVEL OF THE SYSTEM

B.- SIGNAL B = 50,000 μVOLTS

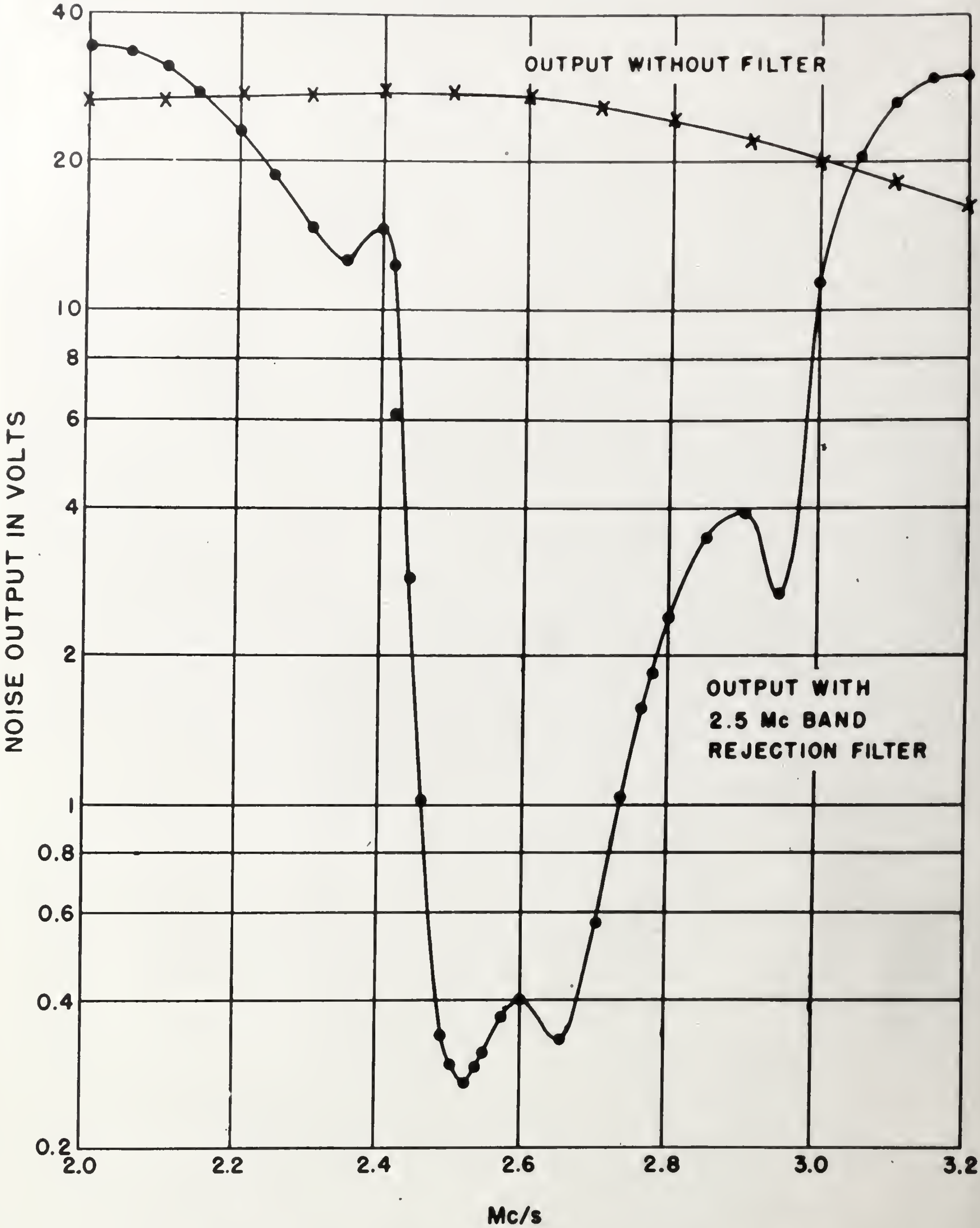
C.- SIGNAL B = 20,000 μVOLTS

D.- SIGNAL B = 10,000 μVOLTS



CIRCUIT OF THE APPARATUS FOR TEST OF CROSSMODULATION OF NOISE

Fig. 21



CROSSMODULATION OF NOISE BY PREAMPLIFIER

Fig. 22

