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A New Near-Zone Electric-Field-Strength Meter*

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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. The instrumentation is intended for use in evaluating hazards of high-level electromagnetic radiation to electroexplosive ordnance devices at military installations. The measuring range is from 0.1 to 1000 V 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, which apparently has not been fully exploited heretofore. This involves the use of a completely nonmetallic electrical transmission line over which the field information is transmitted from the measuring antenna to a remote readout unit. The line is essentially "transparent" to the field being measured, and reduces the perturbation of the field two orders of magnitude below that normally experienced when using a metallic line. The high r-f line loss involved necessitates miniaturizing the r-f portions of the receiving and calibrating instrumentation and placing them and their associated battery supplies *inside* the measuring antenna. The design and performance of the meters are discussed in some detail.

Key Words: Device, electroexplosive ordnance; field, near-zone electromagnetic; hazards, electromagnetic radiation; line, nonmetallic electrical transmission; line, semiconducting plastic transmission; meter, electric field-strength; telemetry, novel form of.

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 V 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 electroexplosive 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 nonmetallic electrical transmission line to avoid perturbing the field being measured. This approach has apparently not been fully exploited, heretofore. The extremely high r-f loss of the line used attenuates any r-f currents induced on the line by the surrounding field and essentially eliminates reradiation from the line, or unwanted coupling between the line and the measuring antenna. The high line-loss, however, necessitates miniaturizing the r-f 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 develped 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 "Semiconducting" 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* r-f transmission

*For complete design details the reader is referred to "A New Near-Zone Electric-Field-Strength Meter"—Frank M. Greene, National Bureau of Standards Technical Note No. 345, November 15, 1966. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402. Price 35 cents.

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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, either seldom exists, or the orientation of such a path, if it *does* 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 r-f currents induced on the line can be coupled into the antenna and contribute to the total response of the field-strength meter.

2.2. The Use of a Nonmetallic Line

The NBS near-zone meters avoid this difficulty by making use of a special nonmetallic balanced transmission line in which the conductor r-f loss has been purposely made extremely high compared to that of the usual copper line. If the conductors are made of sufficiently high resistance material, the line can be made essentially "transparent" to the surrounding field. This is to say that the r-f currents induced on the transmission line by the field will be negligibly small, resulting in insignificant reradiation, or that any r-f 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 therefore be said to be "semiconducting."

2.3. Description of the "Semiconducting" Line

The material used in the NBS lines is basically polytetrafluoroethylene (PTFE), rendered "semiconducting" by uniformly dispersing finely divided carbon black (approximately 30 percent by weight) throughout the plastic while it is in the semifluid 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 multifiber 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 semiconducting PTFE material. The line conductors are in the form of 0.03 in diam monofilaments in place of the usual copper conductors. They are coated with a thin nylon film (approximately 0.005 in 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 in 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 ft.

2.4. Electrical Characteristics of the Line

The semiconducting PTFE material used in the line has a volume resistivity of approximately 3.0 Ω-cm (compared to 1.7×10^{-6} Ω-cm for copper), giving a resistance of approximately 20,000 Ω per lineal foot, or a loop resistance of approximately 1.2 MΩ for a line 30 ft 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 d-c a-f 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 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. However, the differential-mode component is appreciably smaller and does not present a problem in the NBS meters at the level of d-c transmission used (see table 1).

3. Description of the Near-Zone Field-Strength Meters

3.1. Principles of Operation

Two prototype near-zone field-strength meters were developed for the Defense Atomic Support Agency, and cover the frequency ranges 150 to 250 kHz, and 18 to 30 MHz, respectively. These meters make use of a tuned r-f type of receiver to amplify the voltage induced in the receiving antenna by the component of

