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A SMALL ELF ELECTRIC FIELD PROBE

U. S. Naval Electronic Systems Command
Washington, D.C.

Prepared by

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13. ABSTRACT

The design and development of a probe for measuring electric fields at Extremely Low Frequencies (ELF) is described. The probe is spherically shaped and relative small (6.3 cm in diameter) and uses a fiber-optic readout to avoid unnecessary disturbance of the measured electric field. The probe is capable of measuring fields between 10 mv/meter and 100 volts/meter. Problems encountered in the design and packaging of the probe and operational data for the probe are presented.

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FOREWORD

The ELF electric-field probe described in this memorandum was developed at the direction of the Sanguine Division of the Naval Electronic Systems Command, which is responsible for the management of the Sanguine Program.

The probe was designed by Mr. A. R. Valentino with aid from Mr. J. Goode on the experimental work. The probe was fabricated by Mr. R. Heidelmeier.

Respectfully submitted,

IIT RESEARCH INSTITUTE

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A SMALL ELF ELECTRIC FIELD PROBE

Abstract

The design and development of a probe for measuring electric fields at extremely low frequencies is described. The probe is spherically shaped and relatively small (6.3 cm in diameter) and uses a fiber-optic readout so as not to unnecessarily disturb the measured electric field. The probe is capable of measuring fields between 10 mv/meter and 100 volts/meter. Problems encountered in the design and packaging of the probe and operational data for the probe are presented.

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1. INTRODUCTION

The objective of this memo is to describe the design and development of a probe for measuring the electric field in air at extremely low frequencies (20-200 Hz). The primary application for this probe is that of mapping the electric field in certain electric-field simulators used for biological research. The fact that the probe is to be used to map the electric field over small volumes (e.g., 2 x 2 x 2 meters and smaller) requires that it be small by comparison.

A secondary application for the probe is that of measuring and mapping the ambient 60-Hz electric field. The small size of the probe will allow it to be used to seek out regions of high electric field.

It is of interest to measure field levels as low as 10 mv/meter and in order to properly map the field in an electric-field simulator or other regions of interest, a dynamic range of at least 40 dB is desired. Since certain of the simulators are operated at 10 volts/meter, it was decided that a probe which could measure fields between 10 mv/meter and 100 v/m was what was desired.

2. SYSTEM DESIGN

Since it is required that extremely low frequencies (20-200 Hz) be measured with a very small probe, the output impedance of the probe can be expected to be very high and its open-circuit voltage very low. Therefore, the plan must be to follow the probe with a high-input impedance, voltage-amplifier stage. This stage can also be used to provide the variable gain necessary to achieve the desired dynamic range.

The electric field to be measured must not be perturbed any more than is necessary. For this reason, the use of metallic cable to carry the measured information from the probe to the receiver is undesireable. A fiber-optic light-guide system is selected to provide this link. It is anticipated that a buffer, in the form of a power amplifier, will be required between the voltage-amplifier stage and the light source.

The receiver will consist of a light-sensitive diode followed by an amplifier, the output of which may be monitored by a laboratory oscilloscope or voltmeter.

A block diagram of this system is shown in Fig. 1.

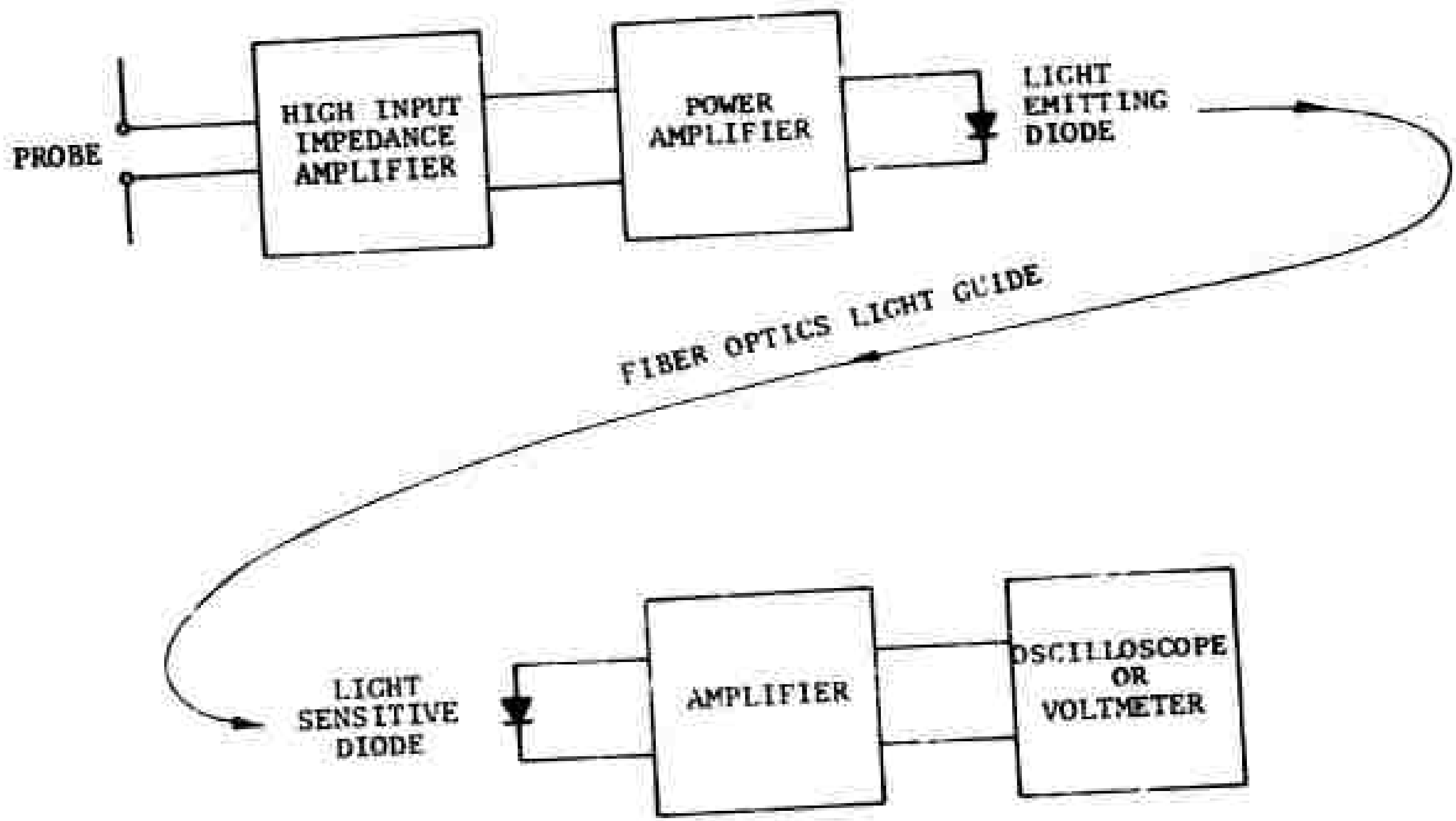


Fig. 1 SYSTEM BLOCK DIAGRAM

3. COMPONENT SELECTION OR DESIGN

3.1 Probe

The two primary requirements for the probe are conflicting. First, it is important that the probe be small so that it can be used to map electric fields. In this way the probe can be used to evaluate the uniformity of the electric field in certain simulators. Second, the sensitivity of the probe will increase with its size and for this reason it is important that the probe be as large as possible.

In order to avoid unnecessary distortion of the electric field to be measured, it was decided to place the electronics inside of the probe. Therefore, the probe should provide a large internal volume.

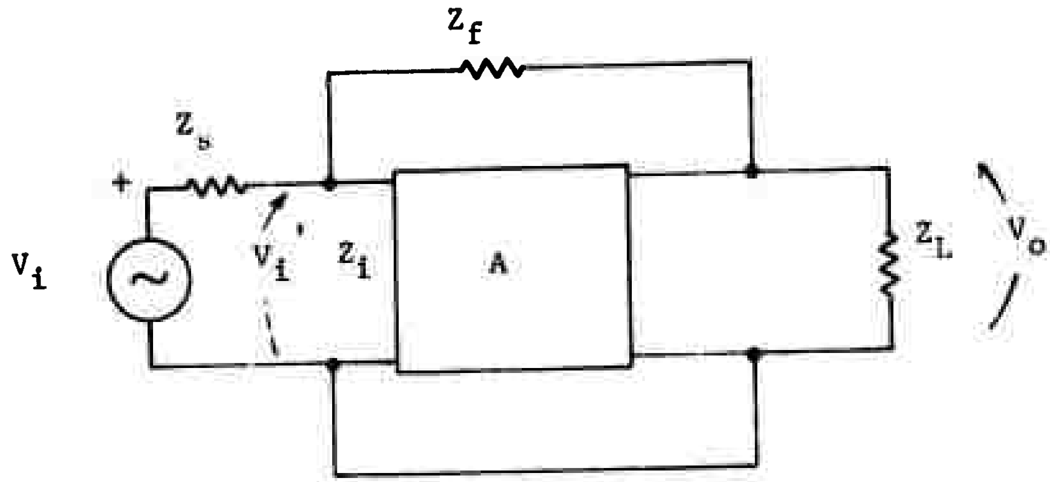
The shape chosen for the probe is that of a sphere for the following reasons:

1) for a given maximum dimension the sphere provides the largest internal volume, and

2) the behavior of the spherical shape in an electric field can be analyzed (see Appendix A) providing theoretical understanding for the operation of the probe.

