NBS TECHNICAL NOTE
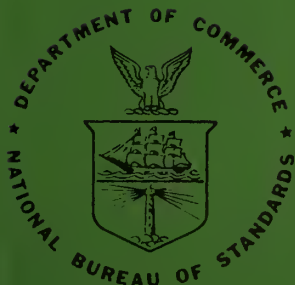
345

A New Near-Zone Electric Field-Strength Meter

FRANK M. GREENE

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards

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Frank M. Greene

Abstract-The National Bureau of Standards has recently completed the development of prototype instrumentation for measuring the electric-field components of complex, high-level, near-zone electromagnetic fields from 0.1 to 1000 volts per meter, at frequencies from 150 kHz to 30 MHz with a present uncertainty of less than ±2 dB. The design of the NBS meters is based on the use of a novel form of telemetry, employing a completely non-metallic electrical transmission line, which apparently has not been fully exploited heretofore. This avoids the perturbing effects on the field being measured, usually caused by field-strength meters employing metallic RF transmission lines. The design and performance of the meter are discussed in some detail.

1. Introduction

The National Bureau of Standards, under the sponsorship of the Defense Atomic Support Agency, has recently completed the development of prototype instrumentation for measuring the electric-field components of complex, high-level, near-zone electromagnetic fields. The instrumentation is capable of measuring both the magnitude and direction of elliptically polarized CW electric fields having strengths in the range from 0.1 to 1000 volts per meter at frequencies from 150 kHz to 30 MHz. This represents one step in the effort to develop accurate and meaningful measuring and calibrating instrumentation, for use in evaluating hazards of electromagnetic radiation to electro-explosive ordnance devices. It is well known that high-level fields of powerful nearby radio transmitters may cause premature detonation of missile and rocket type weapons during storage or loading operations on shipboard, or at other military installations. It was from the standpoint of improving both the weapons reliability, as well as the safety of operating personnel and equipment, that the program was undertaken.

The design of the NBS meters is based on the use of a novel form of telemetry, employing a completely non-metallic electrical transmission line to avoid perturbing the field being measured. This approach has apparently not been fully exploited, heretofore. The extremely-high RF loss of the line used attenuates any RF currents induced on the line by the surrounding field and essentially eliminates re-radiation from the line, or unwanted coupling between the line and the measuring antenna. The high line-loss, however, necessitates miniaturizing the RF portions of the receiving and calibrating instrumentation and placing them and the associated battery supplies inside the measuring antenna. The field information contained in the detected DC-AF output of the receiver is transmitted over the line to a remote readout unit, where the strength of the electric-field component parallel to the axis of the antenna is read directly.

Interim electric-field standards and calibration techniques were also developed at NBS to evaluate the performance of the field-strength meters during their development, as well as to provide a tentative calibration of the completed instruments. The present uncertainty of the standards is believed to be less than ±2 dB, but further development effort is expected to reduce this to less than ±1 dB.

2. The New "Semi-Conducting" Plastic Transmission Line

2.1 Errors Caused by Metallic Lines.

In the past, electric field-strength meters have usually made use of a long metallic RF transmission line to connect the measuring antenna with its receiver, usually located at a point remote from the antenna. Such metallic lines often cause large measurement errors, especially when measuring near-zone fields having complex spatial distributions. In these cases, a neutral-field path, along which the line can be placed,

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either seldom exists, or the orientation of such a path, if it <u>does</u> exist
is usually not known in advance of making the measurements. Under
these conditions, it is difficult or impossible to orient the line so that it
is everywhere normal to existing electric-field components. Thus, the
line not only may perturb the field being measured, but unwanted RF
currents induced on the line can be coupled into the antenna and contrib-
ute to the total response of the field-strength meter.

2.2 The Use of a Non-Metallic Line.

The NBS near-zone meters avoid this difficulty by making use of a
special non-metallic balanced transmission line in which the conductor
RF loss has been purposely made extremely high compared to that of the
usual copper line. If the conductors are made of sufficiently high resist-
ance material, the line can be made essentially "transparent" to the
surrounding field. This is to say that the RF currents induced on the
transmission line by the field will be negligibly small, resulting in insig-
nificant reradiation, or that any RF energy propagating along the line
will be heavily attenuated because of the extremely high loss of the line.
It has been found that this can be achieved if the volume resistivity of the
conductor material used is of the order of a million times or more higher
than that of copper. This is roughly midway (on a logarithmic scale)
between the volume resistivity of metals, on the one hand, and that of
insulators such as glass or mica on the other. Such materials can there-
fore be said to be "semi-conducting."

2.3 Description of the "Semi-Conducting" Line.

The material used in the NBS lines is basically polytetrafluoro-
ethylene (PTFE), rendered "semi-conducting" by uniformly dispersing
finely-divided carbon black (approximately 30 percent by weight) through-
out the plastic while it is in the semi-fluid state during its manufacture.

Tests at NBS have indicated the PTFE material to be more stable electrically than other types tried, such as silicone rubber, polyethylene, carbon-coated multi-fiber glass, etc. Other types of conductor materials (including high-resistance metallic alloy wire and thin deposited metallic films) were examined, but were not found to be practical for this use, either because of unsuitable electrical characteristics or excessive cost.

Several parallel-conductor balanced transmission lines were made at NBS using the semi-conducting PTFE material. The line conductors are in the form of 0.03 inch diameter monofilaments in place of the usual copper conductors. They are coated with a thin nylon film (approximately 0.005 inch thick) to further improve their strength and electrical stability. Each of the filaments is in turn enclosed in a vinyl-coated woven fiber-glass sleeve approximately 0.1 inch O.D. Two such insulated conductors are encased in a polyvinyl chloride outer jacket, for added strength and protection, to form the completed transmission line. Military Type JJ-048 or PJ-291 twin-conductor plugs are used at the two ends for connecting to the dipole antenna, and to the remote indicator unit, respectively. The overall length of the lines is approximately 30 feet.

2.4 Electrical Characteristics of the Line.

The "semi-conducting" PTFE material used in the line has a volume resistivity of approximately 3.0 ohm-cm (compared to 1.7×10^{-6} ohm-cm for copper), giving a resistance of approximately 20,000 ohms per lineal foot, or a loop resistance of approximately 1.2 megohms for a line 30 feet in length. The measured mutual capacitance between the two line conductors is approximately 10 pF per foot, or roughly 300 pF for the entire line. The transmission loss, to the desired field-strength information at DC and low AF, is negligible if a high-impedance DC-AF

vacuum-tube voltmeter is used as the readout device at the receiving end of the line. The line attenuation increases as the square-root of frequency, reaching a theoretical as well as a measured value of approximately 53 dB per foot at a frequency of 30 MHz, for the differential mode of transmission. The common-mode attenuation with the line lying flat on a metal ground plane turns out to have essentially the same value. The use of a high-loss, parallel-conductor, balanced transmission line of this type has been found to reduce the perturbation of the surrounding field by more than two orders of magnitude below that existing in the case of a copper line. This renders any effect of the line on the field wholly negligible in most instances.

A type of "flexural" noise is generated on the "semi-conducting" transmission line when it is suddenly flexed or moved physically. The common-mode component of this "noise" may be relatively high, having a peak value of several volts on open circuit, for a 30 foot line. However, the differential-mode component is appreciably smaller, having a peak value of the order of 0.2 volt with the line open circuited at both ends. This can be decreased to approximately 0.02 volt by terminating either the sending or receiving end of the line in a resistance of 10 megohms. This noise does not present a problem in the NBS meters where the level of transmission over the balanced line is in the range 0.75 to 7.5 volts, as shown in Table 1.

3. Description of the NBS Field-Strength Meters

3.1 Principles of Operation.

Two prototype, near-zone, CW electric field-strength meters were developed for the Defense Atomic Support Agency. These meters cover the frequency ranges 150 to 250 kHz, and 18 to 30 MHz, respectively, and are capable of measuring fields over the range 0.1 to 1000 volts per
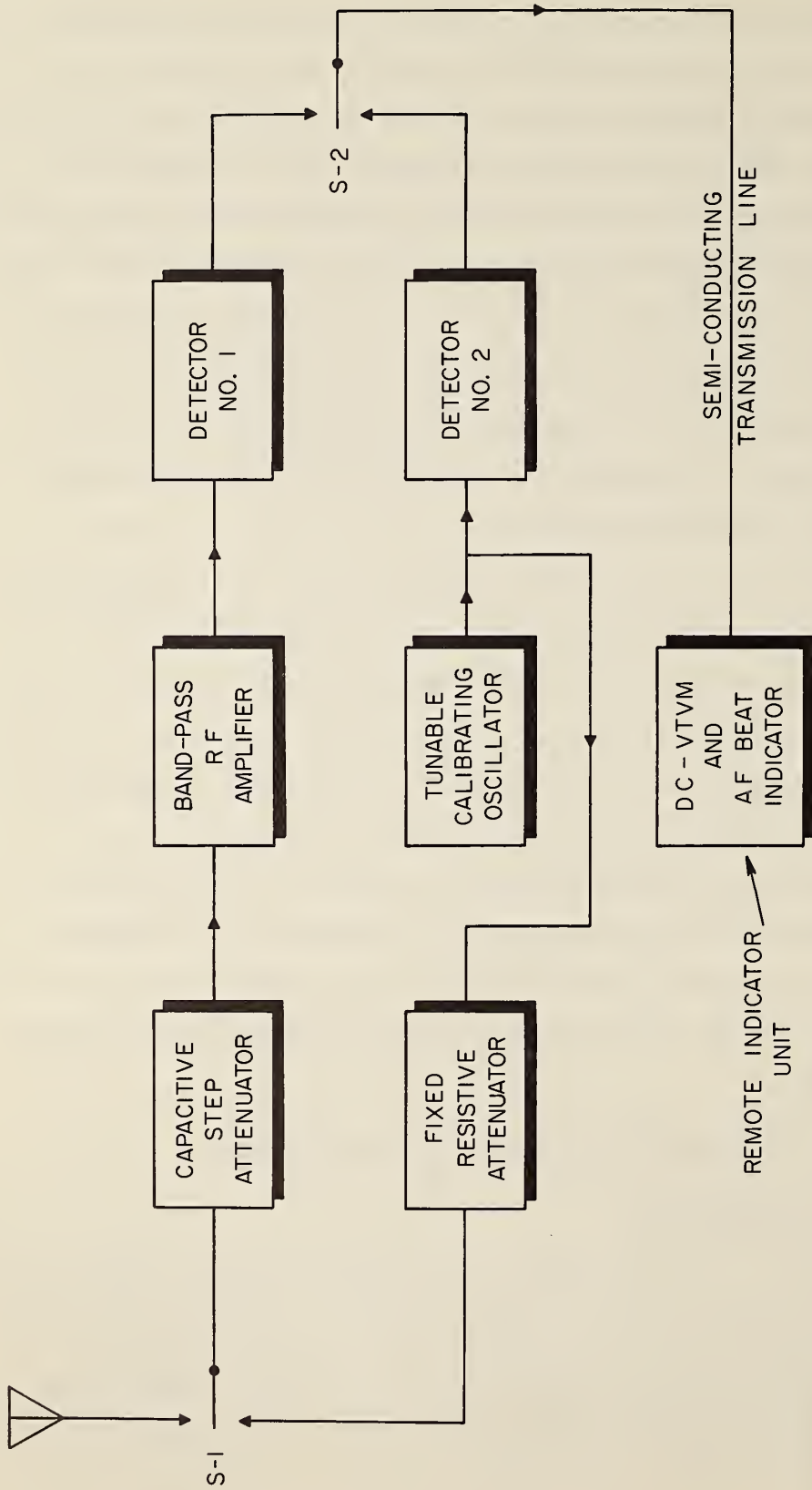
FIG. I BLOCK DIAGRAM OF THE NBS FIELD-STRENGTH METER

meter (RMS). Both meters make use of a selective TRF receiver to amplify the voltage induced in the receiving antenna by the component of the electric field being measured. The detected output of the receiver is transmitted over the special non-metallic transmission line to a remote indicator unit where the strength of the field is read directly. A block diagram of the basic circuitry is shown in Fig. 1.

These meters employ the same basic method of receiver-gain calibration that has been used in CW-type field-strength meters in this country for many years. Meters of this basic type are somewhat simpler in construction, but, at the same time, have proven themselves to have much better long-term amplitude stability than present-day so-called "interference" meters.

A CW oscillator is included to permit calibrating the overall receiver gain periodically during a sequence of measurements in the field. This oscillator is tunable over the same frequency range as the receiver. This method permits setting the receiver gain each time to the same value that existed when the instrument was previously calibrated in a standard field.