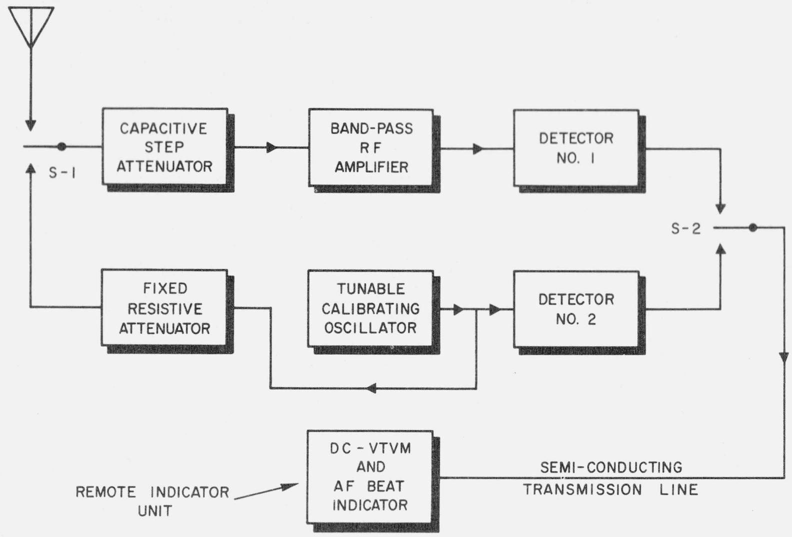

FIGURE 1. *Block diagram of the NBS field-strength meter.*

the electric field being measured. A tunable CW oscillator is included to permit calibrating the overall receiver gain periodically during a sequence of measurements in the field. A block diagram of the basic circuitry is shown in figure 1. The 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. The receiver portion of the field-strength meter consists basically of an r-f input capacitive step attenuator, a fixed-tuned band-pass r-f amplifier (with manual gain control), and a diode detector. The r-f output level of the oscillator is monitored by its own detector. When calibrating, the receiver gain is simply adjusted until the d-c outputs of the two detectors are identical. In this method, the exact level of the calibrating signal is not important, and does not have to be known. However, it *is* important that the oscillator monitoring detector remain stable.

TABLE 1. *Distribution of nominal operating rf-voltage levels (in the TRF field-strength meter)*

E(V/m)	α(dB)	V_i(volts)	V_0(volts)	V_1(volts)	V_2(volts)	V_3(volts)
0.1–1.0	0	0.015–0.15	0.003–0.03	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) = Electric field strength, volts per meter
α(dB) = Measuring dipole attenuator setting
V_i = Induced voltage in measuring dipole
V_0 = Output voltage of measuring dipole
V_1 = Input voltage to rf amplifier
V_2 = Output voltage of rf amplifier
V_3 = Output voltage of amplifier detector (DC).

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

Effective length of measuring dipole..., $L_{\mathrm{eff}} \cong 0.15$ m
Induced voltage in dipole.................., $V_i = E \cdot L_{\mathrm{eff}}$
Dipole voltage-transfer ratio, $V_0/V_i = C_a/(C_a + C_s) \cong 0.20$
$C_a \equiv$ Internal capacitance of dipole......, $C_a \cong 3$ pF
$C_s \equiv$ Residual gap and circuit capacitance, $C_s \cong 12$ pF
RF amplifier nominal voltage gain......, $V_2/V_1 \cong 100$.

3.2. Electrical Design

The Dipole Antenna. A cutaway view of the dipole assembly is shown in figure 2, and a view of an assembled unit is shown in figure 3. The dipole is made of 1/16 in wall copper tubing 1 3/8 in O.D. The length is approximately 13 in with a 1/32 in insulated gap at the center. The miniaturized solid-state receiver and its battery supply are contained in the left half, and the CW calibrating oscillator and its battery supply are in the right half. The capacitive step attenuator, the DPDT line-transfer switch, and the oscillator ON-OFF control comprise the five rotary switch wafers seen in the central portion of the dipole assembly. The balanced transmission-line plug connects to two insulated stainless steel pins at the center of the dipole. The line enters the interior of the dipole through a two-section balanced RC filter to help preserve the electrical symmetry or balance of the dipole with respect to the transmission line, and to attenuate any differential, as well as common-mode r-f pickup that might exist on the line. The symmetry is important if the antenna is to respond only to the component of the electric field parallel to its axis. The symmetry of the NBS dipole is such that its response to the cross-polarized component of the electric field is 40 dB or more below the principal response.