3.2 High-Input-Impedance Voltage Amplifier

The diagram and equations in Fig. 2 show how a high-gain amplifier and a variable-feedback resistor might be employed to provide the required variable voltage-amplification stage. However, since the source which will drive this stage is a small, low-frequency electric field probe, the source impedance, Z_s, will be a very large, capacitive reactance (see Appendix A).



$$V_i' A = V_o$$

$$\frac{V_i - V_i'}{Z_s} = \frac{V_i'}{Z_i} + \frac{V_i' - V_o}{Z_f}$$

$$\frac{V_i}{Z_s} = \frac{V_o}{A}\left[\frac{1}{Z_s} + \frac{1}{Z_i} + \frac{1}{Z_f}\right] - \frac{V_o}{Z_f}$$

For A large

$$\frac{V_o}{V_i} = -\frac{Z_f}{Z_s}$$

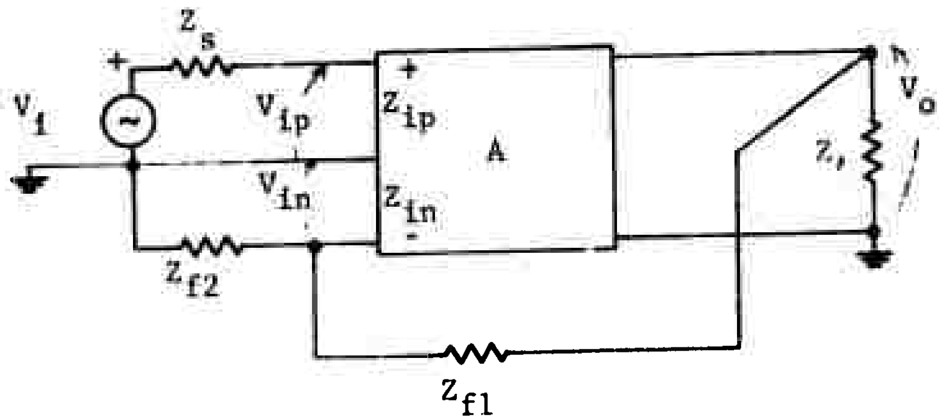
Fig. 2 FEEDBACK AMPLIFIER

Furthermore, the source voltage, V_i, will be the probe's open circuit voltage (V_{oc}) which is given by definition as the product of the electric field and the effective length (ℓ_{eff}) of the probe. Since we expect ℓ_{eff} to be on the order of the radius of the sphere, we do not expect a very large V_{oc}. It has, in fact, been shown experimentally that the configuration presented and analyzed in Fig. 2 is inadequate.

The problem discussed above is circumvented by employing a commercially available operational amplifier which provides two separate inputs. The operation of such an amplifier is analyzed in Fig. 3. Note that if the input impedance, Z_{ip}, is of the same order of magnitude as the source impedance, Z_s, the ratio of V_o to V_i will be adequate. Note also, that this ratio may be controlled by varying the feedback impedance, Z_{f1}. The magnitude of Z_{f1} is limited by the oscillation problem. That is, the negative feedback provides stability and prevents spurious oscillation.

A copy of the specification sheet for the amplifier chosen for this purpose is presented as Fig. 4. This amplifier was chosen for its high input impedance and its low-power drain.

A difficulty which is encountered when feeding an amplifier of this type from a capacitive source impedance is that no dc path exists between the positive input lead and ground. Under this condition the proper input bias current is not allowed to flow and the amplifier does not function. This problem is solved by providing a dc path from the input lead to ground. Of course, the resistance of this path must be made as large as possible so that the source is not loaded down unnecessarily. For the amplifier used here, it was found that a 500MΩ resistor was adequate. Additional source loading due to stray capacitance internal to the sphere will swamp this resistance.



$$V_o = A\,(V_{ip} - V_{in})$$

$$V_o = A\left(V_i \frac{Z_{ip}}{Z_s+Z_{ip}} - V_o \frac{Z_{f2}Z_{in}}{Z_{f2}Z_{in}+Z_{f1}Z_{f2}+Z_{in}Z_{f1}}\right)$$

$$\frac{V_o}{V_i} = \frac{A\,Z_{ip}}{Z_s+Z_{ip}} \cdot \frac{Z_{f2}Z_{in}+Z_{f1}Z_{f2}+Z_{in}Z_{f1}}{Z_{f1}Z_{f2}+Z_{f1}Z_{in}+Z_{f2}Z_{in}(1+A)}$$

For A large

$$\frac{V_o}{V_i} = \frac{Z_{ip}}{Z_s+Z_{ip}} \cdot \left(1 + \frac{Z_{f1}}{Z_{f2}} + \frac{Z_{f1}}{Z_{in}}\right)$$

for $|Z_{in}| \gg |Z_{f1}|$

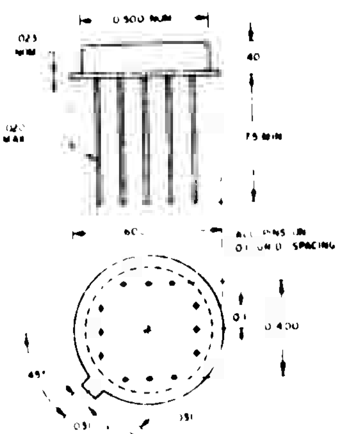
$$\frac{V_o}{V_i} = \frac{Z_{ip}}{Z_s+Z_{ip}} \left(1 + \frac{Z_{f1}}{Z_{f2}}\right)$$

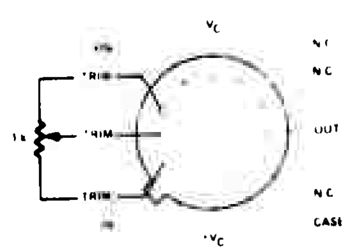
Fig. 3 ANALYSIS OF A TWO INPUT OPERATIONAL AMPLIFIER

Fig. 4 OP-AMP SPECIFICATION SHEET

model 1402/01/02
microcircuit FET operational amplifier

TO-8 CASE
BIAS CURRENT 15 pA
$Z_{in} = 10^{12}\ \Omega$
OUTPUT = ±14 V ±5 mA
SUPPLY RANGE ±4 to ±24 VOLTS
QUIESCENT CURRENT ±0.5 mA





DESCRIPTION

Philbrick/Nexus Type 1402 is a FET input, hybrid thin-film microcircuit operational amplifier. The unit is packaged in a TO-8 case to match modern demands for a versatile FET amplifier in minimum dimensions.

Hybrid construction of Type 1402 combines the advantages of both discrete and of monolithic construction. FET inputs are specially matched and optimized for best thermal performance, as well as high input resistance ($10^{12}\ \Omega$) and low offset voltages (300µV). A smooth roll-off at 6 dB octave is assured by internal phase compensation.

Alternate Types 1402-01 and 1402-02 are available for critical applications; see design data for tabulation of improved offset voltages, bias currents and temperature coefficients. Design for performance over a wide range of supply voltages (±4 to ±24 volts) assures versatility in a wide variety of applications. Suggested applications are as integrators, sample and hold circuits, voltage comparators, and with wide dynamic range log functions modules and accurate multipliers.

DESIGN DATA*

	Typical	Guaranteed
OUTPUT		
Full load output voltage	±14 V	±13 V min
Output current	5 mA	2 mA min
Maximum capacitive load		0.005 µF max
Output impedance open loop	1 kΩ	
INPUT		
Common mode rejection ratio	76 dB	
Common mode voltage range		±12 V min
Input impedance, common mode	$10^{12}\ \Omega$	
Input impedance, differential	$10^{12}\ \Omega$	
Voltage offset Type 1402		3 mV max
Type 1402-01		1 mV max
Type 1402-02		0.3 mV max
vs supply [illegible]	400 µV/V	
vs common mode volts	500 µV/V	
vs temperature		
Type 1402		50 µV/°C max
Type 1402-01	—	30 µV/°C max
Type 1402-02		10 µV/°C max
Temperature [illegible]	15 µV/°C	50 µV/°C max
Bias current		30 pA max
vs temperature		3 pA/°C max
OPERATION		
Gain full load	20,000	10,000 min
Frequency for unity gain	2.5 MHz	
Maximum full output frequency	80 kHz	70 kHz min
Slewing rate full load		3 V/µsec min
Overload recovery time		15 µsec max
Wideband noise	3 µV rms	
Operating temperature		−25°C to +85°C
Storage temperature		−55°C to +125°C
POWER		
Supply voltage		±4 to ±24 V
No load current	0.5 mA	[illegible] max
Full output current	2.5 mA	

*At +25°C, ±15 V except where indicated

2 kΩ load including feedback resistance — 0.16 kHz to 1.6 kHz

Without instability — −25°C to +85°C

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Allied Drive at Route 128, Dedham, Massachusetts 02026
Tel: (617)329 1600 TWX: (710)348 6726 Telex: 92-4439

Printed in U.S.A. 10/70

3.3 Light-Emitting Stage

In order to transmit the measured information from the probe to the receiver without using metallic cable, a fiber-optic light guide is used. The light-emitting source is a Gallium Arsenide electroluminescent diode. A copy of the specification sheet for this diode is presented as Fig. 5. The primary requirements for the drive circuit for this diode are that:

1) it provide a buffer between the relatively high output impedance operational amplifier, and
2) it provide adequate forward bias current for the LED without undue battery drain.

The circuit design for the drive circuit is shown in Fig. 6.

3.4 Glass-Fiber Light Guide

Specifications for the light guide used in this system are presented as Fig. 7. A six-foot length of light guide is used in this system.

3.5 Receiver

The receiver portion of this system employs a light sensitive diode followed by a high-input-impedance amplifier. These components were chosen rather arbitrarily and based on their availability. The specifications of the LSD are presented as Appendix B. Appendix C presents the specifications for the amplifier.