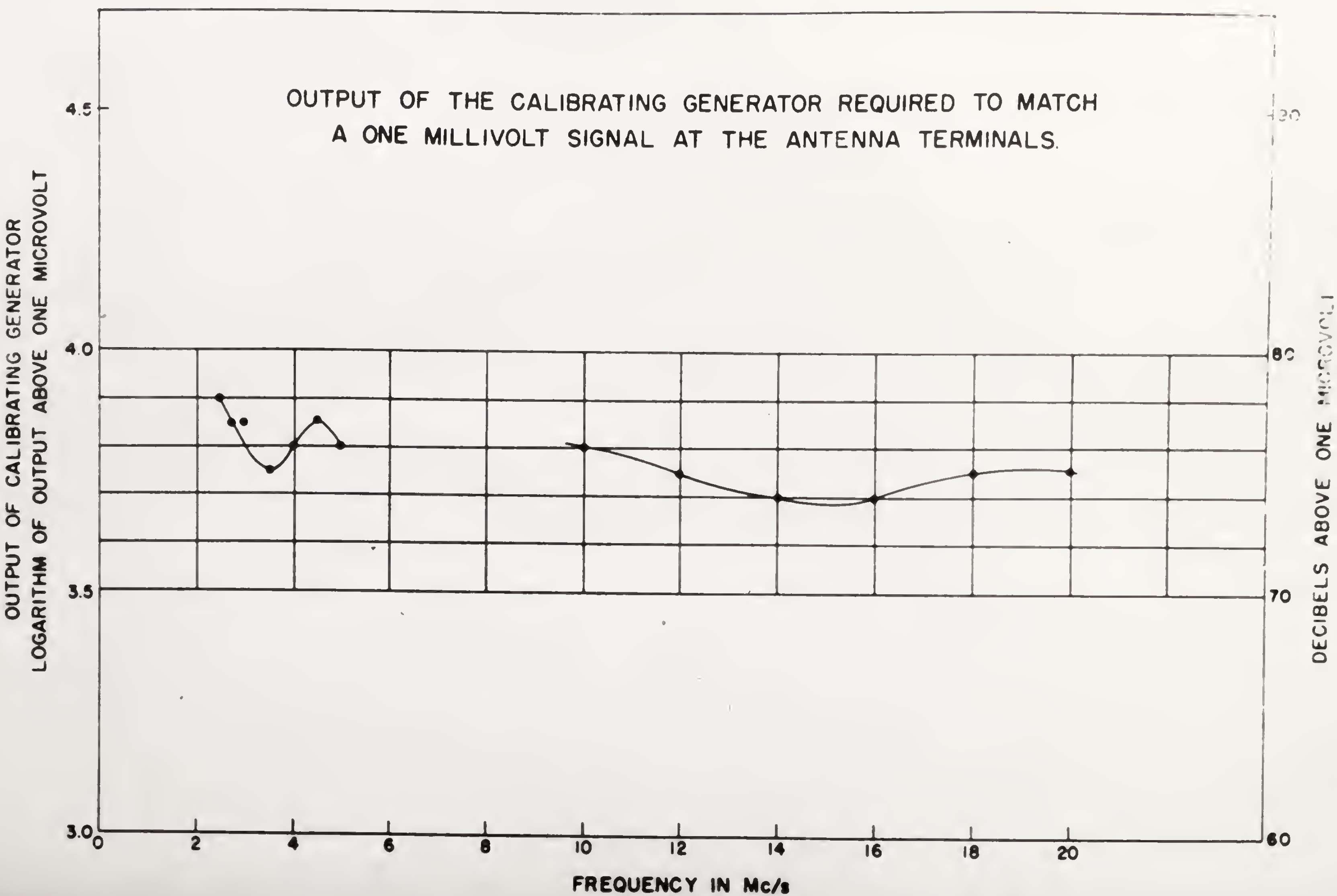

OUTPUT OF THE CALIBRATING GENERATOR REQUIRED TO MATCH
A ONE MILLIVOLT SIGNAL AT THE ANTENNA TERMINALS.
OUTPUT OF CALIBRATING GENERATOR
LOGARITHM OF OUTPUT ABOVE ONE MICROVOLT
4.5
4.0
3.5
3.0
0
2
4
6
8
10
12
14
16
18
20
80
70
60
DECIBELS ABOVE ONE
FREQUENCY IN Mc/s

Fig. 23.