It can be shown that if the length of the measuring dipole does not exceed 0.03 wavelength, its effective

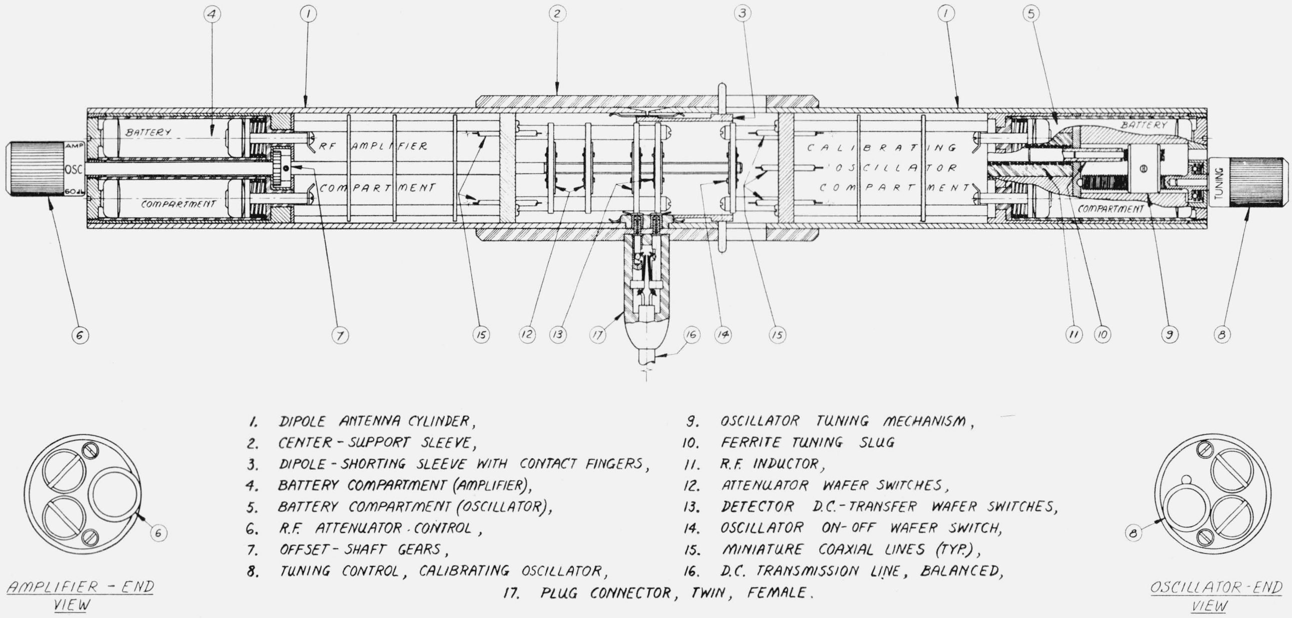

FIGURE 2. *Cutaway drawing of the measuring dipole.*

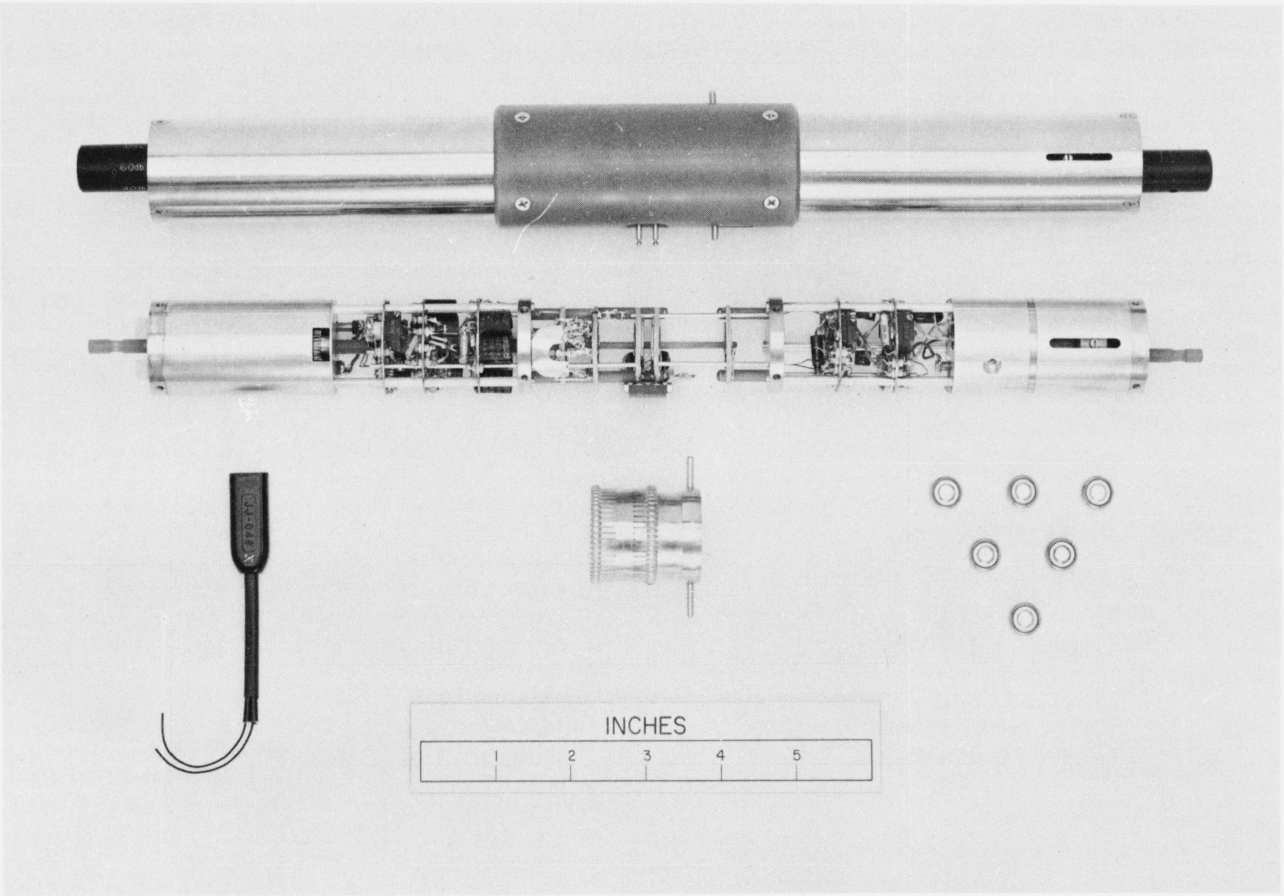

FIGURE 3. *View of the complete measuring dipole.*

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 2 or 3 ft to the ground or large metallic objects.

RF Capacitive Step Attenuator. This attenuator has four principal steps, 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 automatically turned ON, and the "semiconducting" transmission line can then be switched between the d-c outputs of the oscillator and amplifier detectors, while calibrating the amplifier gain. The attenuator is constructed using special subminiature rotary wafer switches. Miniature low-temperature coefficient ceramic capacitors are used in either an "L" or a "Pi" configuration for the various attenuator pads. The attenuator steps are accurate to ± 0.1 dB. The attenuator module is approximately 1 in O.D. by 1 in long.

Band-Pass Amplifier and Detector. 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. This is followed by a six-pole, fixed-tuned, bandpass filter having a 3 dB pass-band of 150 to 250 kHz, and 18 to 30 MHz respectively in the two units and a 40 dB pass-band of 100 to 300 kHz and 12 to 36 MHz, respectively. The filter is followed by a 3-stage r-f amplifier. In the low-frequency unit, this is broadband resistance-coupled, using overall negative r-f feedback to improve gain stability with respect to temperature and supply-voltage variations. In the high-frequency