3.6 Batteries

The minimum requirements for the electric-field-probe batteries were determined as:

1) they deliver both positive and negative 5v ± 10% at 4 ma for approximately four hours, and

HEWLETT hp PACKARD

COMPONENTS

Fig. 5 LED SPECIFICATION SHEET

SOLID STATE LAMPS

5082-4403
5082-4440

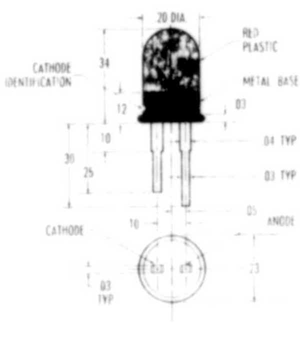
INCLUDES
-4409, -4415,
-4418, -4444

TENTATIVE DATA 1 JUN 71

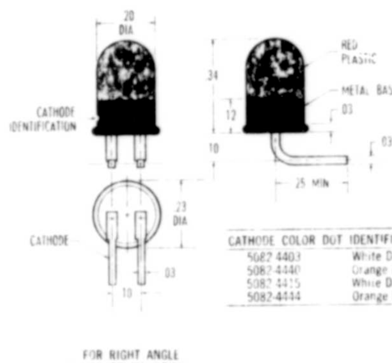
FEATURES

- Easily Panel Mountable
- High Brightness Over a Wide Viewing Angle
- Rugged Construction for Ease of Handling
- Sturdy Leads on 0.10-inch Centers
- IC Compatible/Low Power Consumption
- Long Life

ACTUAL SIZE



FOR PANEL MOUNTING
5082-4403
5082-4440



FOR RIGHT ANGLE
PC BOARD MOUNTING
5082-4415
5082-4444

CATHODE COLOR DOT IDENTIFICATION	
5082-4403	White Dot
5082-4440	Orange Dot
5082-4415	White Dot
5082-4444	Orange Dot

DESCRIPTION

The **5082-4403, -4415, -4440 and -4444** are plastic encapsulated Gallium Arsenide Phosphide Light Emitting Diodes. They radiate light in the 655 nanometer (red light) region.

The **5082-4403 and -4415** are LEDs with a red diffused plastic lens, providing high visibility for circuit board or panel mounting with a clip.

Both LEDs are designed for low power consumption, thus applicable for use in mobile and portable equipment.

The **5082-4440 and -4444** are economically priced LEDs with a red diffused plastic lens, providing a wide viewing angle for circuit board or panel mounting with clip. Both LEDs are designed for circuit status and other light indicating functions.

The **5082-4415 and -4444** have the added feature of a 90° lead bend for edge mounting on circuit boards.

MAXIMUM RATINGS (25°C)

DC Power Dissipation .... 100 mW

DC Forward Current .... 50 mA

Peak Forward Current .... 1 Amp
(1 μsec pulse width, 300 pps)

Isolation Voltage (between lead and case) .... 300 V

Operating and Storage
Temperature Range .... -55°C to +100°C

Lead Soldering Temperature .... 230°C for 7 sec

ELECTRICAL CHARACTERISTICS (25°C)

Symbol	Parameters	5082-4403 5082-4415			5082-4440 5082-4444			Units	Test Conditions
		Min.	Typ.	Max.	Min.	Typ.	Max.		
I	Luminous Intensity	0.8	1.2		0.3	0.7		mcd	$I_F = 20$ mA
λ_{pk}	Wavelength	640	655	670	640	655	670	nm	Measurement at Peak
τ_s	Speed of Response		10			10		ns	
C	Capacitance		200			200		pF	
θ_{JC}	Thermal Resistance		270			270		$^oC/W$	Junction to Cathode Lead
V_F	Forward Voltage		1.6	2.0		1.6	2.0	V	$I_F = 20$ mA
BV_R	Reverse Breakdown Voltage	3	4		3	4		V	$I_R = 10\ \mu A$

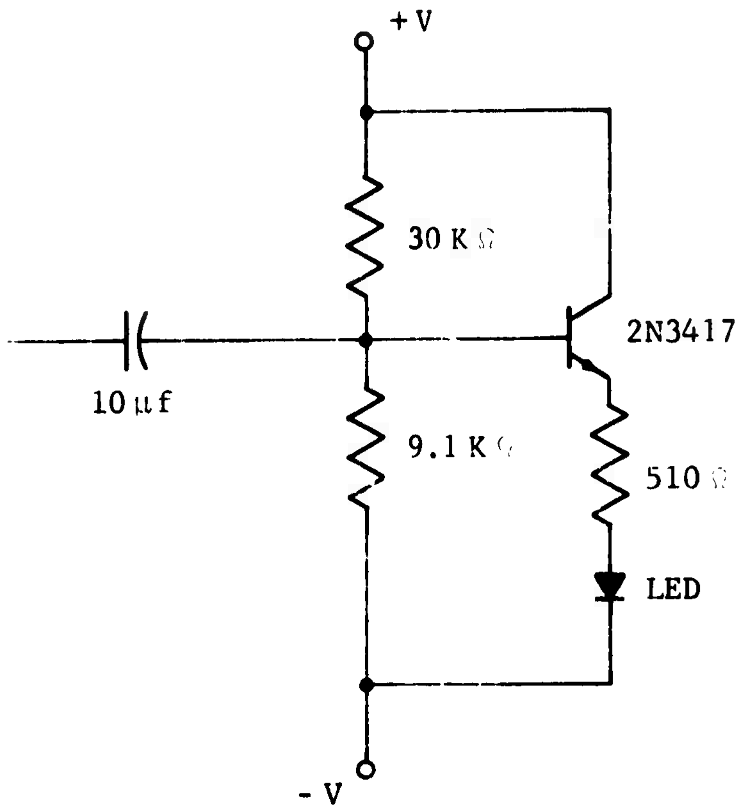


Fig. 6 LED DRIVE CIRCUIT

FLEXIBLE FIBER OPTICS LIGHT GUIDE

This Light Guide is made of precision optical fibers .003" in diameter. Each fiber has a core of 1.62 index glass and has been coated or clad with a 1.52 index glass to serve as optical insulation and thus protect the reflective surface of the core. This combination of indices provides a numerical aperture (N.A.) of .55. The guide will accept 70% of the light incident upon the input end. 50% of the light entering the fibers will be absorbed for every 7 feet of length. These fibers will transmit wavelengths from 4000 to 20,000 Angstroms.

For additional information on Fiber Optics please write to:

American Optical Co., Dept. 4624

14 Mechanic Street, Southbridge, Mass.

AMERICAN OPTICAL COMPANY

Fig. 7 LIGHT GUIDE SPECIFICATIONS

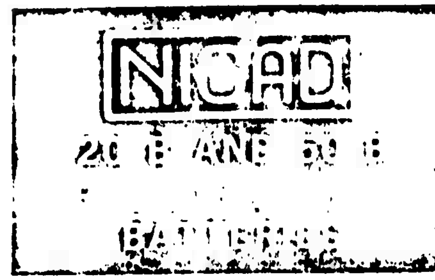
2) they be small enough so as not to limit the utility of the probe.

Specifications for the NiCad batteries chosen for the application are presented as Fig. 8.

3.7 Summary

As a summary to this section and a prelude to the following discussions of packaging and operation of the probe system, Fig. 9 presents a schematic diagram of the system.

NICKEL-CADMIUM
RECHARGEABLE



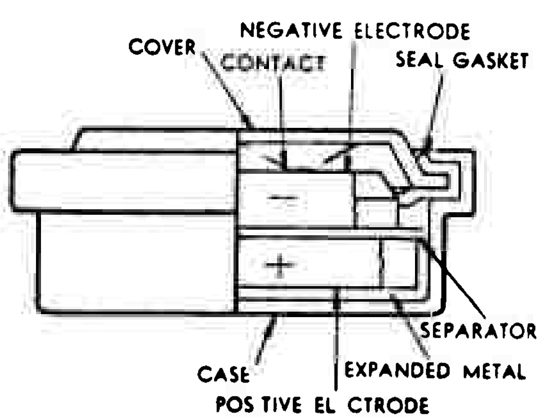
SEALED CELLS

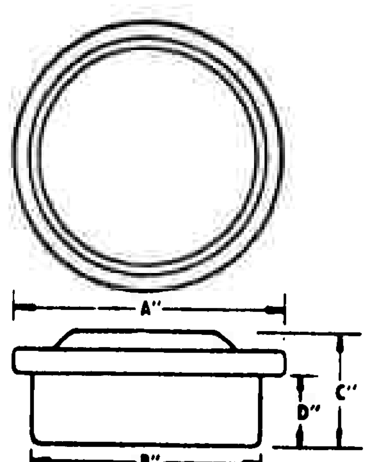
Fig. 8 BATTERY SPECIFICATIONS .020/.050 AMPERE HOUR CAPACITY

- BUTTON TYPE CELL
- PRESSED PLATE ELECTRODES
  - POSITIVE ELECTRODE—NICKEL
  - NEGATIVE ELECTRODE—CADMIUM
- HERMETIC SEAL—MECHANICAL PRESSURE
- CONTAINER—NICKEL PLATED STEEL
- MAY BE CONNECTED IN SERIES FOR INCREASED VOLTAGES
- AVAILABLE WITH SOLDER LUGS

		20 B	50 B
SERVICE CAPACITY—10 HOUR RATE		20 M.A.H.	50 M.A.H.
RECOMMENDED CHARGE—14 HOURS		[illegible].0 MILLIAMPS	5.0 MILLIAMPS
TRICKLE CHARGE RATE		0.[illegible] MILLIAMPS	0.5 MILLIAMPS
MAXIMUM CHARGE VOLTAGE		1.[illegible] VOLTS	1.5 VOLTS
OPERATING TEMPERATURE	CHARGE	32°[illegible] TO 11[illegible]	32°F. TO 115°F
	DISCHARGE	−[illegible] TO 1[illegible]	−5°F. TO 115°F
STORAGE TEMPERATURE		−40°F. TO [illegible]40°F	−40°F. TO 140°F.
CHARGE RETENTION—STORED AT 70°F. NOTE Higher temperature will decrease charge retention during storage. Charge prior to use for full capacity.		1 MONTH—75% 3 MONTHS—70% 6 MONTHS—60%	1 MONTH—75% 3 MONTHS—70% 6 MONTHS—60%
CELL WEIGHT		0.0[illegible] OUNCES	0.09 OUNCES
INTERNAL RESISTANCE NOTE: Initial load voltage for high rate discharge equals open circuit voltage (1.33 volts), minus load current times internal resistance. $V_L = V_O - IR$		[illegible].0 OHMS	2.0 OHMS
INTERNAL IMPEDANCE—FULLY CHARGED CELL NOTE: For semi-discharged cells impedance increases approximately 20%. For fully discharged cells increase value shown by a factor of 3		60 CPS—2 OHMS	60 CPS—1 OHM

Individual cells available with solder lugs or snap on terminals. (Refer to Button Cell Battery Bulletin).