The receiver portion of the field-strength meter consists basically of an RF input capacitive step attenuator, a fixed-tuned band-pass RF amplifier (with manual gain control), and a diode detector. The internal calibrating oscillator is tunable over the pass-band of the receiver to permit adjusting the receiver gain to a "standard" value for any signal frequency within its pass band. The RF output level of the oscillator is monitored by its own detector. During calibration this output is applied to the receiver input through a fixed resistive attenuator and transfer switch, S-1. With the receiver input attenuator set to its reference or "calibrate" position, the receiver gain is manually adjusted until the DC outputs of detectors 1 and 2 are identical. The exact output level of the

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calibrating oscillator is not important and need not be known, nor does it have to be exactly the same each time a calibration is performed. However, it is important that the oscillator detector remain stable. In this way, slow changes in the gain of the receiver (including its detector) due to variations in ambient temperature, battery supply voltage, component aging, tuning drift, etc., are compensated for each time the receiver gain is calibrated.

While not a necessary condition, it can be seen, for simplicity, that if detectors 1 and 2 have identical characteristics, the loop gain of the circuitry between them is adjusted to unity each time the field-strength meter is calibrated. That is, the overall amplifier gain is adjusted so that it is equal to the total loss in the two tandem attenuators. The overall long-term calibration stability of this field-strength meter is thus seen to depend principally upon the stability of the two attenuators and the oscillator detector. These components are relatively easy to stabilize. The RF amplifier need have only relatively good short-term stability over the period between interim calibrations in the field of roughly 30 minutes or so. The calibrating oscillator, on the other hand, only needs to have good short-term amplitude stability over a period of roughly 60 seconds or so, during calibration procedures in the field, or whenever the instrument is being calibrated in a standard field.

The original design goals, followed in developing these field-strength meters, specified the measurement of the field strength produced by a single CW source. If two signals, having different frequencies, were present within the fixed-tuned pass-band of the instrument, the resulting response would tend toward the peak of the combined, or composite input, rather than the RMS, or average.

3.2 Electrical Design.

3.2.1 General.

The two near-zone TRF electric field-strength meters developed at NBS-BL consist of the following principal components:

(a)   a short hollow cylindrical dipole antenna in which is induced an RF voltage proportional to the component of the electric field parallel to the dipole axis;

(b)   an RF capacitive step attenuator, contained within the dipole, to reduce the antenna-output RF voltage to the working level of the receiver;

(c)   a miniaturized solid-state selective amplifier (or receiver) and CW calibrating oscillator, both contained within the hollow dipole antenna, along with their respective battery supplies;

(d)   a special semi-conducting plastic transmission line, approximately 30 feet in length, over which the detected DC-AF output of the receiver is transmitted;

(e)   a remote-indicator unit where the strength of the desired component of the electric field is read directly on a highly-stable battery-operated vacuum-tube voltmeter. A miniaturized solid-state audio amplifier and speaker are included for use as a zero-beat tuning indicator, when adjusting the frequency of the calibrating oscillator to that of the field being measured.

Before discussing these components in detail, it is of interest to examine the range of nominal RF voltage levels over which they will operate. The components are all directly interrelated in their electrical design. As an example, the required RF amplifier gain is dictated by several factors, some of which are: the dipole length as well as its internal and residual capacitances; the required linearity of response and dynamic range; the "flexural" noise level of the semi-conducting plastic transmission line.

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A list of the various ranges of RF voltage over which the principal components operate is shown in Table 1 for the range of electric field strength from 0.1 to 1000 volts per meter. An explanation of how the ranges were calculated is given in the following:

Effective Length of Measuring Dipole . . . ., $L_{eff} \cong 0.15$ m
Induced Voltage in Dipole . . . ., $V_i = E \cdot L_{eff}$
Dipole Voltage-Transfer Ratio, $V_o/V_i = C_a/(C_a + C_s) \cong 0.20$
$\quad C_a \equiv$ Internal Capacitance of Dipole . . . . . ., $C_a \cong 3$ pF
$\quad C_s \equiv$ Residual Gap and Circuit Capacitance.., $C_s \cong 12$ pF
RF Amplifier Nominal Voltage Gain . . . . . ., $V_2/V_1 \cong 100$

TABLE 1

DISTRIBUTION OF NOMINAL OPERATING·RF-VOLTAGE LEVELS
(in the TRF field-strength meter)

$E(V/m)$	$a(dB)$	V_i (volts)	V_o (volts)	V_1 (volts)	V_2 (volts)	V_3 (volts)
0.1-1.0	0	.015-0.15	.003-0.03	0.003-0.03	0.3-3.0	0.75-7.5
1.0-10.	20	0.15-1.50	0.03-0.30	0.003-0.03	0.3-3.0	0.75-7.5
10.-10^2	40	1.50-15.0	0.30-3.00	0.003-0.03	0.3-3.0	0.75-7.5
10^2-10^3	60	15.0-150.	3.00-30.0	0.003-0.03	0.3-3.0	0.75-7.5

$E(V/m) \equiv$ Electric Field Strength, volts per meter
$a(dB) \quad \equiv$ Measuring Dipole Attenuator Setting
$V_i \quad\quad \equiv$ Induced Voltage in Measuring Dipole
$V_o \quad\quad \equiv$ Output Voltage of Measuring Dipole
$V_1 \quad\quad \equiv$ Input Voltage to RF Amplifier
$V_2 \quad\quad \equiv$ Output Voltage of RF Amplifier
$V_3 \quad\quad \equiv$ Output Voltage of Amplifier Detector (DC)

3.2.2 The Dipole Antenna.

A cutaway drawing of the measuring dipole is shown in Fig. 2, and a view of the complete assembly is shown in the upper portion of Fig. 3. The two dipole cylinders are made of gold-plated copper tubing 1-3/8 inches outside diameter, with a 1/32 inch insulating gap between them at the center. They are aligned and held together by an epoxy-glass sleeve as shown. The overall length of the antenna is approximately

AMPLIFIER - END VIEW

OSCILLATOR - END VIEW

RF ATTENUATOR CONTROL

CALIBR. OSC. TUNING CONTROL

④ ① ② ③ ① ⑤

BATTERY

RF AMPLIFIER COMPARTMENT

CALIBRATING OSCILLATOR COMPARTMENT

BATTERY

AMP OSC COMPARTMENT

TUNING

⑥ ⑦ ⑮ ⑫ ⑬ ⑰ ⑯ ⑭ ⑮ ⑪ ⑩ ⑨ ⑧

ORIGINAL DATE OF DRAWING JUNE 15th, 1965

FIG. 2   CUTAWAY DRAWING OF THE MEASURING DIPOLE

AMPLIFIER - END VIEW
⑥

OSCILLATOR - END VIEW
⑧

LIST OF PARTS

1. DIPOLE ANTENNA CYLINDER,   SEAMLESS COPPER TUBING (HARD DRAWN), 1 3/8" O.D. × .062 WALL THICKNESS, 2 PIECES
2. CENTER - SUPPORT SLEEVE,   NEMA GRADE G-10, GLASS EPOXY
3. DIPOLE - SHORTING SLEEVE WITH CONTACT FINGERS,   BRASS AND BERYLLIUM COPPER
4. BATTERY COMPARTMENT (AMPLIFIER),   CELLS, 2 PARALLELED STACKS, 8 CELLS EACH, 12 VOLTS
5. BATTERY COMPARTMENT (OSCILLATOR),   CELLS, 2 PARALLELED STACKS, 9 CELLS EACH, 13.5 VOLTS
6. R.F. ATTENUATOR CONTROL,   KNOB (NYLON), SHAFT (3/16 D. NEMA GRADE G-10 GLASS EPOXY)
7. OFFSET - SHAFT GEARS,   SPUR (2), BRASS
8. TUNING CONTROL, CALIBRATING OSCILLATOR,   KNOB (NYLON), SHAFT (3/16 D. NEMA GRADE G-10 GLASS EPOXY)
9. OSCILLATOR TUNING MECHANISM,   LEAD SCREW (STAINLESS STEEL), SPLIT DRIVE NUT (BRASS)
10. FERRITE TUNING SLUG
11. R.F. INDUCTOR,   150 TO 250 KHz UNIT: 500 TURNS 7/44 LITZ 4 LAYER PROGRESSIVE UNIVERSAL WINDING,   18 TO 30 MHz UNIT: 22 TURNS No. 22 SINGLE-LAYER SOLENOID
12. ATTENUATOR WAFER SWITCHES,
13. DETECTOR D.C.-TRANSFER WAFER SWITCHES,
14. OSCILLATOR ON-OFF WAFER SWITCH,
15. MINIATURE COAXIAL LINES (TYP.),   OUTER CONDUCTOR 1/16 O.D. BRASS TUBING FOR ALL RF AND DC LINES
16. D.C. TRANSMISSION LINE, BALANCED,   SEMI - CONDUCTING
17. PLUG CONNECTOR, TWIN, FEMALE,   MILITARY TYPE JJ-048

NATIONAL BUREAU OF STANDARDS
BOULDER, COLORADO

ASSEMBLY (CUTAWAY VIEW)

FOR NEAR-ZONE ELECTRIC-FIELD PROBE

MODEL TUNED RF   TYPE   SCALE

DRAFTSMAN VICTOR LECHASKI

F.M. GREENE

DASA
MD-1102-3171-0001

2520415-102

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FIG. 3 VIEW OF THE COMPLETE MEASURING DIPOLE

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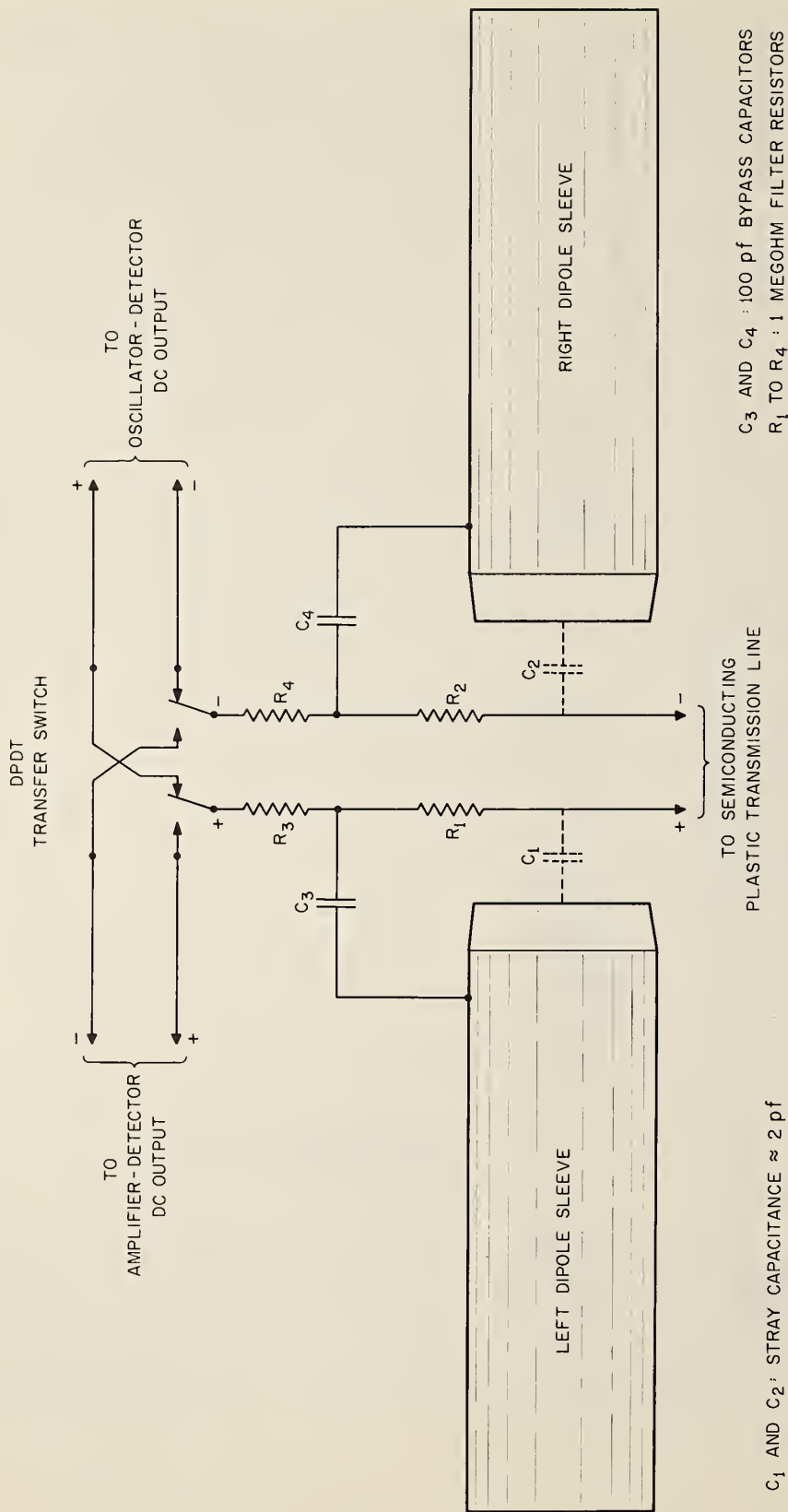
FIG. 4   DETECTOR-DC-OUTPUT TRANSFER-WIRING SCHEMATIC

C_3 AND $C_4 = 100$ pf BYPASS CAPACITORS
R_1 TO $R_4 = 1$ MEGOHM FILTER RESISTORS

C_1 AND C_2: STRAY CAPACITANCE ≈ 2 pf

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13 inches, not including the nylon control knob on each end. A view of the interior instrumentation with the copper dipole sleeves removed is shown in the central portion of Fig. 3. The miniaturized, solid-state, band-pass amplifier (receiver) and its battery supply are in the left half of the dipole. The tunable CW calibrating oscillator and its battery supply are in the right half. The RF capacitive step attenuator is located in the central portion of the dipole, and is comprised of the two rotary wafer switches on the extreme left and associated fixed capacitors. The two center wafers comprise a DPDT switch used for transferring the semi-conducting line to the DC output of either the amplifier detector or the oscillator detector. The single wafer switch on the extreme right of center energizes the calibrating oscillator when the attenuator control knob (located on the extreme left end of the dipole) is in either of the CALIBRATE positions. At the bottom of Fig. 3 are shown (left to right):

(a)   a short piece of the semi-conducting plastic transmission line and its twin-conductor plug;

(b)   an internal dipole-shorting sleeve, used to attenuate strong local signals while calibrating the amplifier gain;

(c)   some of the miniature silver-oxide cells used in the internal battery supplies.