unit, the r-f amplifier has 3 stages using wide-band synchronously tuned interstage transformers. The overall gain of both amplifiers can be manually adjusted to the required operating value of approximately 40 dB. The output detectors of both amplifiers employ two stable silicon diodes in a voltage-doubling circuit, to ease voltage-swing requirements on the final stage and consequently to reduce battery drain. A 12 V silver-oxide battery supply is used, having a useful life of from 10 to 20 hr. The complete amplifier module measures 1¼ in O.D. by 5 in long including its filter and battery supply.

Calibrating Oscillator and Detector. This unit is also transistorized. It consists of a permeability-tuned Clapp-Colpitts oscillator followed by a two-stage automatic-level-control amplifier to maintain the r-f output essentially constant over its tuning range. 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. The r-f output of the oscillator is adjustable to roughly 3.0 V and fed into a fixed 30 dB resistive attenuator pad. When calibrating the gain of the band-pass amplifier, the output of approximately 0.1 V from the pad is applied to the amplifier input 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 is used to monitor the 3.0 V oscillator level at the input terminals of the 30 dB pad. A 13.5 V silver-oxide battery supply is used, having a useful life of about 20 hr. A portion of the supply is Zener regulated and applied to the transistor base circuits for improved amplitude stability. The complete calibrating oscillator module measures 1¼ in O.D. by 5 in long including the battery supply.