20 B BUTTON CELL
A .449 ± .008 D
B .370 ± .008 D
C .201 + .012 − .000
D .110 + .004 − .000

50 B BUTTON CELL
A .606 ± .008 D
B .516 ± .008 D
C .230 ± .008
D .102 + .004 − .000

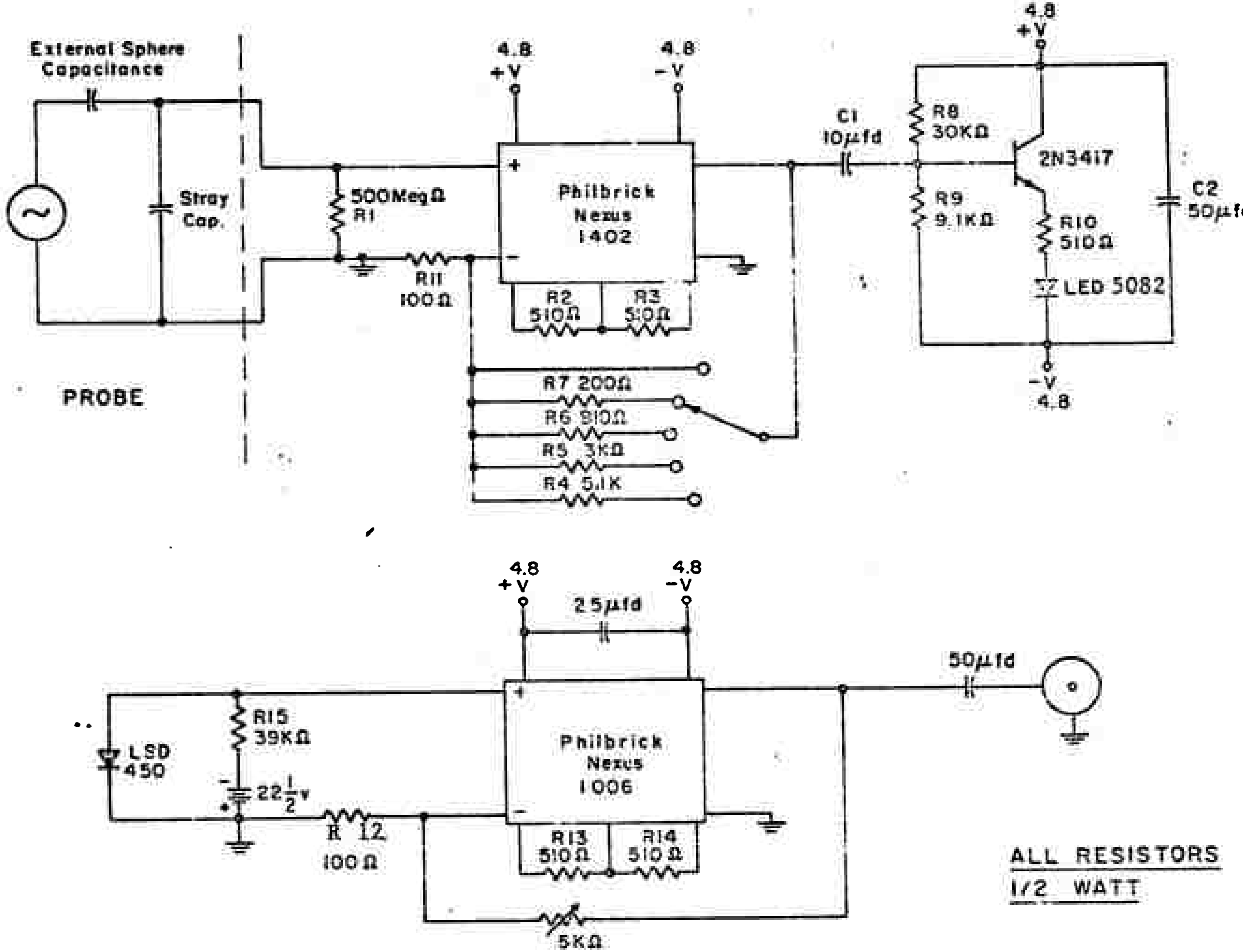


Fig. 9 SYSTEM SCHEMATIC

4. PACKAGING

Since we require a small probe which must enclose electronics and batteries, the internal layout and packaging becomes an important and critical task. The probe package will be described here through a series of photographs.

Figure 10 shows the complete system. That is, the spherical probe, the light guide, and the receiver package. Figure 11 shows one view of the layout of the electronics internal to the probe and identifies the visible components. Figure 12 is a view of the other side. Figure 13 shows the inside of the receiver package and identifies some of the components.

As shown in Fig. 9, one probe hemisphere is connected to circuit ground and the other to the positive input of the amplifier. The hemisphere chosen to be connected to the positive input is the one which covers the batteries; (i.e., that side shown in Fig. 12). It was found that if the positive input were connected to the other hemisphere (i.e., that which covers the side shown in Fig. 11), the circuit was unstable and oscillated. This is due to the capacitive coupling between the output and the positive input by the hemisphere. By connecting the hemisphere which covers the batteries to the positive input, this problem was avoided.

The problem of stability described above is critically dependent on the physical layout of the circuit. Based on the experience obtained in packaging this probe, it is recommended that in the design of the physical circuit layout for a probe of this type, care should be taken to separate the output circuit from the high-impedance input to the amplifier. A shielding compartment enclosing the output circuitry would probably increase the circuit stability.