The transmission-line plug connects to the two stainless-steel pins at the center of the dipole. The detector DC-transfer and RF-filtering circuitry is shown in Fig. 4. The RF filter is composed of resistors R1 to R4 and bypass capacitors C3 and C4. It serves to preserve the electrical symmetry or balance of the dipole with respect to the transmission line, and to attenuate any transverse, as well as common-mode RF pickup that might exist on the line. Special care was exercised in the design and construction of the measuring dipole, so as to maintain accurate electrical symmetry. This is essential if the antenna is to respond only
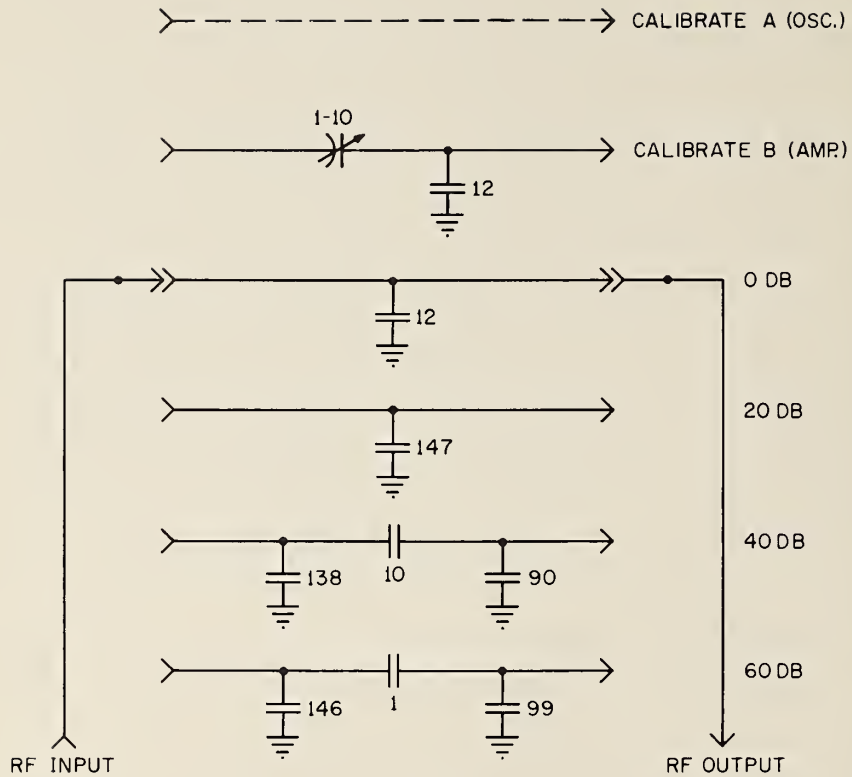
FIG. 5 CIRCUITRY OF CAPACITIVE STEP ATTENUATOR
(CAPACITANCE VALUES SHOWN ARE NOMINAL VALUES IN pf,
AND INCLUDE WIRING AND RESIDUAL CAPACITANCES.)

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to the component of the electric field parallel to its axis. The electrical symmetry, or balance, of the NBS dipole is such that its response to the cross-polarized component of the electric field is 40 dB or more below its principal response.

It can be shown that if the length of the measuring dipole does not exceed 0.03 wavelength, its effective length when measuring a field having a highly-complex spatial distribution will not differ by more than 2 or 3 percent (in the worst case) from the effective length when immersed in a uniform plane wave. Likewise, the interaction error, resulting from coupling between such a short antenna and its image, will be small provided the loading is light and that measurements are not made closer than two or three feet to the ground or large metallic objects.

3.2.3 RF Capacitive Step Attenuator.

The circuitry and capacitance values used in this attenuator are shown in Fig. 5. This unit is constructed using special 60-degree detent, subminiature, rotary wafer switches (glass-silicone wafers and coin-silver contacts). The fixed capacitors used are low-temperature coefficient ceramic miniatures. Special capacitance values, which have been selected to 1 percent tolerance, are used as shown. The input and output trimmer capacitors (not shown) are 1-10 pF ceramic subminiatures. The step attenuator proper has four positions, 0, 20, 40, and 60 dB, with two additional 0 dB positions, Calibrate A (OSC) and Calibrate B (AMP). In the latter two positions, the calibrating oscillator is turned ON, and the semi-conducting plastic transmission line can then be switched between the DC outputs of the oscillator and amplifier detectors while calibrating the amplifier gain.

The attenuator design is based on a dipole internal capacitance of 3 pF and a residual gap and circuit capacitance of 12 pF, as given in
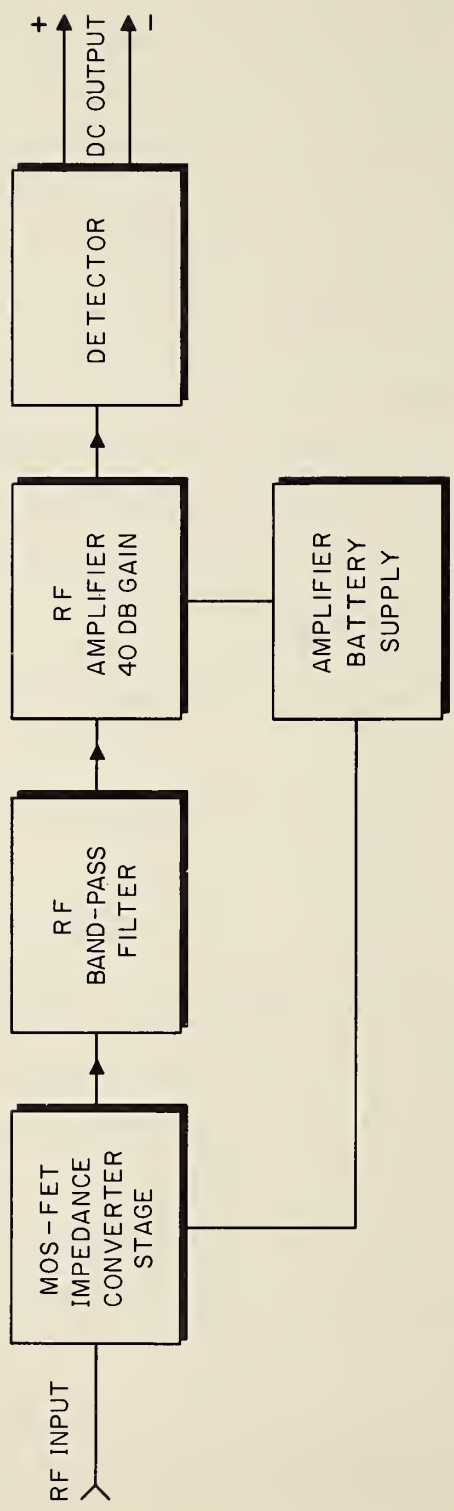
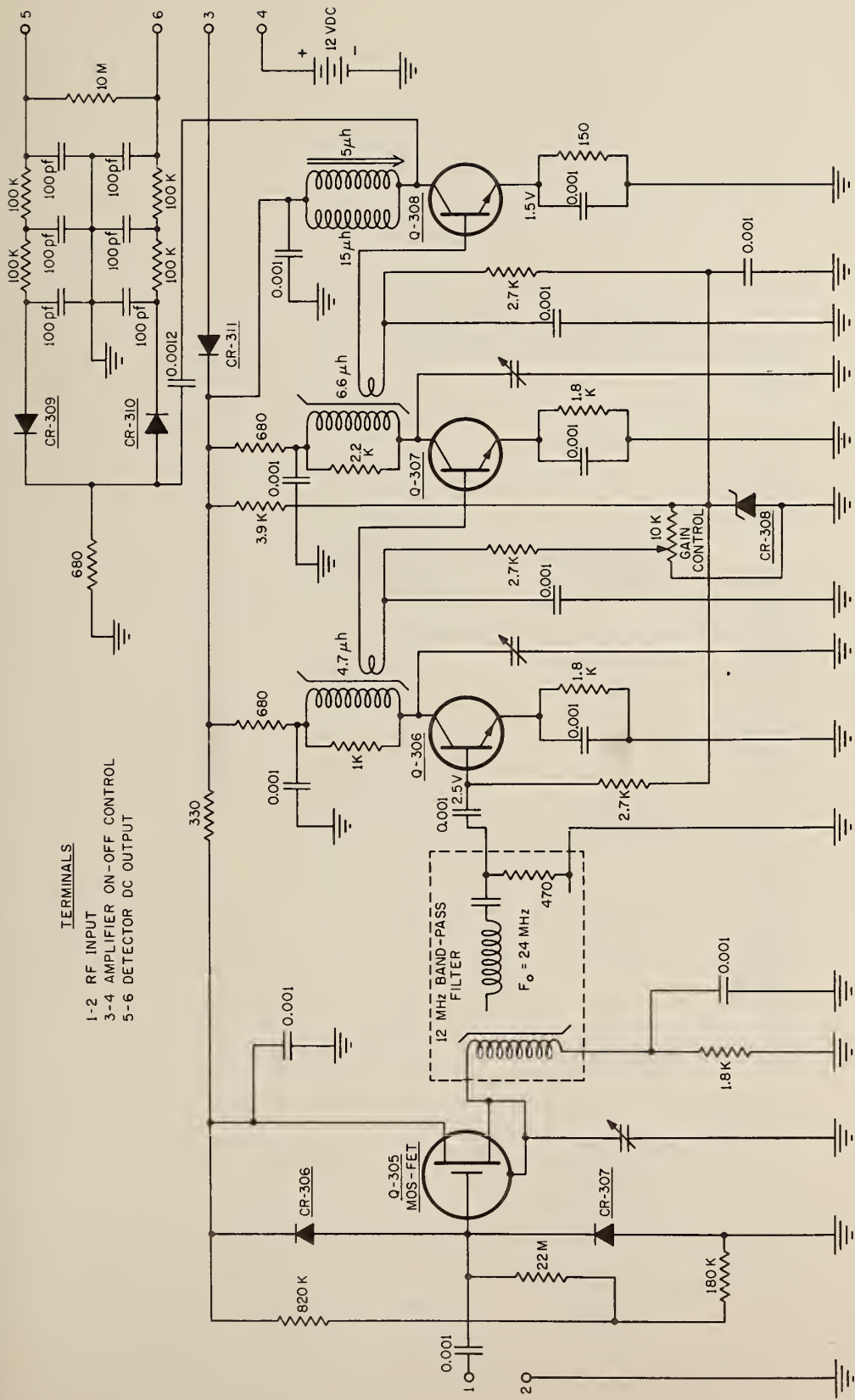FIG. 6 BASIC LAYOUT OF RF BAND-PASS AMPLIFIER

Table 1. The latter value is the <u>total</u> input-circuit capacitance when the attenuator is in the 0-dB position. In the 40 and 60 dB positions, the residual capacitance divides into two parts, 7 pF for the antenna or input side of the attenuator, and 5 pF for the amplifier or output side. The overall size of the complete miniaturized attenuator module is approximately 1 inch diameter by 1 inch long.