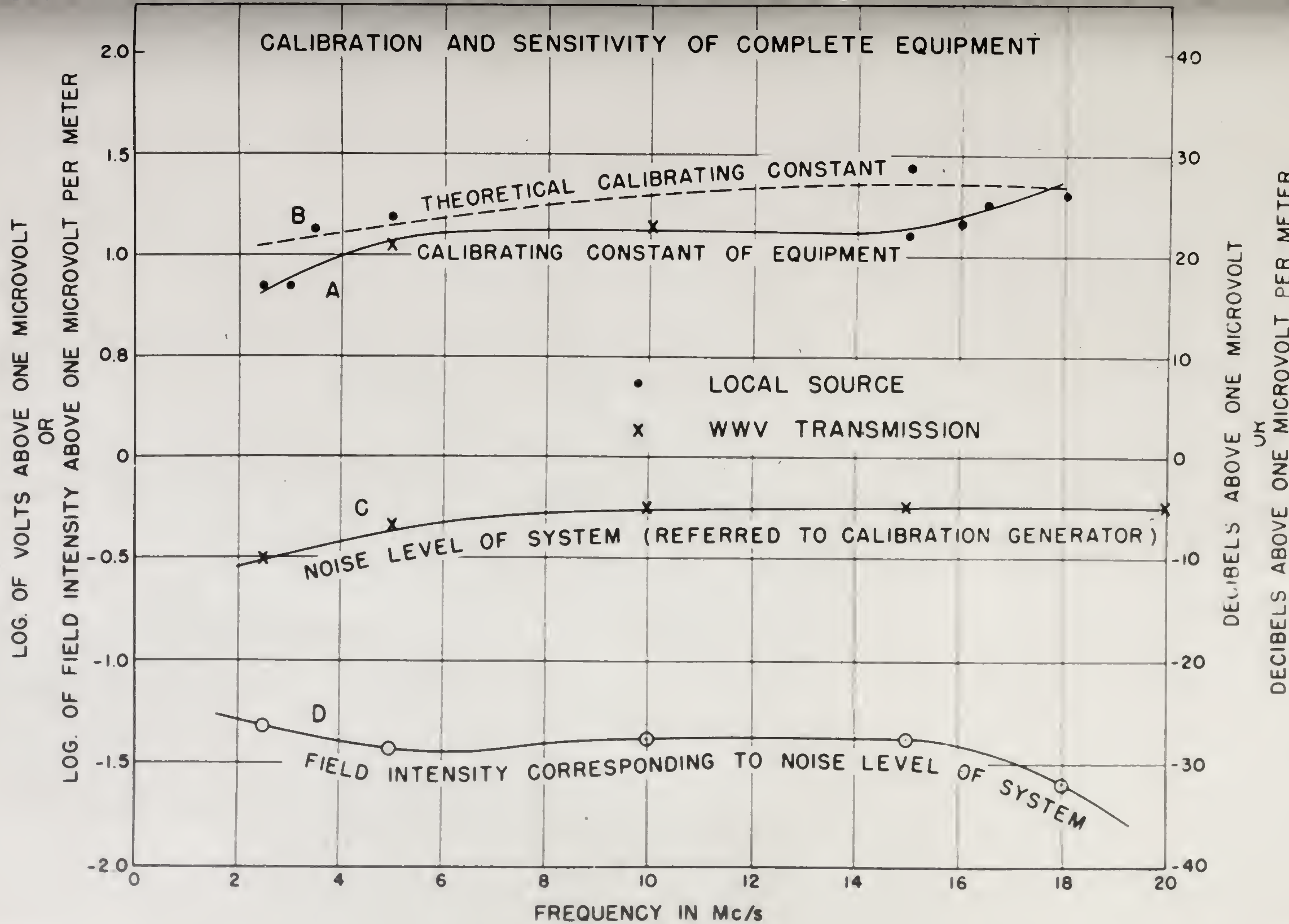

CALIBRATION AND SENSITIVITY OF COMPLETE EQUIPMENT
THEORETICAL CALIBRATING CONSTANT
CALIBRATING CONSTANT OF EQUIPMENT
B
A
LOCAL SOURCE
WWV TRANSMISSION
C
NOISE LEVEL OF SYSTEM (REFERRED TO CALIBRATION GENERATOR)
D
FIELD INTENSITY CORRESPONDING TO NOISE LEVEL OF SYSTEM
LOG. OF VOLTS ABOVE ONE MICROVOLT
OR
LOG. OF FIELD INTENSITY ABOVE ONE MICROVOLT PER METER
DECIBELS ABOVE ONE MICROVOLT
OR
DECIBELS ABOVE ONE MICROVOLT PER METER
FREQUENCY IN Mc/s
2.0
1.5
1.0
0.8
0
-0.5
-1.0
-1.5
-2.0
40
30
20
10
0
-10
-20
-30
-40
0
2
4
6
8
10
12
14
16
18
20

Fig. 24