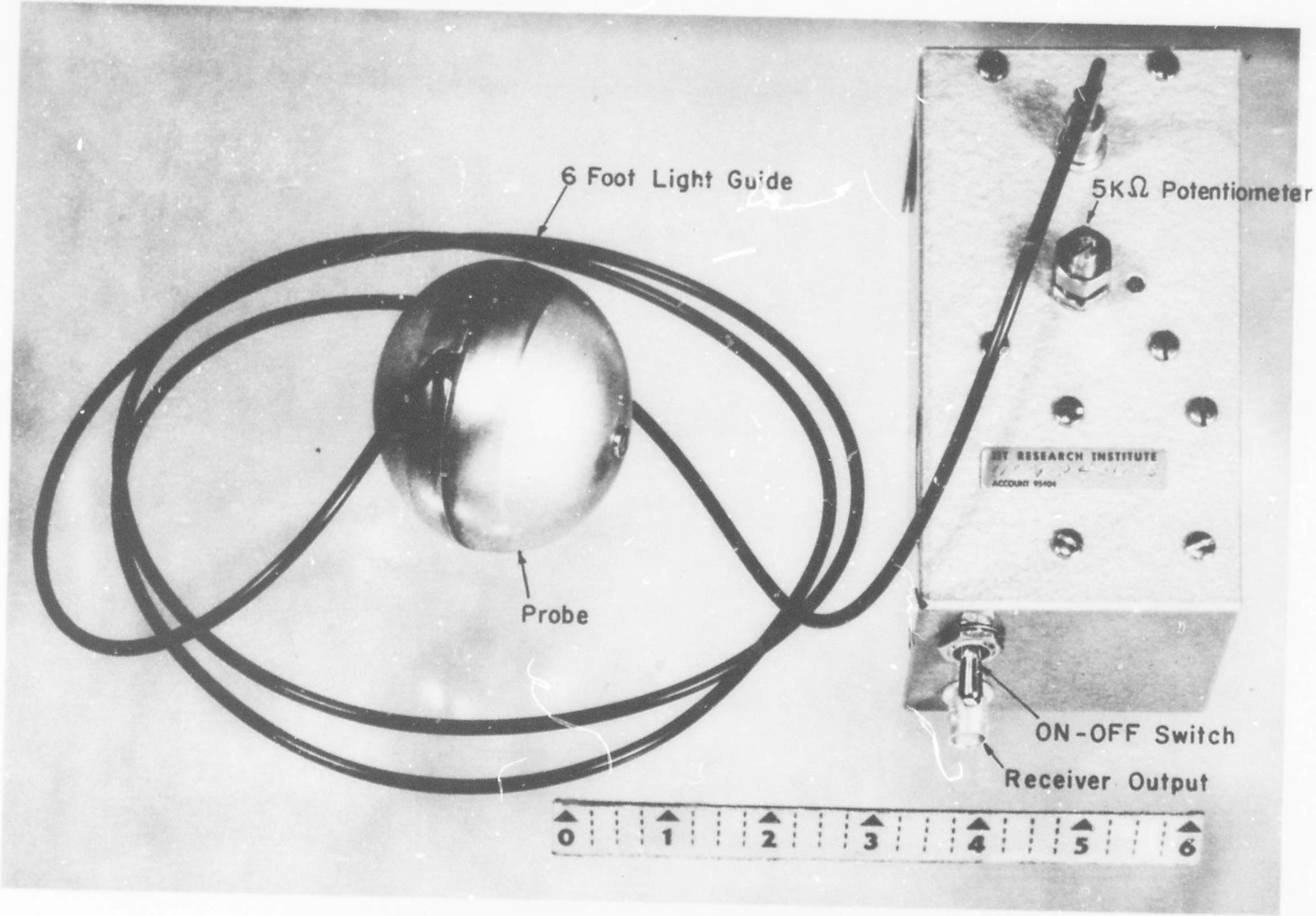


Fig. 10 PROBE - RECEIVER SYSTEM

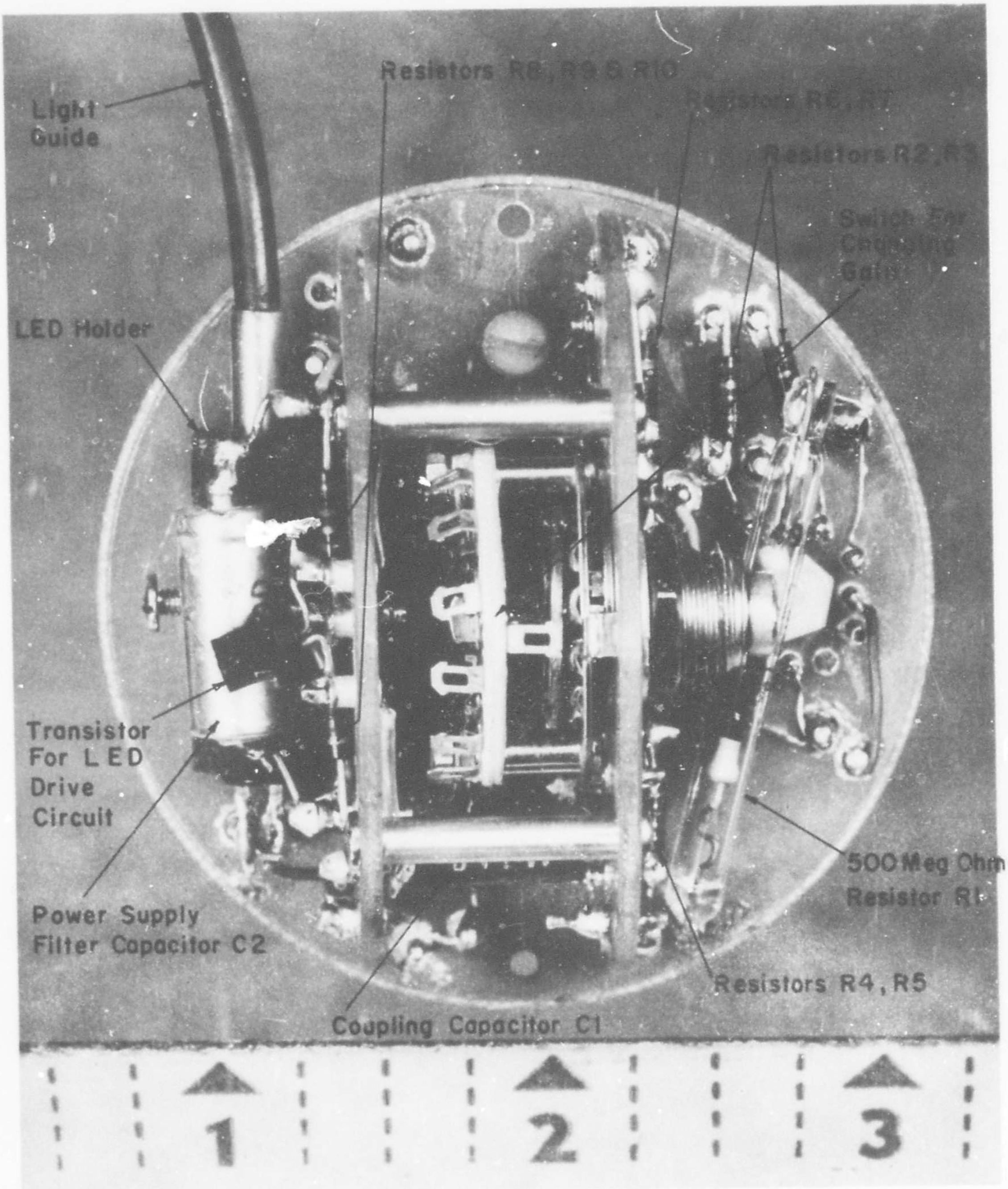


Fig. 11 INTERNAL VIEW OF PROBE ELECTRONICS

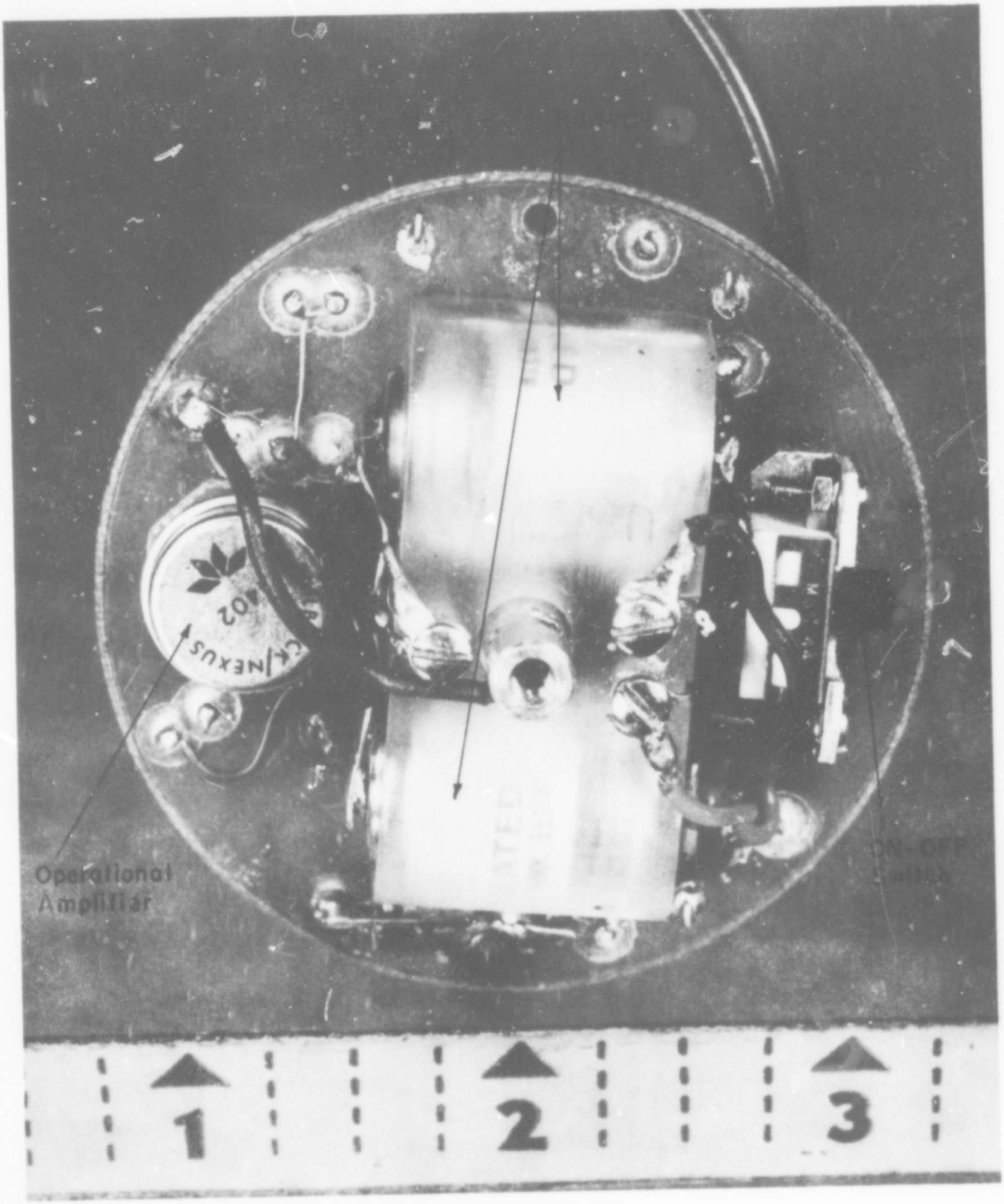


Fig. 12 INTERNAL VIEW OF PROBE ELECTRONICS

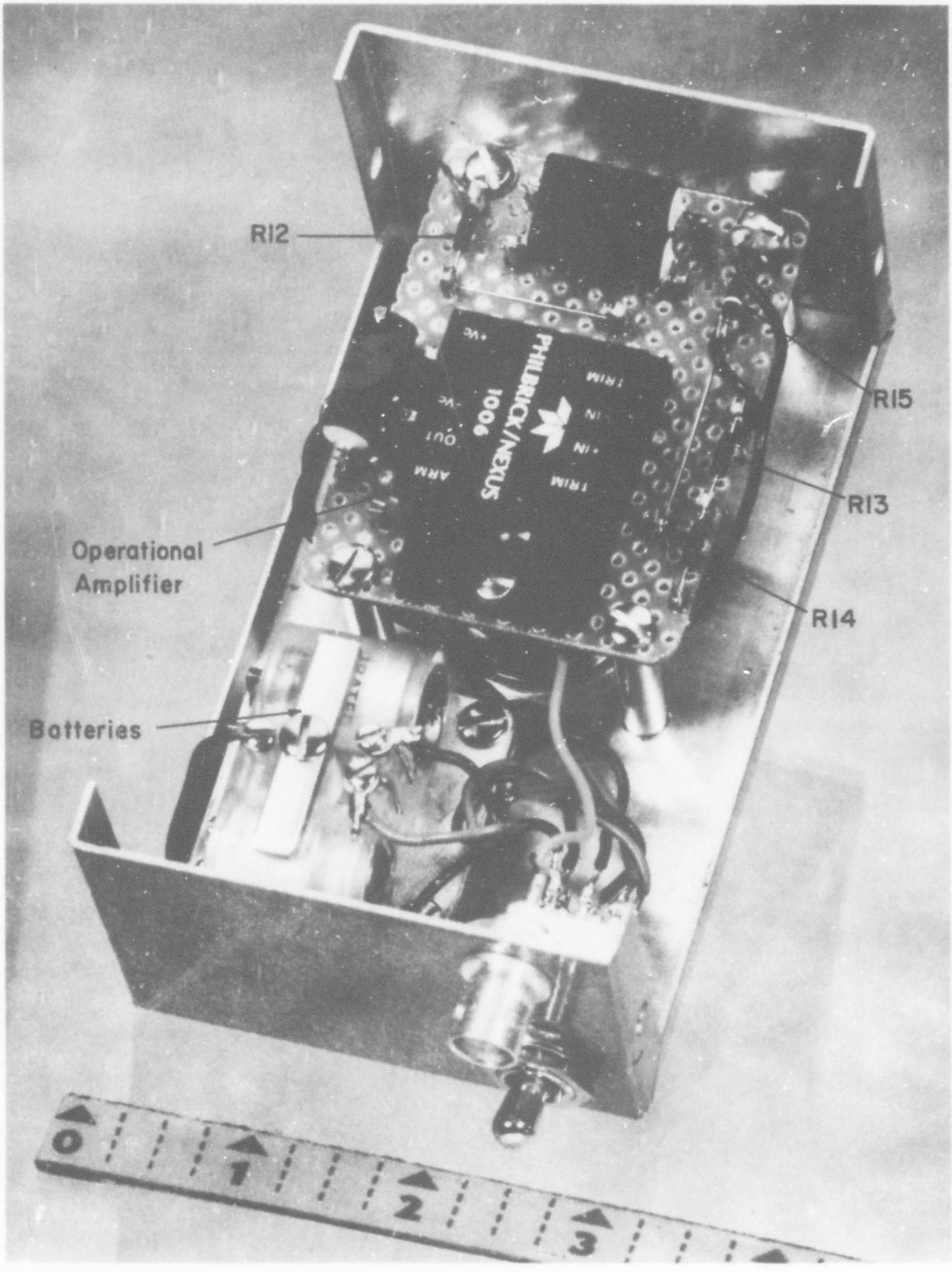


Fig. 13 INTERNAL VIEW OF RECEIVER

5. OPERATIONAL DATA

The voltage-amplifier stage has been provided with five different feedback resistors and, therefore, five different range settings. In each range the minimum electric field which can be measured is determined by the signal-to-noise ratio at the input to the receiver. The maximum signal which can be handled is determined by the linearity of the LED and therefore its bias current. Figure 14 presents the calibration curves for each of the five ranges at 60 Hz. The calibration was performed by placing the probe in a known electric field established between one-meter-by-one-meter parallel plates separated by 30 cm. Note that the probe can measure electric fields as small as 10 mv/meter and as large as 100 volts/meter. Of course, the probe could be made to measure much larger fields simply by loading it down at the input to the voltage-amplifier stage.