3.2.4 <u>Band-Pass Amplifier and Detector.</u>

The basic layout of this unit is shown in the block diagram of Fig. 6. In order to provide a high input impedance, so as not to appreciably load the dipole antenna or the capacitive step attenuator, a Metal-Oxide-Silicon Field-Effect Transistor (MOS-FET) is used in the first stage as an untuned input-impedance converter (source-follower configuration). This is an insulated-gate N-channel FET having an extremely high input resistance of several megohms and a low input capacitance of approximately 2 pF. In order to protect this MOS-FET from burn-out due to excessive RF or static potentials, two back-biased shunt diodes are used connected back-to-back across the RF input. This is shown in the schematic diagrams of Figs. 7 and 8, for the low-frequency and high-frequency amplifiers, respectively.

In the low-frequency amplifier (150 to 250 kHz) the untuned input stage is followed by a 7-pole Butterworth band-pass filter, the circuit of which is given in Fig. 9. This is in turn followed by a 3-stage, broadband, resistance-coupled amplifier using overall negative RF feedback to improve gain stability with respect to temperature and supply voltage variations. In the high-frequency amplifier (18 to 30 MHz) a 6-pole Tschebyscheff band-pass filter is used to determine the overall selectivity. The circuit diagram of this filter is shown in Fig. 10. The main amplifier has three stages using wide-band synchronously-tuned interstage transformers, with a low-Q LC tank in the collector circuit of the

FIG. 7 CIRCUIT OF THE BAND-PASS RF AMPLIFIER (150 TO 250 kHz)

TERMINALS

1-2 RF INPUT
3-4 AMPLIFIER ON-OFF CONTROL
5-6 DETECTOR DC OUTPUT

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FIG. 8 CIRCUIT OF THE BAND-PASS RF AMPLIFIER (18 TO 30 MHz)

TERMINALS

1-2 RF INPUT
3-4 AMPLIFIER ON-OFF CONTROL
5-6 DETECTOR DC OUTPUT

12 VDC

12 MHz BAND-PASS FILTER

F_0 = 24 MHz

Q-305 MOS-FET

CR-306

CR-307

CR-311

CR-309

CR-310

CR-308

Q-306

Q-307

Q-308

GAIN CONTROL

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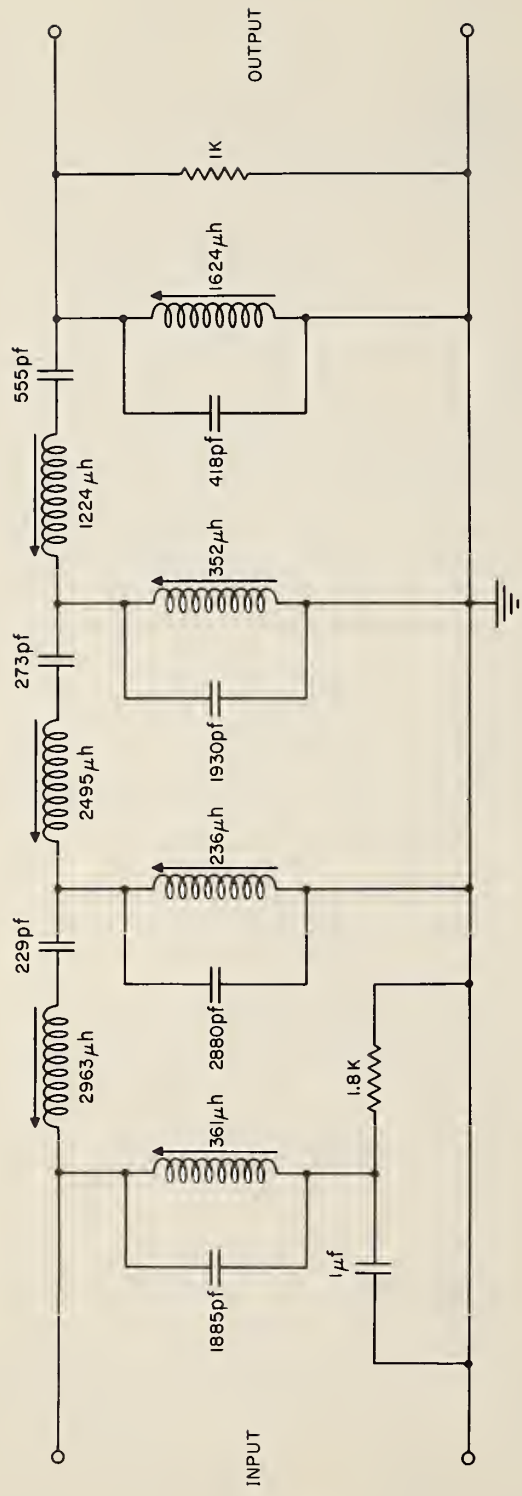
FIG. 9 SEVEN-POLE BUTTERWORTH BAND-PASS FILTER (F_o = 200 kHz)
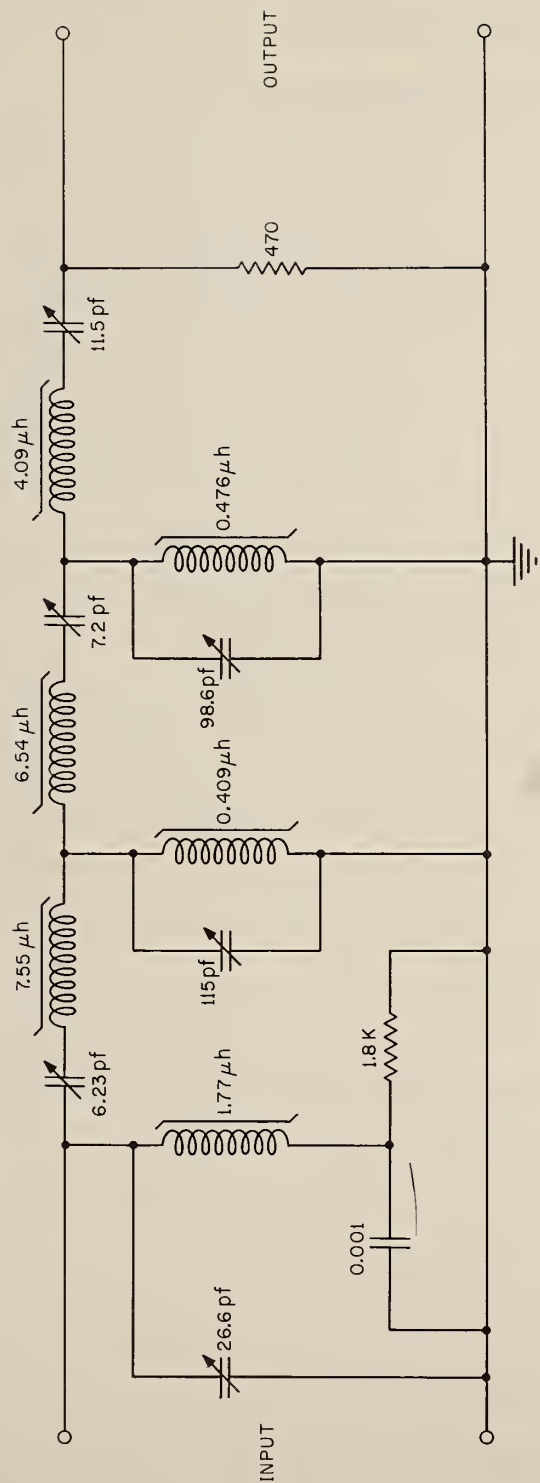
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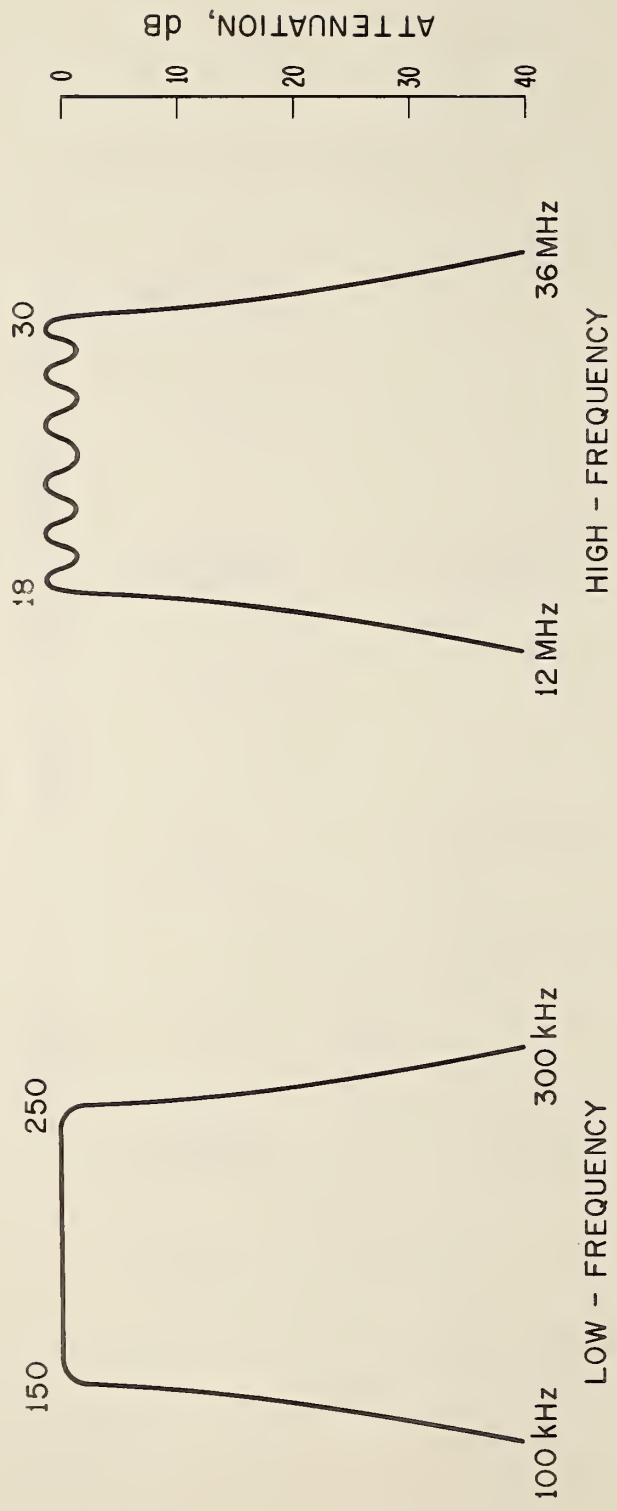FIG. 10 SIX-POLE TSCHEBYSCHEFF BAND-PASS FILTER ($F_0 = 24$ MHz)

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FIG. II NOMINAL OVERALL SELECTIVITY CHARACTERISTICS
OF THE TWO BAND-PASS AMPLIFIERS

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final stage. These low-Q tuned circuits do not contribute appreciably to the overall selectivity of the high-frequency amplifier, but do contribute to its stability and serve to reduce the output noise to a satisfactory level by limiting the bandwidth of this portion of the receiver. No overall negative RF feedback is employed in the design of this amplifier because of the difficulty in maintaining proper RF phase relations over the pass-band. However, the gain stability was improved by Zener-regulating the DC bias supplied to the bases of the three transistors.

The overall gain of both amplifiers can be manually adjusted to the required operating value, which is approximately 40 dB. The output detectors of both amplifiers employ two stable silicon diodes in a voltage doubling circuit as shown. This eases somewhat the voltage-swing requirements on the final amplifier stage, and also reduces the battery drain accordingly. Subminiature rigid coaxial lines 1/16 inch O.D. are used for the RF input and detector DC output leads, as indicated in Fig. 2. The nominal overall selectivity characteristics of the low-frequency and high-frequency band-pass amplifiers are shown in Fig. 11. The battery supply for the amplifiers is 12 volts, being composed of silver-oxide cells in two paralleled stacks of eight cells each. A silicon diode is used, as shown, to provide reversed-polarity protection for the amplifier. This supply has a useful life of from 10 to 20 hours. The two band-pass amplifier modules were developed to NBS specifications by a private manufacturer and are approximately 1-1/4 inches O.D. by 5 inches long, overall, including the battery supply.