The Remote Indicator Unit. This unit consists basically of a battery-operated, balanced d-c vacuum-tube voltmeter, with its d-c microammeter, on which the magnitude of the electric field strength is indicated. This VTVM has exceptionally good stability and linearity of response because of the large amount of negative d-c feedback employed in its design. It is used over a single 20 dB input range of approximately 0.75 to 7.5 V. The balanced input circuitry 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 r-f filter provides at least 40 dB suppression of common and differential-mode input at the higher r-f frequencies. An output circuit in the VTVM is used to drive a transistorized audio amplifier and loud speaker. These units are used as a zero-beat indicator when adjusting the frequency of the calibrating oscillator to that of the field being measured. Separate, self-contained battery supplies are used with the VTVM and a-f amplifier. The complete remote indicator is housed in a drawn-aluminum case, using a tight-fitting panel to minimize r-f leakage into the unit. A small drawn-aluminum case is used to enclose the rear side of the d-c microammeter to reduce r-f entry through the meter face.

The Assembled Field-Strength Meter. The measuring dipole of the near-zone field-strength meter is mounted on a hollow fiber-glass shaft which is perpendicular to its axis. This shaft is in turn supported in plastic bearings in a circular reinforced polyfoam gimbal, approximately 21 in. in diameter, as shown in figure 4. This assembly is mounted on a sturdy wooden surveyor's tripod, in such a manner that manual adjustments in both azimuth and elevation can be readily made in the orientation of the dipole. A view of the complete field-strength meter is shown in figure 5. The balanced transmission line connects to the dipole through the hollow shaft on the right. The other end of the 30 ft line connects to the remote indicator unit, a closeup view of which is shown in figure 6.

3.3. Performance

The two near-zone field-strength meters underwent extensive field tests at the U.S. Naval Weapons Laboratory at Dahlgren, Va. Electric field strengths were

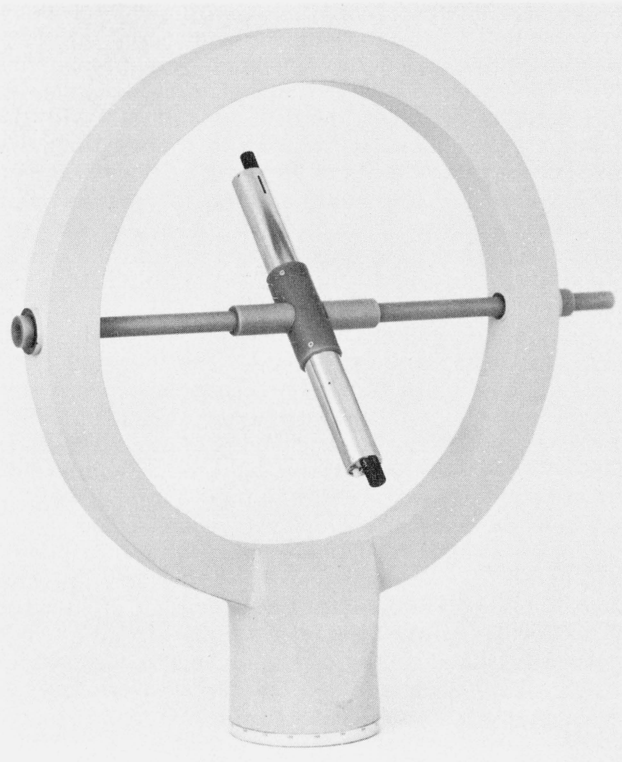

FIGURE 4. *View of the measuring dipole and mounting gimbal.*

FIGURE 6. *View of the remote indicator unit.*

FIGURE 5. *The complete near-zone field-strength meter.*

measured without difficulty over the entire range from 0.1 to 1000 V per meter (CW-RMS). There was no observable susceptibility to out-of-band CW signals having levels as high as 200 V per meter, or to pulsed signals from nearby high-powered radar transmitters. No interaction was observed between the semiconducting transmission line and the field being measured. In general, the agreement was about ± 1 dB between the instrument readings as calibrated in the NBS standard field at Boulder and those obtained in the NWL standard field at Dahlgren. The uncertainty in the calibration accuracy of the instruments is believed to be less than ± 2 dB. Further development effort on the standard fields is expected to reduce this to less than ± 1 dB.

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