In Fig. 14, a reference voltage is given for each of the five calibration curves. By applying the given input voltage directly across the probe and then adjusting the receiver gain to obtain the reference voltage at the receiver output, one can be assured that the calibration curve is valid and that minor drifting due, for example, to battery drain has been compensated. A convenient jig has been fabricated so that the voltage may be applied with ease.

5.1 Frequency Response

Figure 15 presents the frequency response for each of the five ranges. The roll-off at the low end is due to the very high, capacitive source impedance. For this 6.3-cm diameter probe, the source capacitance is about 3 pf which represents a 900M Ω reactance at 60 Hz. The equivalent-source circuit for this probe is derived in Appendix A. At the high end the roll-off is due to the limited frequency response of the voltage amplifier as it is configured and packaged.

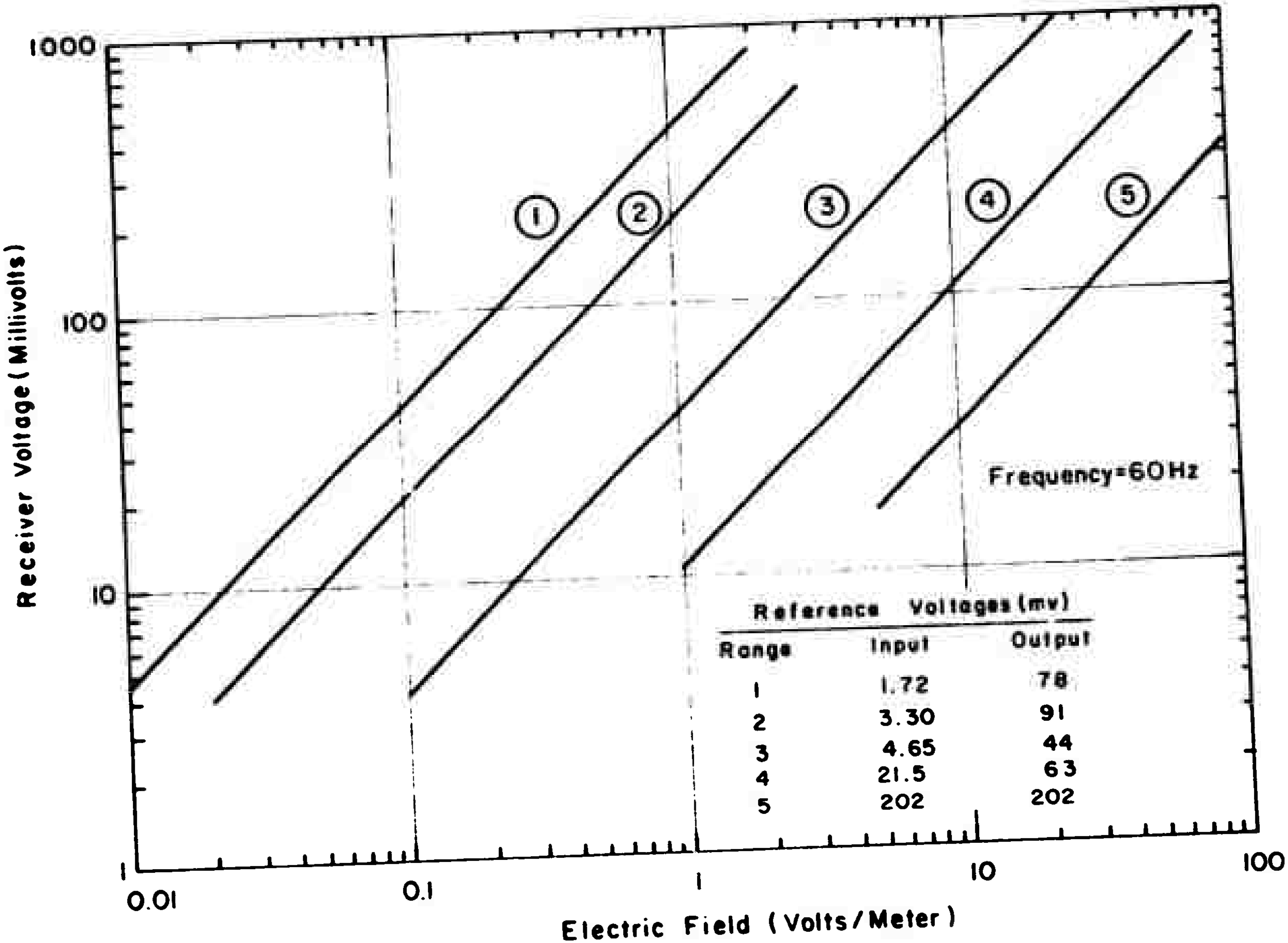


Fig. 14 E-FIELD PROBE CALIBRATION CURVE

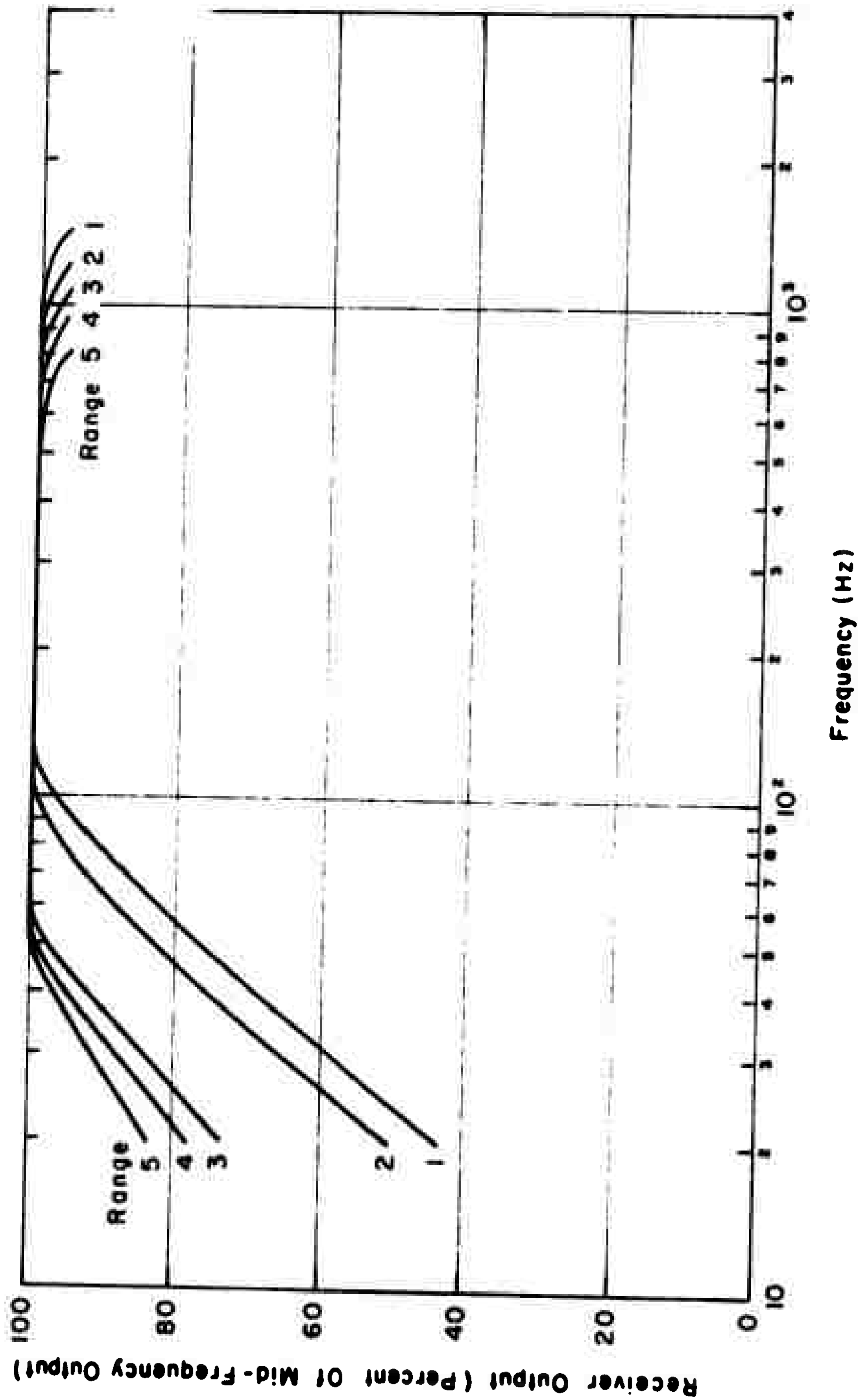


Fig. 15 SYSTEM FREQUENCY RESPONSE

5.2 Battery Life

The probe may be operated for approximately four hours without need for a change in batteries. Periodic spot checks of the reference voltage using the calibrator are required.