3.2.5 Calibrating Oscillator and Detector.

The basic circuit arrangement of the calibrating oscillators is shown in the block diagram of Fig. 12. The tuning range of each of the two oscillators is the same as the 3 dB bandwidth of the band-pass amplifier with which it is used, i.e., 150 to 250 kHz for the low-frequency
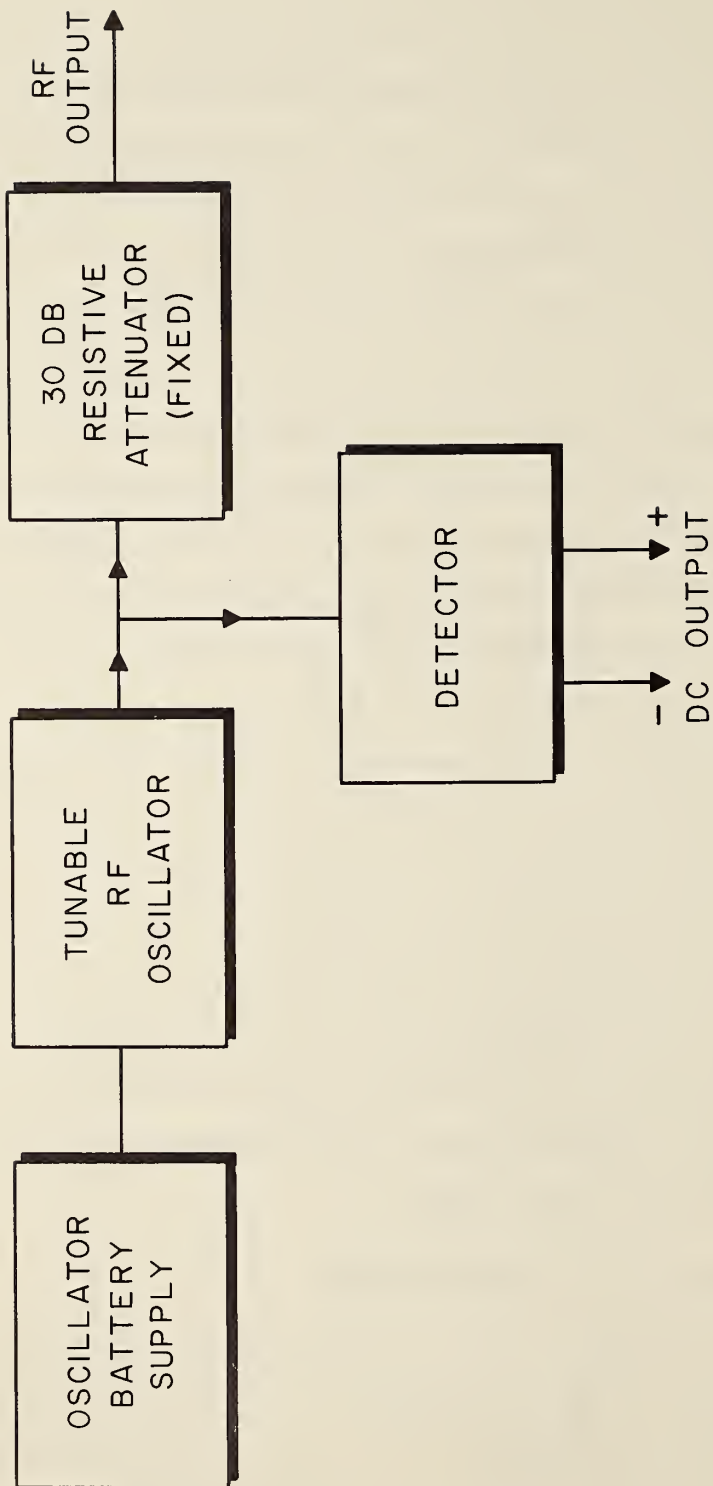
FIG. 12 BASIC LAYOUT OF CALIBRATING OSCILLATOR

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unit, and 18 to 30 MHz for the high-frequency unit. The detailed circuitry of these two oscillators is shown in Figs. 13 and 14, respectively. Tuning is accomplished by means of a ferrite slug core, driven by a steel lead screw, as can be seen in Fig. 2. The inductor of the low-frequency unit is a four-layer progressive-universal winding having 500 turns of 7/44 Litz wire, while that of the high-frequency oscillator is a single-layer solenoid having 22 turns of No. 20 A.W.G. solid-copper wire. The windings are molded on the inside of an epoxy form to minimize the air gap, and to increase the tuning range and Q. Tuning linearity is achieved by varying the winding pitch along the winding. An amplifier and AGC system is incorporated to maintain the oscillator RF output level essentially constant over the tuning range.

The RF output of the oscillator is adjustable to 3.16 volts and fed into the input terminals of a fixed 30-dB resistive attenuator pad. When calibrating the gain of the band-pass amplifier, the output of 0.1 volt from the pad is applied through a small variable capacitor (adjusted to approximately 3 pF) which simulates the dipole probe capacitance. The detector circuit is identical to that used with the band-pass amplifiers and employs two stable silicon diodes in a voltage-doubling circuit. The detector monitors the 3.16 volt RF oscillator level at the input terminals of the 30 dB pad. Subminiature rigid coaxial lines 1/16 inch O.D. are used for the RF output and detector DC output leads. The battery supply is essentially the same as that used with the band-pass amplifier unit, and uses two paralleled stacks of silver-oxide-cells (nine cells per stack). This gives a nominal supply voltage of 13.5 volts for the collector supply of the three transistors, as shown. A portion of this supply is Zener-regulated and applied to the transistor base circuits for improved amplitude stability over the useful life of the batteries, which is about 20 hours. The two calibrating-oscillator modules were developed to NBS specifications
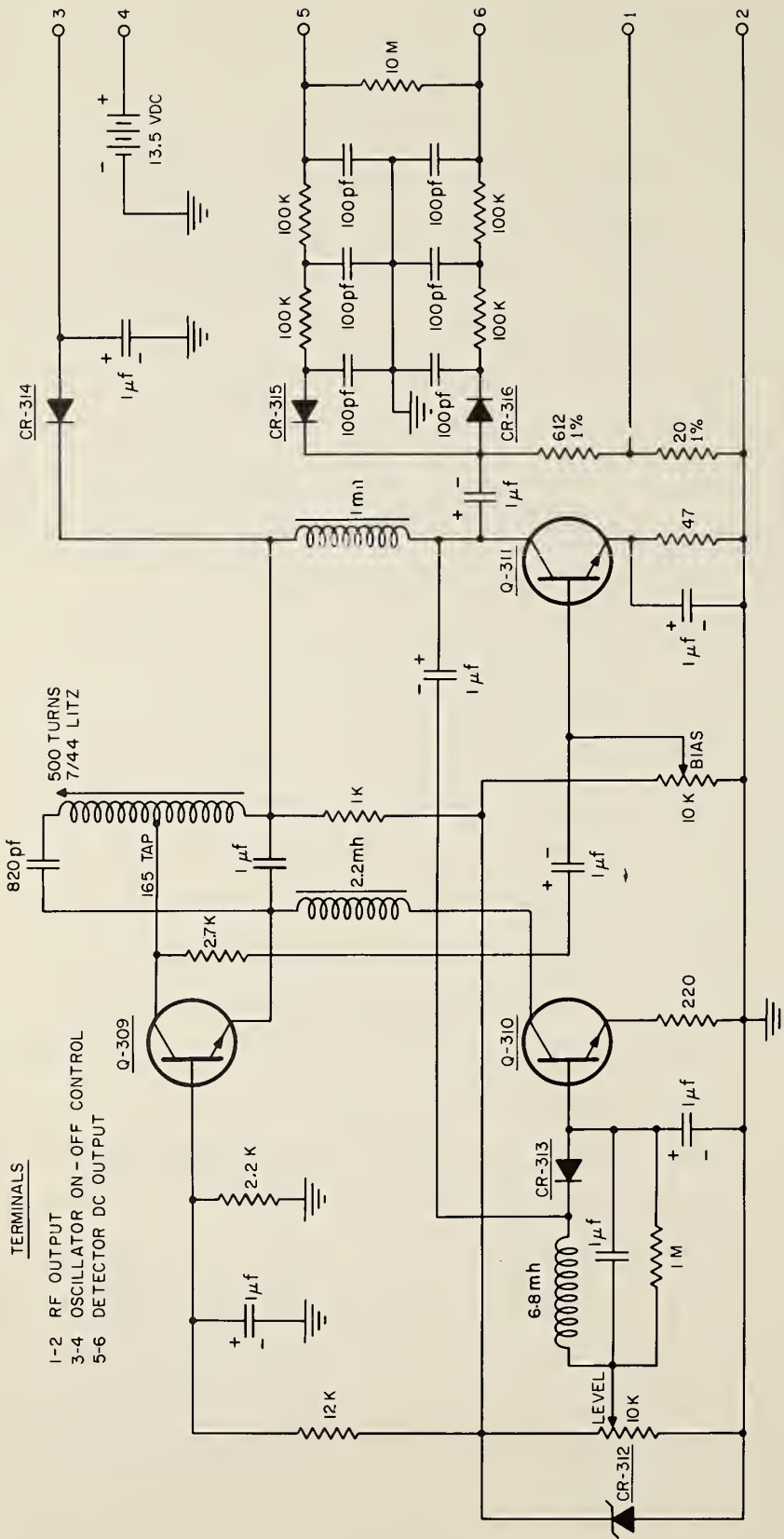
FIG. 13   CIRCUIT OF THE LOW-FREQUENCY CALIBRATING OSCILLATOR (150 TO 250 kHz)

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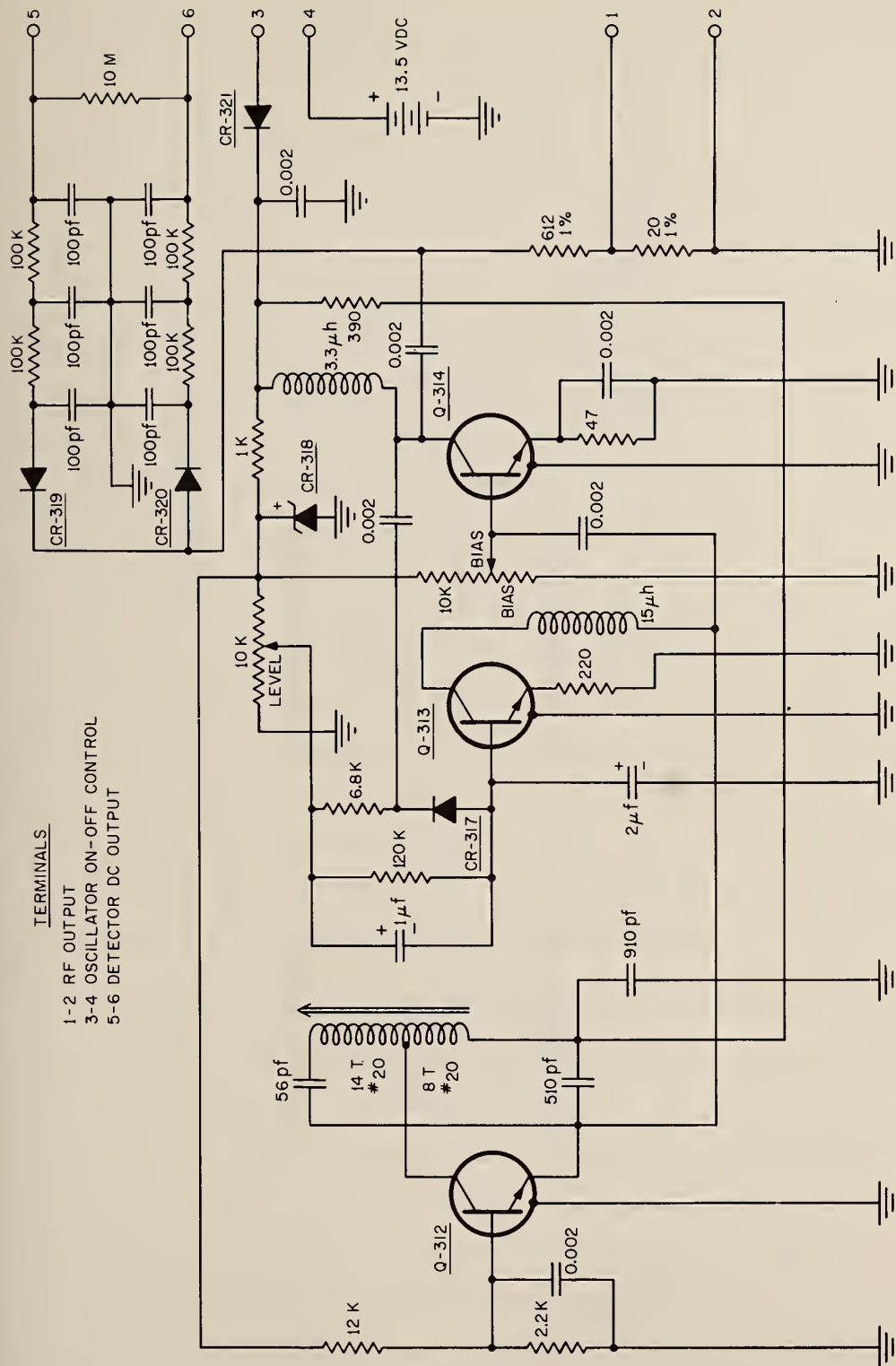
TERMINALS

1-2 RF OUTPUT
3-4 OSCILLATOR ON-OFF CONTROL
5-6 DETECTOR DC OUTPUT

FIG. 14   CIRCUIT OF THE HIGH-FREQUENCY CALIBRATING OSCILLATOR (18 TO 30 MHz)

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LOUDSPEAKER
(BEAT INDICATOR)

DC
MICROAMMETER

AUDIO
AMPLIFIER

BATTERY
SUPPLY
№ 2

BALANCED
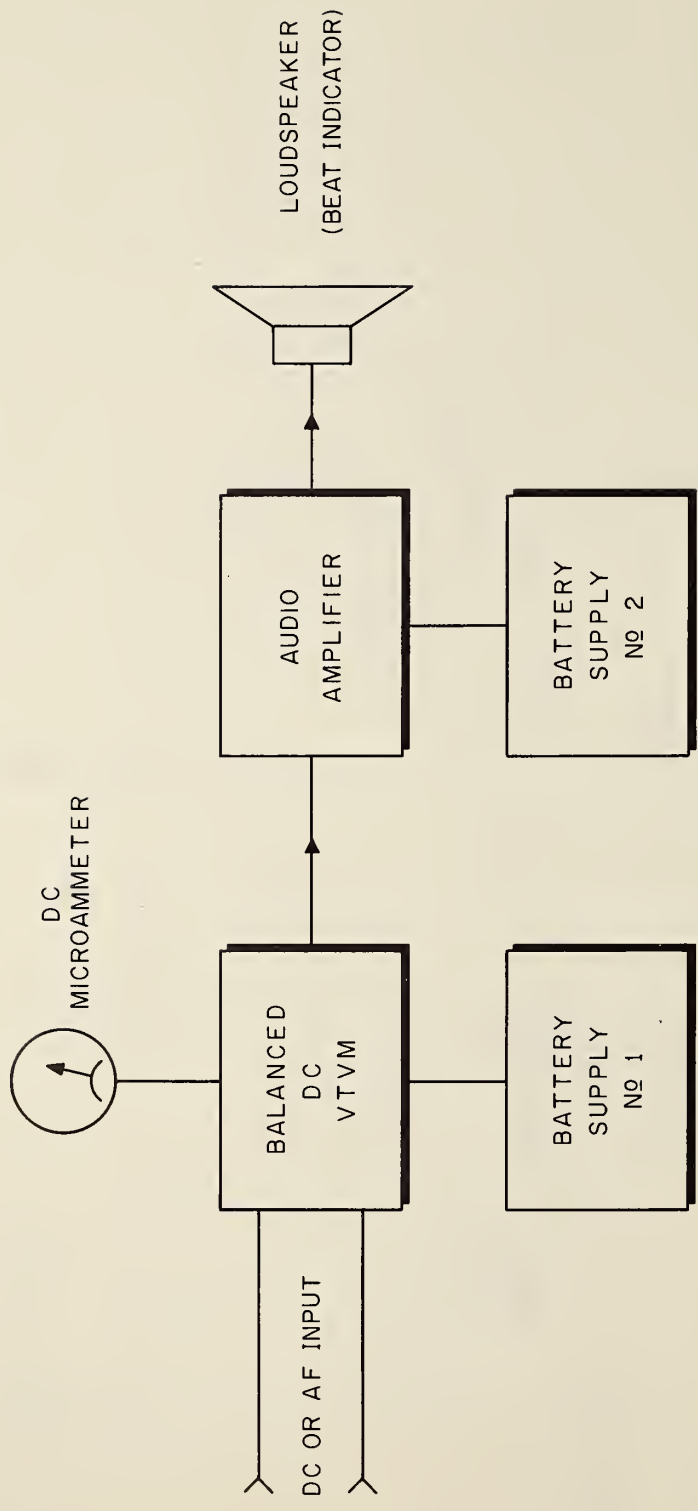DC
VTVM

BATTERY
SUPPLY
№ 1

DC OR AF INPUT

FIG. 15 BASIC LAYOUT OF REMOTE INDICATOR UNIT

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by a private manufacturer and are approximately 1-1/4 inches O. D. by 5 inches long, overall, including the battery supply.

3.2.6 Remote Indicator Unit.

The basic makeup of this unit is shown in the block diagram of Fig. 15. It consists, in the main, of a balanced DC vacuum-tube volt-meter with its DC microammeter, on which the magnitude of the electric field strength is indicated. The VTVM is a battery-operated unit and has extremely good stability and linearity of response because of the large amount of negative DC feedback used in its design. It is used over a single 20 dB input range of approximately 0.75 to 7.5 volts DC. A schematic circuit diagram of the VTVM is shown in Fig. 16.

The input circuitry of the VTVM is balanced to ground and provides from 40 to 60 dB rejection of common-mode input in the 60 to 400 Hz power-frequency range. In addition, a two-section balanced RF filter is used to suppress common as well as transverse-mode input at RF fre-quencies. This filter provides at least 40 dB suppression over the range from 2 to 30 MHz. The input resistance of the VTVM has been adjusted to approximately 200 megohms, making the DC voltage drop on the semi-conducting transmission line less than 1.0 percent.

An output circuit of the VTVM is used to drive a transistorized audio amplifier and loud speaker contained in the same case with the VTVM, as indicated in the block diagram. This unit is of conventional design and is used as a zero-beat indicator when adjusting the frequency of the calibrating oscillator to that of the field being measured. It is always necessary to calibrate the gain of the RF amplifier in the field-strength meter at the particular frequency at which a measurement is to be made. The schematic circuit diagram of the AF amplifier is shown in Fig. 17.
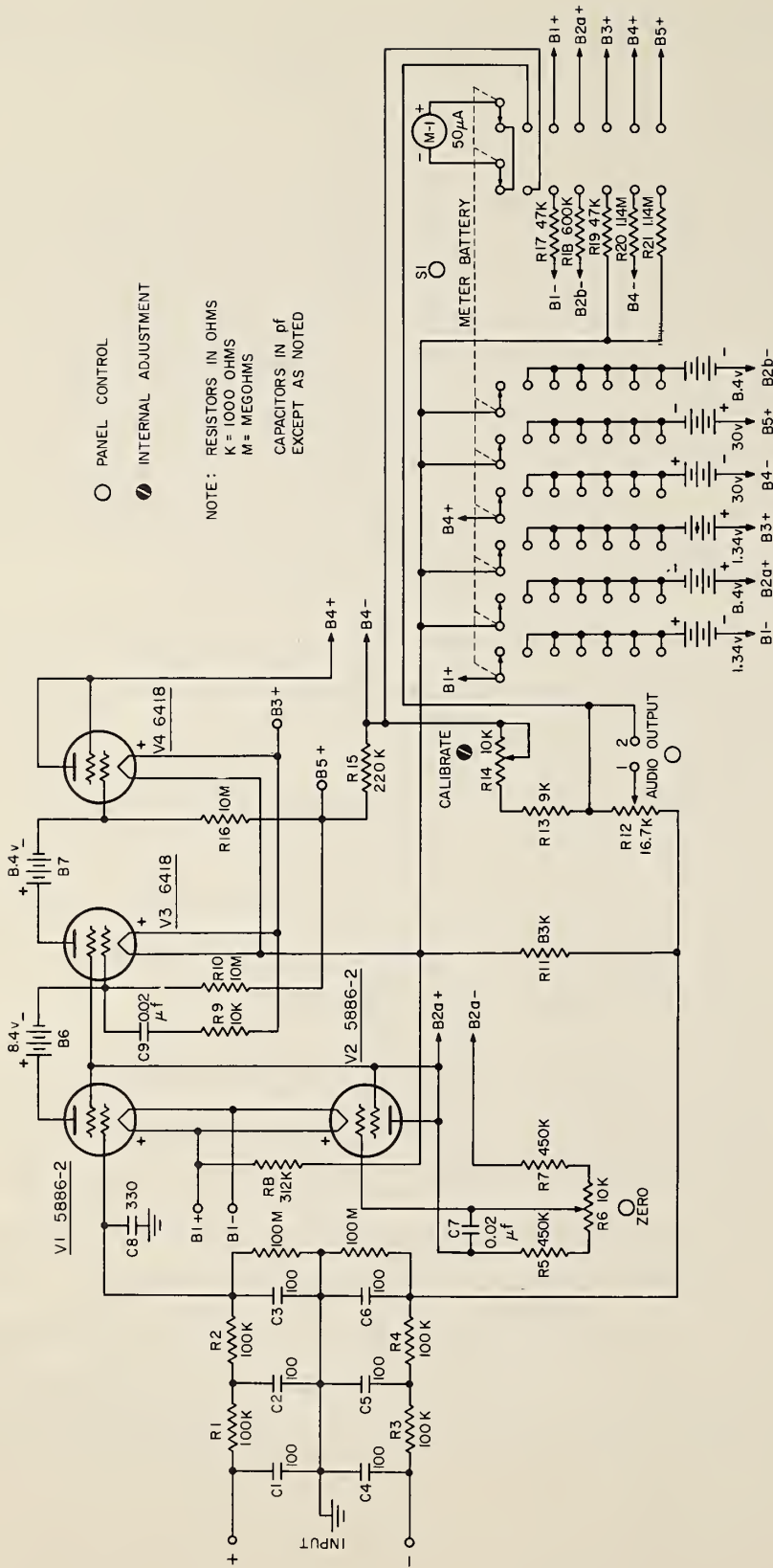
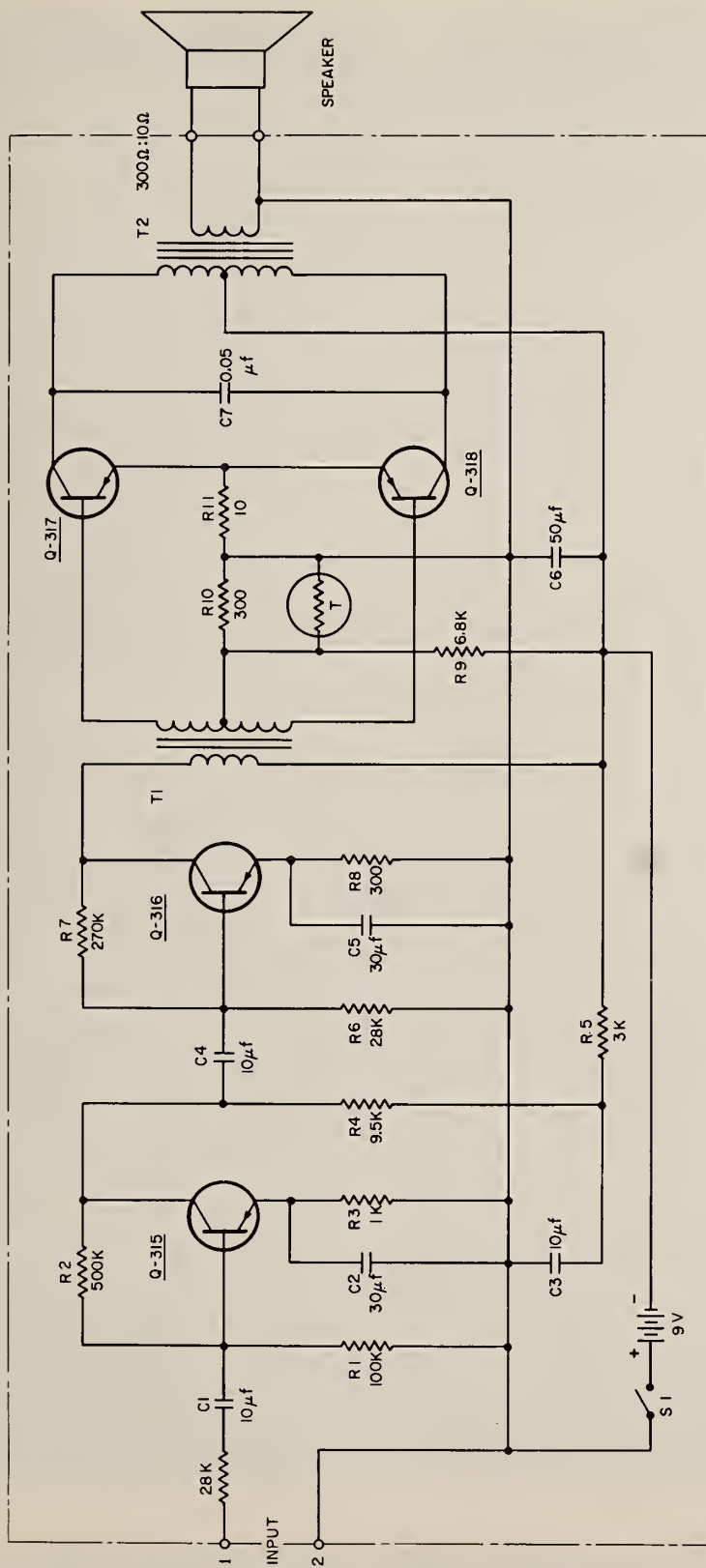FIG. 16 CIRCUIT OF THE DC VACUUM-TUBE VOLTMETER