6. CONCLUSIONS AND RECOMMENDATIONS

Details in the design of a small ELF probe have been presented. The probe can measure electric fields from 10 mv/meter to 100 volts/meter in the 20-1000 Hz range. It has been used successfully to survey the electric field environment in and near a private dwelling and to measure the electric field near small electrical appliances. A memo describing a survey of this type is presented as Appendix D.

Based on the experience gained in the design and packaging of this probe, it is recommended that the following be considered in any probe design of this type.

1) Provision should be made for additional battery and/or electronic circuitry to provide a constant LED bias current over a longer time period.

2) The positive input to the operational amplifier must be carefully isolated from the output circuitry to provide stable operation. A shielding compartment for the output circuitry is recommended.

3) A smaller switch should be used. Five operating ranges are not necessary, and a smaller switch would probably reduce the input-to-output coupling.

APPENDIX A

ANALYSIS OF SMALL SPHERICAL PROBE

APPENDIX A

ANALYSIS OF SMALL SPHERICAL PROBE

Two equivalent circuit representations for a small (largest dimension much less than one-tenth of a wavelength) antenna are shown in Fig. A-1. For our case, that of a small spherical probe, the short-circuit current, I_{sc}, may be determined by considering a solid metallic sphere immersed in a uniform electric field and computing the total current passing through a plane perpendicular to the field and cutting the equator of the sphere. This is done by solving the static-field problem for the total charge, Q, induced on the surface of the sphere and taking the current for low frequencies to be $j\omega Q$ (quasi-static solution). The result of this calculation is:

$$I_{sc} = j\omega\ (3\pi a^2)\ \varepsilon_o E$$

where

I_{sc} = the short circuit current

ω = $2\pi f$

f = frequency

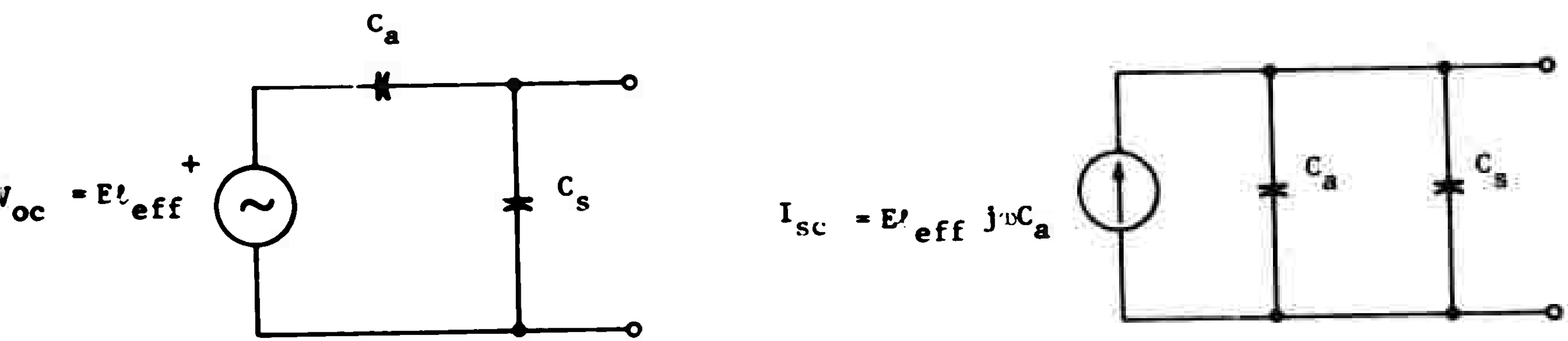
ε_o = vacuum permittivity

E = the electric field

a = radius of the sphere.

The probe capacitance, C_a, is found by computing the total charge, Q, on one hemisphere using the model shown in Fig. A-2. The result is

$$C_a = \pi\varepsilon_o a \sum_{n_{odd}} \frac{n+1}{n} \quad P_{n+1}(0) \quad \left[P_{n+1}(x) - P_{n-1}(x)\right]$$



V_{oc} = open circuit voltage

I_{sc} = short circuit current

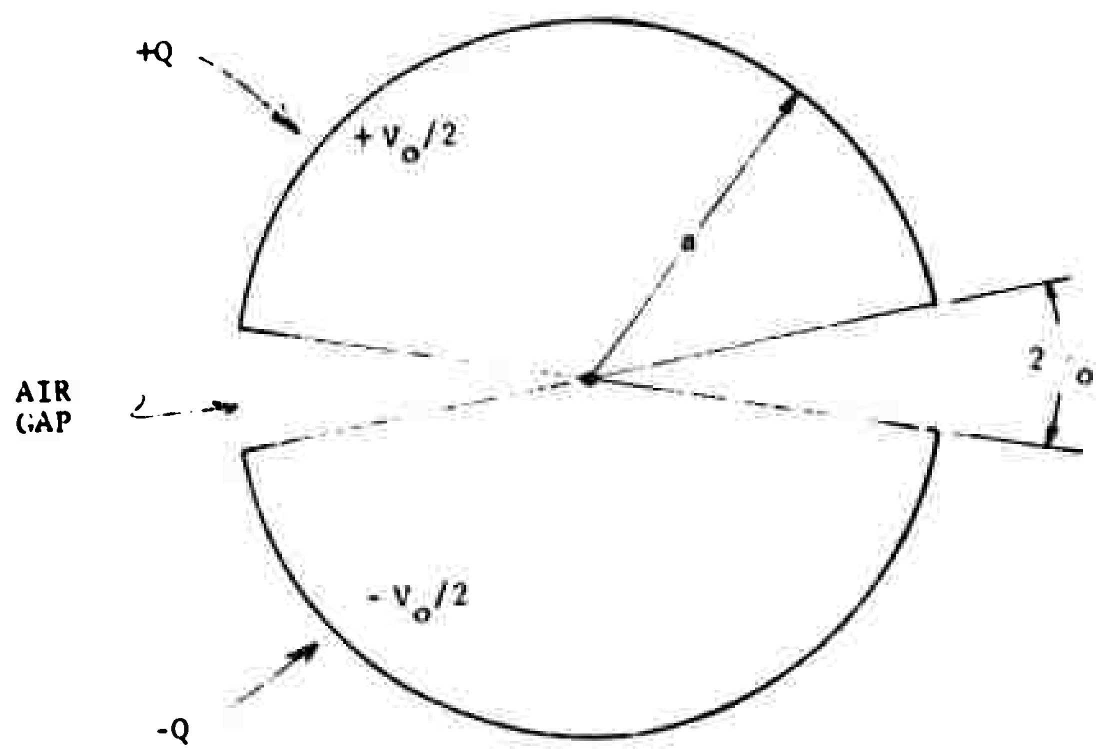
E = electric field measured

ℓ_{eff} = effective length of the antenna

C_a = antenna capacitance

C_s = shunt capacitance

Fig. A-1 EQUIVALENT CIRCUITS FOR A SMALL ANTENNA



V_o = applied voltage difference

Q = induced voltage

Capacitance = $\frac{Q}{V_o}$

Fig. A-2 MODEL FOR CALCULATING EXTERNAL CAPACITANCE OF SPHERE where P_n is the Legendre Function of the first kind,

$$P_o(x) = 1$$

$$P_1(x) = x$$

$$P_{n+1}(x) = \frac{2n+1}{n+1} x P_n(x) - \frac{n}{n+1} P_{n-1}(x)$$

and

$$x = \sin\theta_o.$$

Sample numerical results are:

x	$C_a/\pi\varepsilon_o a$	
0.01	3.6	
0.025	3.0	(x = 0.025 for the probe described in this memo)
0.1	2.1	

Note that, given I_{sc} and C_a, we may compute ℓ_{eff} as follows:

$$j\omega C_a E\, \ell_{eff} = I_{sc}$$

$$j\omega C_a E\, \ell_{eff} = j\omega 3\pi a^2 \varepsilon_o E$$

$$\ell_{eff} = \frac{3\pi a^2 \varepsilon_o}{C_a}$$

The capacitance, C_s, is the shunt capacitance. C_s is determined by the packaging of the electronics internal to the sphere and must be obtained experimentally.

APPENDIX B

SPECIFICATIONS FOR THE LIGHT SENSITIVE DIODE

MOTOROLA

MRD450

PLASTIC NPN SILICON PHOTO TRANSISTOR

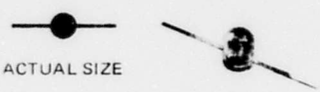
. . . designed for application in industrial inspection, processing and control, counters, sorters, switching and logic circuits or any design requiring radiation sensitivity, and stable characteristics.