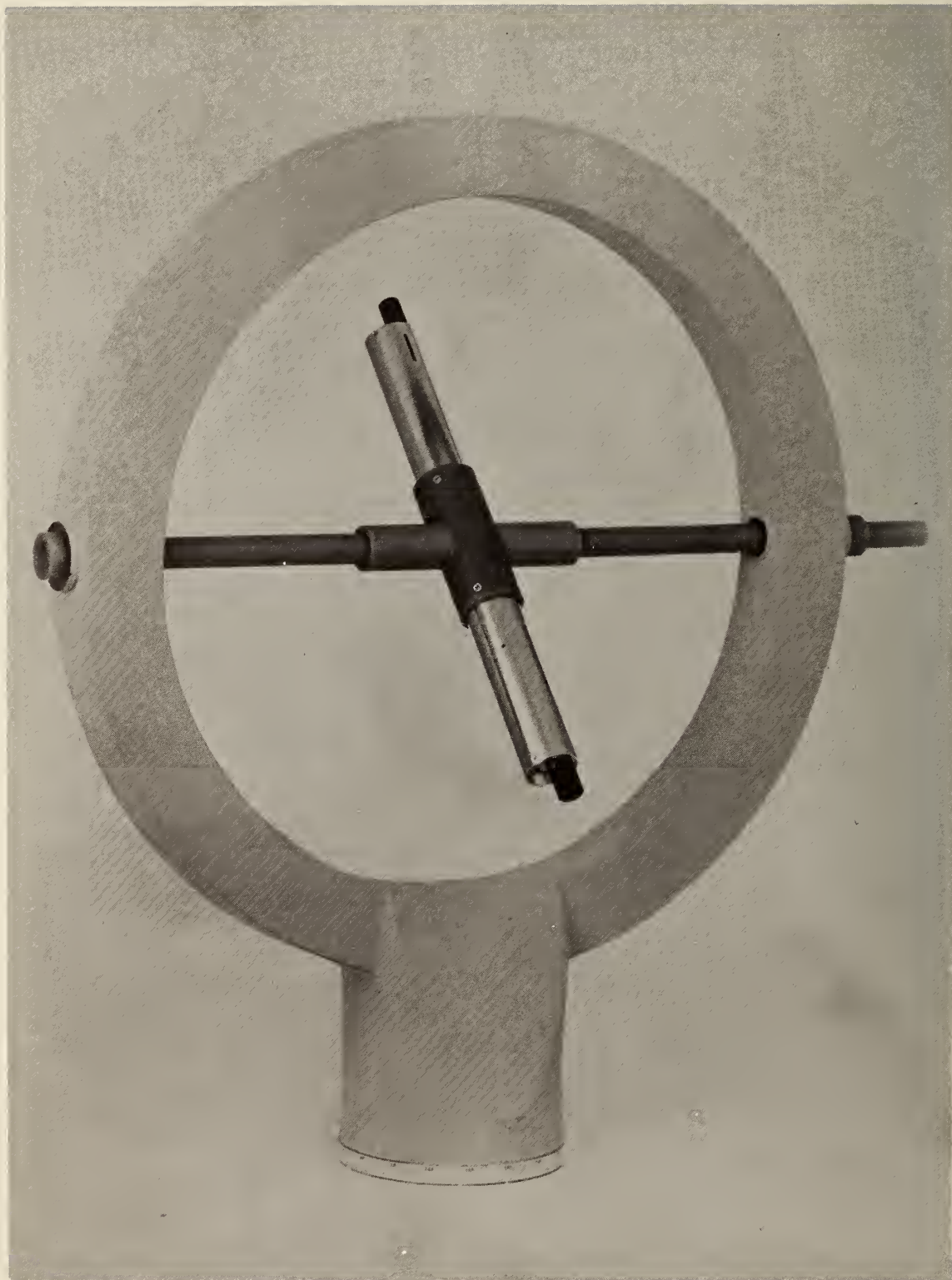FIG. 17 CIRCUIT OF THE AUDIO-AMPLIFIER BEAT INDICATOR

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FIG. 18   VIEW OF THE MEASURING DIPOLE AND MOUNTING GIMBAL

The DC-VTVM and AF amplifier each has its own self-contained battery supply. The complete remote indicator unit is housed in a drawn-aluminum case, using a tight-fitting panel to minimize RF leakage into the unit. A small drawn-aluminum case is used to enclose the rear side of the DC microammeter to reduce RF entry through the meter face.

3.2.7 The Assembled Field-Strength Meter.

The measuring dipole of the near-zone TRF field-strength meter is mounted on a hollow fiberglass shaft which is perpendicular to the dipole axis. This shaft is, in turn, supported in plastic bearings in a circular reinforced polyfoam gimbal, approximately 21 inches in diameter, as shown in Fig. 18. The gimbal has been coated with a thin film of epoxy to increase its strength. This assembly is mounted on a sturdy wooden surveyor's tripod in such a manner that manual adjustments in azimuth and elevation can be readily made in the orientation of the dipole.

The complete field-strength meter consists of three units:

(a)   the tripod-mounted dipole measuring antenna;

(b)   the 30-foot "semi-conducting" plastic transmission line;

(c)   the battery-operated remote-indicator unit.

A view of the complete operating instrument is shown in Fig. 19, in which these components can be seen. The balanced transmission line connects to the dipole through the hollow shaft on its right. A simple split cylindrical tool is used to facilitate inserting the twin-conductor transmission-line plug through this shaft. The other end of the line connects to the balanced input of the remote-indicator unit on the right. It is necessary to observe the correct polarity, as marked, when making this connection. A close-up view of this unit is shown in Fig. 20.

FIG. 19   THE COMPLETE NEAR-ZONE FIELD-STRENGTH METER

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FIG. 20   VIEW OF THE REMOTE INDICATOR UNIT

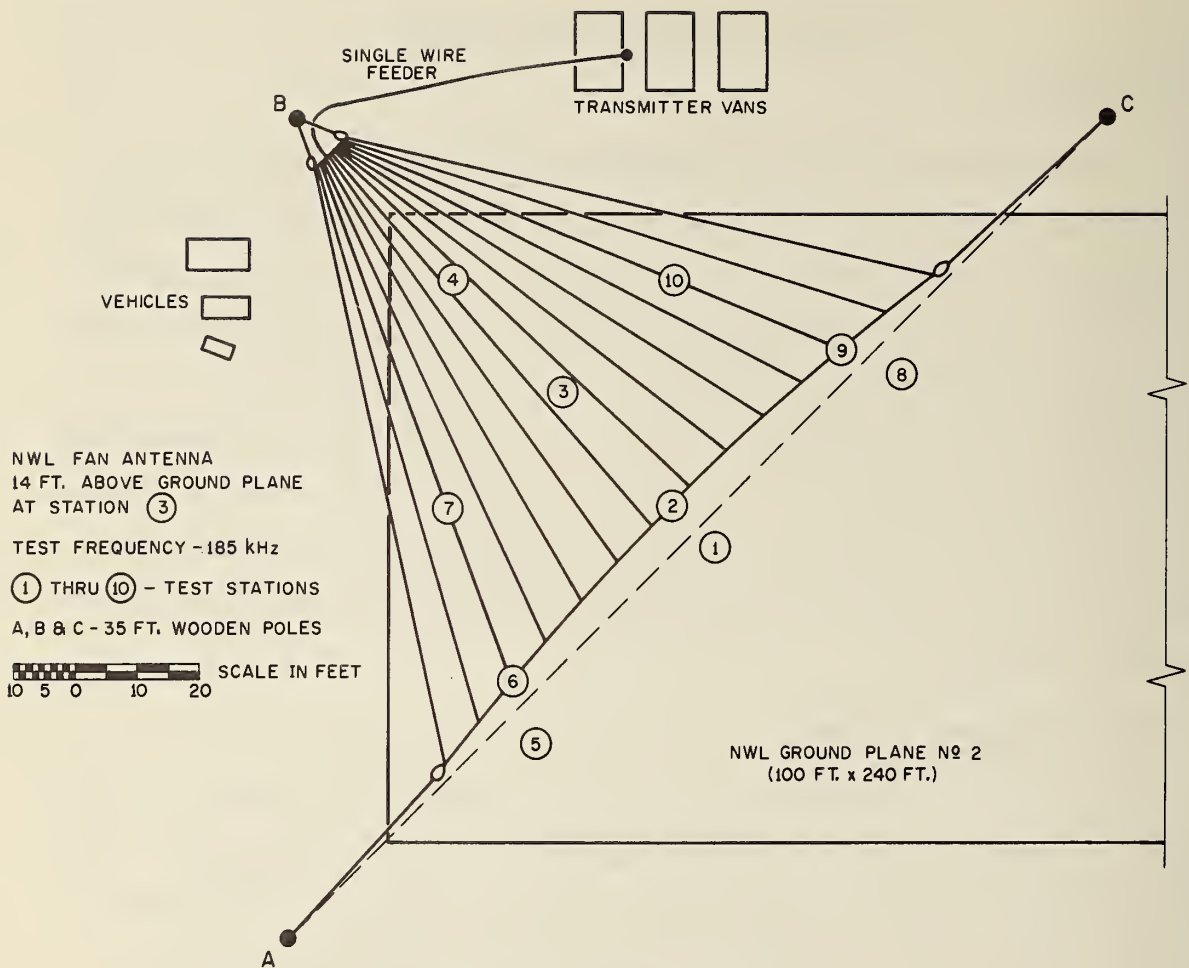- NOTES -

4. DASA Final Acceptance Tests

4.1 General.

The completed NBS near-zone TRF field-strength meters under-
went extensive acceptance tests at the U. S. Naval Weapons Laboratory
at Dahlgren, Virginia, during the week from October 18 to October 22,
1965. The tests were conducted by FCDASA and NBS-BL personnel and
were witnessed by several representatives of each of the three branches
of the Department of Defense. Of great assistance in the tests were the
NWL metal ground plane No. 2 (100 by 240 feet in size), made of welded
sections of 3/8 inch steel plate, and the Navy transmitting equipment
with sufficient power to produce the required test field strengths at the
specified frequencies.

4.2 Low-Frequency Tests.

The low-frequency TRF field-strength meter was tested at a fre-
quency of 185 kHz, using vertically-polarized electric fields with
strengths up to 1020 volts per meter. The test fields were established
between a large horizontal "fan" antenna and the metal ground plane.
The "fan" was in the approximate shape of an equilateral triangle, about
100 feet long on a side and supported by three wooden poles. The "fan"
was composed of 14 diverging wires, connected at their common end to
a single-wire feed line, and supported by one of the poles. At their
opposite end, the fanned wires connected to a messenger cable stretched
between the other two poles. The height of the horizontal fan was adjust-
ed to approximately 14 feet above the ground plane at the lowest point
(Station 3), increasing to 18 feet at the three points of support.

A Navy Type AN/FRT-39 transmitter having a CW RF power output
of approximately 2 kilowatts was used to excite the antenna system. The
transmitter was housed in one of the vans located beside the ground plane.

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SINGLE WIRE FEEDER

TRANSMITTER VANS

VEHICLES

NWL FAN ANTENNA
14 FT. ABOVE GROUND PLANE
AT STATION ③

TEST FREQUENCY – 185 kHz

① THRU ⑩ – TEST STATIONS

A, B & C - 35 FT. WOODEN POLES

SCALE IN FEET
10 5 0   10   20

NWL GROUND PLANE № 2
(100 FT. x 240 FT.)

FIELD - STRENGTH MEASUREMENTS

STATION NUMBER	③	①	②	②	③	④	⑤	⑥	⑥	③	⑦	⑧	⑨	⑩	③
ANTENNA CURRENT (I_A)	13.0	12.9	12.4	13.0	13.0	12.8	13.0	12.6	13.0	13.0	12.7	12.9	13.0	13.0	13.0
FIELD STRENGTH (V/m) *	1020	240	440	460	1020	880	210	420	440	1020	920	220	460	980	1020

*(AS MEASURED 4.3 FT. ABOVE GROUND)

UNBALANCE TEST AT STATION ③	DIPOLE ORIENTATION	0°	180°	0°
	INDICATED V/m	1020	1020	1020

COMMON MODE TEST AT STA. ③	REMOTE INDICATOR AND LINE MOVED AND HANDLED IN STRONG FIELD	NO CHANGE IN INDICATED V/m

RF - SHIELDING TEST AT STA. ③	TEST CONDITIONS	AMPL. "ON" (60 db STEP)	AMPL. "ON", DIPOLE SHORTED (0 db STEP)	AMPL. "OFF", DIPOLE SHORTED (0 db STEP)	REMOTE INDICATOR UNIT ONLY
	INDICATED V/m	1020	1	0	0

FIG. 21   LOW - FREQUENCY DASA ACCEPTANCE TESTS

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The total antenna RF current was measured in the single-wire feed line at the transmitter and included any stray current that existed to ground. The antenna layout, the locations of the test stations, as well as the test results are shown in Fig. 21. All measurements were made with the center of the dipole antenna of the field-strength meter at a vertical height of 4.3 feet above the ground plane. Values of electric-field strength were measured over the range from 210 to 1020 volts per meter with good reproducibility. Both the dipole unbalance and the common-mode pickup were found to be negligible (less than 1 percent), as indicated. RF shielding of the dipole was effective to approximately 60 dB, as measured in a 1020 volt-per-meter field. Susceptibility tests were also performed which are not indicated in Fig. 21. No measurable susceptibility was found to an interfering 22.91 MHz signal (on alone, or simultaneously), having a strength of 200 volts per meter. The remote-indicator unit was placed in the direct beam of a Type AN/SPS-17 P-Band (222 MHz) radar, about 70 feet from its antenna which was radiating a peak power of about 750 kilowatts. A copper wire several feet long was attached to the input connector of the remote-indicator unit which was held by the operator. The meter showed no indication whatsoever, and the unit was able to withstand the intense RF input without damage. Another scanning radar was in operation near the test site, but the low-frequency TRF meter showed no measurable susceptibility when in its beam.

It was not considered feasible to attempt a theoretical evaluation of the electric-field strength existing between the "fan" antenna and the ground plane. This might have been achieved had it been possible to accurately evaluate the antenna capacitance. However, the uncertain boundary conditions existing prevented this. Unfortunately, as a result, there are no values of theoretical field strength with which to compare these test measurements.
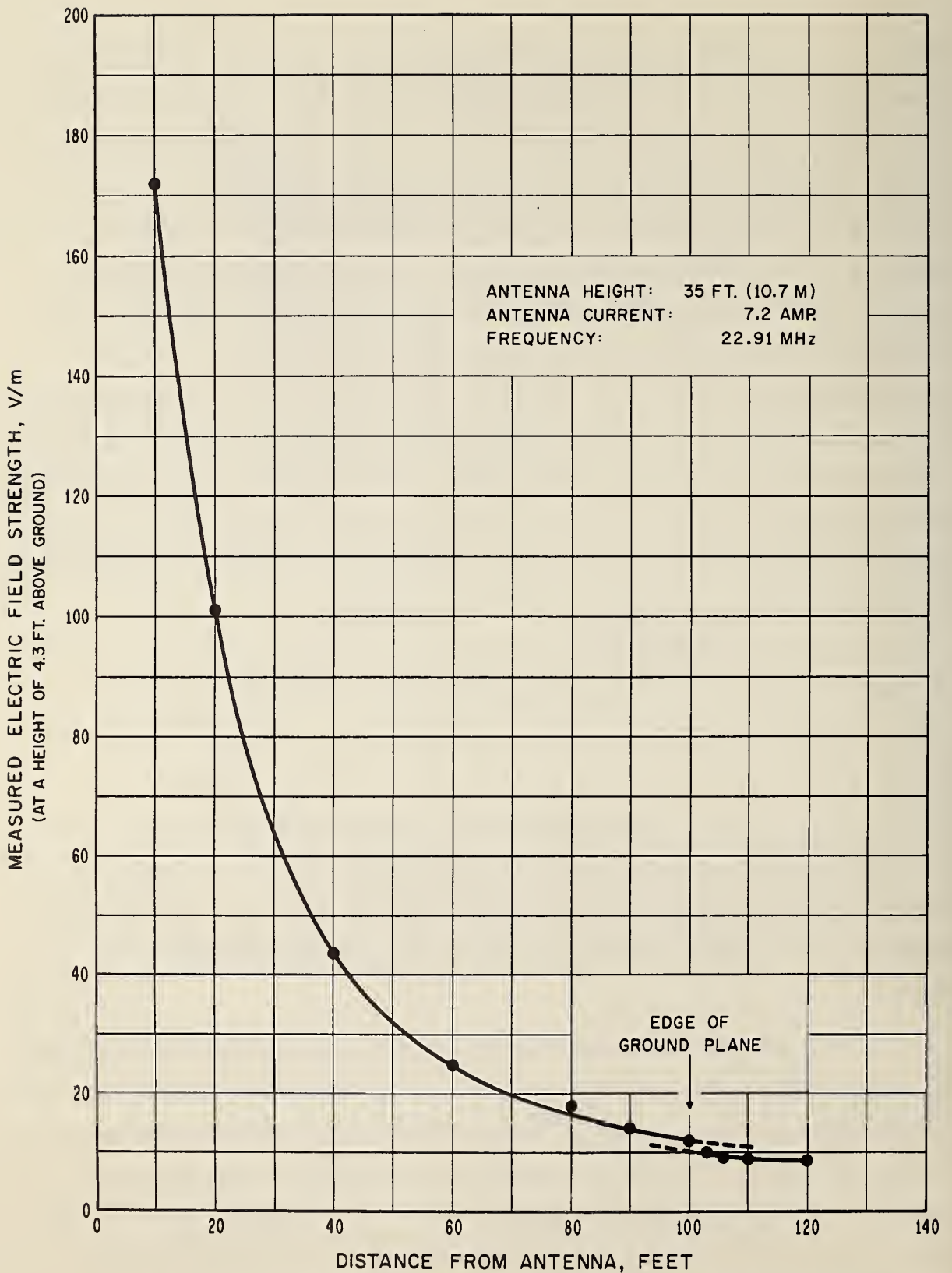
FIG. 22 VERTICAL ELECTRIC FIELD OF A 35 FT. MONOPOLE

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4.3 High-Frequency Tests.

The high-frequency TRF field-strength meter was tested at a frequency of 22.91 MHz. This was one of the normally used transmitter frequencies nearest the center of the passband of the instrument. In the first group of tests, the electric field was produced by a 35-foot self-supporting vertical monopole with a base current of 7.2 amperes. The antenna was located at the edge of the ground plane near the transmitter vans. It was excited by a Navy Type AN/FRT-5 transmitter having a nominal power output of approximately 15 kilowatts. No attempt was made to determine the theoretical field distribution of this antenna because of the uncertain boundary conditions involved.

Field-strength measurements were made at a height of 4.3 feet ($\lambda/10$) above the ground plane at eleven points extending horizontally in a line from the antenna across the ground plane to a point 20 feet beyond the opposite edge (over bare ground). The results of these measurements are shown plotted in Fig. 22, over the range from 8 to 172 volts per meter.

Similar tests to the above were performed using a self-resonant quarter-wave vertical monopole located at the center of the metal ground plane. The same test frequency (22.91 MHz) was used, with antenna base currents of 4.3 and 9.0 amperes. The antenna was a No. 14 A.W.G. copper wire, supported on plastic stand-off insulators mounted on a thin wooden mast (2 inches by 2 inches). A small loop was formed in the wire at the top to minimize corona discharge, and an RF thermocouple type ammeter was inserted at the base. The transmission feed line used was 50 ohm Type RG-221/U low-loss coaxial cable, lying on the ground plane with the sheath grounded near the base of the antenna and the inner conductor connected directly to one of the ammeter terminals. The calculated
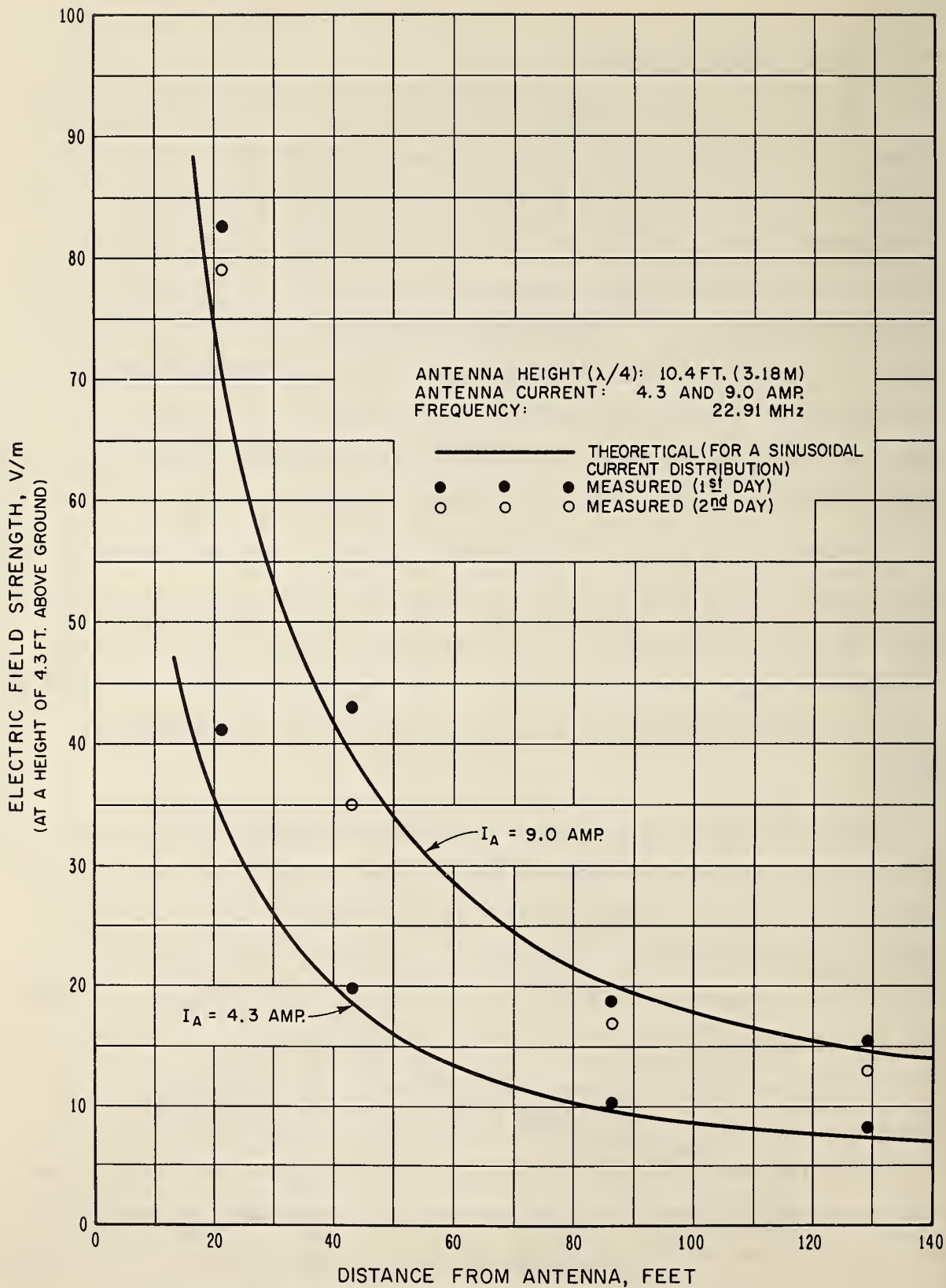
FIG. 23 VERTICAL ELECTRIC FIELD OF A λ/4 MONOPOLE

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self-resonant antenna length was 10.4 feet, which included an estimated 3 percent shortening due to end effect.

Field-strength measurements were made on two successive days at a height of 4.3 feet above the ground plane, at horizontal distances of 0.5, 1.0, 2.0, and 3.0 wavelengths from the antenna. The results are shown in Fig. 23 over the range from roughly 7 to 83 volts per meter. Also shown for comparison is the theoretical field for this antenna based on an assumed sinusoidal current distribution. The measurements agree in general with the theoretical values to within about one dB. The use of an assumed sinusoidal current distribution introduced some error in the computed values of field strength, but this is probably not large because of the small diameter of the antenna (0.064 inch). The effect of edge reflections from the ground plane is another factor that may have introduced additional uncertainty, although this is also believed to be small in this case. The dipole unbalance and common-mode pickup were found to be negligible (less than 1 percent). No penetration of the field into either the dipole or the remote-indicator unit could be observed in a 200 volt-per-meter field. No measurable susceptibility was found to an interfering 185 kHz signal (on alone, or simultaneously), having a strength of 300 volts per meter. The unit showed no susceptibility to the scanning radar mentioned in Section 4.2.

4.4 Summary of the Tests.

The NBS TRF meters showed the capability of measuring electric-field strengths without difficulty over the entire range from 0.1 to 1000 volts per meter (RMS). The tests demonstrated the simplicity of operation of the NBS TRF meters and the reproducibility of measurements free of the perturbing effects of metallic transmission lines usually experienced. There was no observable interaction between the semi-conducting transmission line used and the field being measured. In

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general, the agreement was about ±1 dB between the instrument readings as calibrated in the NBS (vertical monopole) standard field at Boulder and those obtained using a similar technique at NWL at Dahlgren. While this agreement may be somewhat fortuitous, it was also felt to be quite remarkable when considering all the various factors involved at the two sites.

5. Acknowledgement

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