- Economical Plastic Package
- Sensitive Throughout Visible and Near Infra-Red Spectral Range for Wide Application
- Minimum Sensitivity (0.2 mA/mW/cm^2) for Design Flexibility
- Unique Molded Lens for High, Uniform Sensitivity
- Annular† Passivated Structure for Stability and Reliability

40 VOLT
PHOTO TRANSISTOR
NPN SILICON

100 MILLIWATTS

JANUARY 1969 — DS 2606

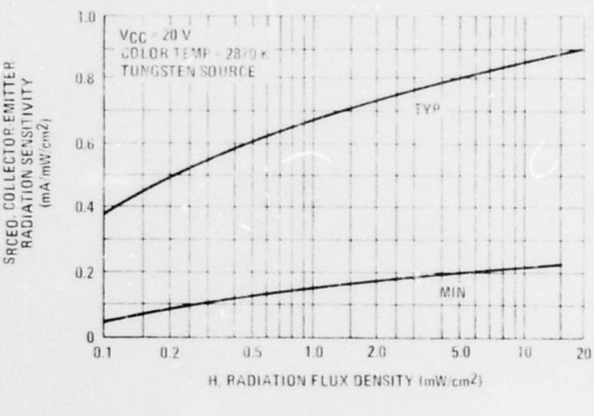


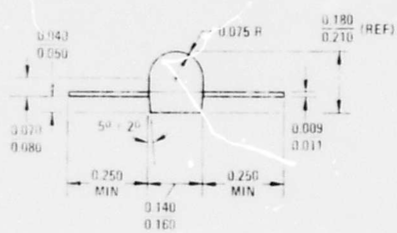
ACTUAL SIZE

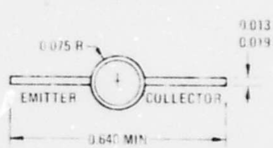
MAXIMUM RATINGS

Rating (Note 1)	Symbol	Value	Unit
Collector-Emitter Voltage	V_{CEO}	40	Volts
Emitter-Collector Voltage	V_{ECO}	6.0	Volts
Total Device Dissipation @ T_A = 25°C Derate above 25°C	P_D	100 1.3	mW mW/°C
Operating Junction Temperature Range Storage Temperature Range	T_J T_{stg}	-40 to +85	°C

FIGURE 1 – COLLECTOR EMITTER SENSITIVITY







CASE 171

Collector indicated by square bonding pad on bottom of device

†Trademark of Motorola Inc.

Figure 8(b)

STATIC ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Typ	Max	Unit
Collector Dark Current (V_{CC} = 20 V, Note 2)	I_{CEO}				μA
T_A = 25°C		—	—	0.10	
T_A = 85°C		—	5.0	—	
Collector-Emitter Breakdown Voltage (I_C = 100 μA; Note 2)	BV_{CEO}	40	—	—	Volts
Emitter-Collector Breakdown Voltage (I_E = 100 μA; Note 2)	BV_{ECO}	6.0	—	—	Volts

OPTICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

Characteristic	Fig No.	Symbol	Min	Typ	Max	Unit
Collector-Emitter Radiation Sensitivity (V_{CC} = 20 V, R_L = 100 ohms, Note 1)	1	S_{RCEO}	0.2	0.8	—	mA/mW/cm²
Photo Current Rise Time (Note 3)	2 and 3	t_r	—	—	2.5	μs
Photo Current Fall Time (Note 3)	2 and 3	t_f	—	—	4.0	μs
Wavelength of Maximum Sensitivity	9	λ_s	—	0.8	—	μm

NOTES:

1. Radiation Flux Density (H) equal to 5.0 mW/cm² emitted from a tungsten source at a color temperature of 2870 K.
2. Measured under dark conditions. (H ≈ 0).
3. For unsaturated response time measurements, radiation is provided by a pulsed GaAs (gallium-arsenide) light-emitting diode ($\lambda \approx$ 0.9 μm) with a pulse width equal to or greater than 10 microseconds (see Figure 2 and Figure 3).

FIGURE 2 – PULSE RESPONSE TEST CIRCUIT

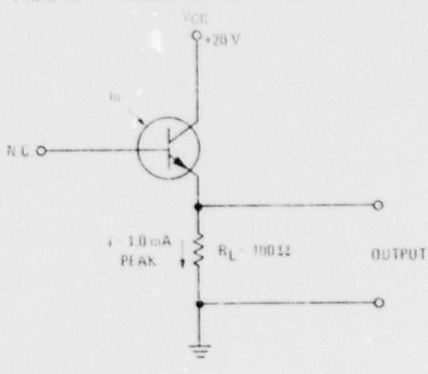
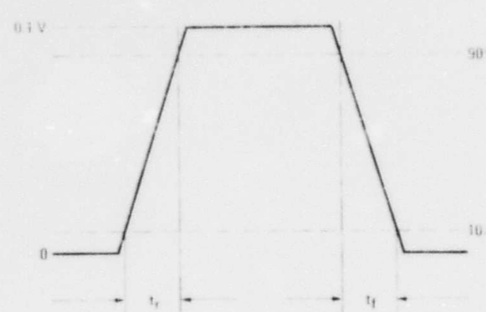


FIGURE 3 – PULSE RESPONSE TEST WAVEFORM



TYPICAL ELECTRICAL CHARACTERISTICS

FIGURE 4 – COLLECTOR-EMITTER CHARACTERISTICS

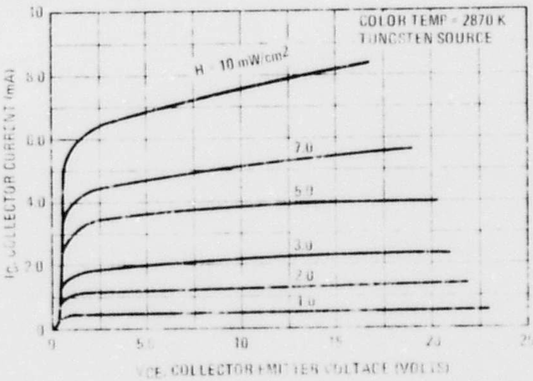


FIGURE 5 – COLLECTOR SATURATION CHARACTERISTICS

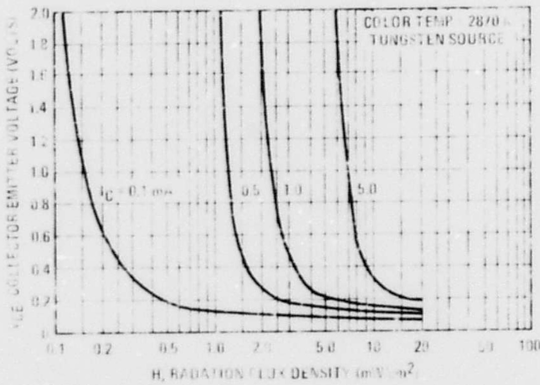


FIGURE 6 – DARK CURRENT versus TEMPERATURE

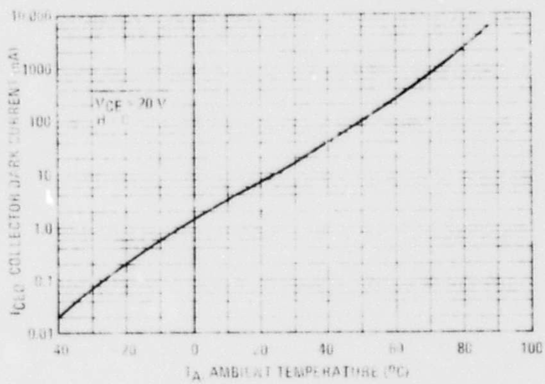


FIGURE 7 – DARK CURRENT versus VOLTAGE

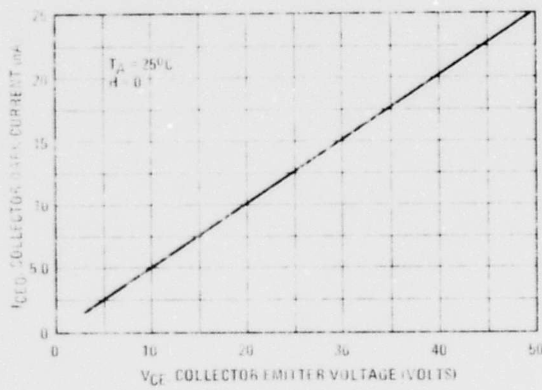


FIGURE 8 – ANGULAR RESPONSE

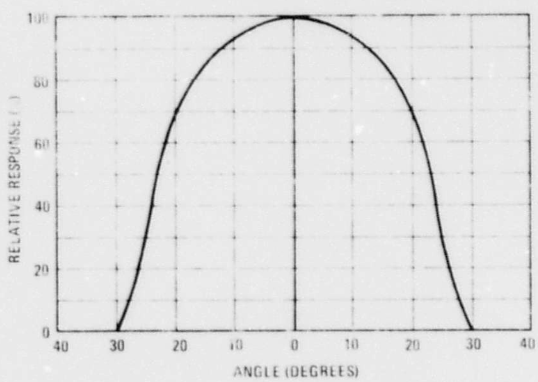
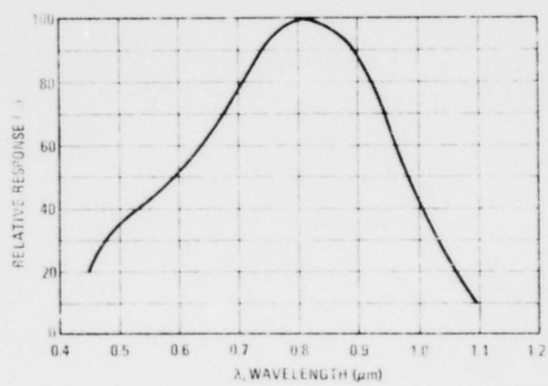


FIGURE 9 – CONSTANT ENERGY SPECTRAL RESPONSE



APPENDIX C

SPECIFICATIONS FOR THE RECEIVER AMPLIFIER

1006

$Z_{in} > 10^{11}\ \Omega$
± 2 V to ± 16 V
Supply Range

FEATURES

- Designed for $\pm$ 2 to + 16V supplies
- FET input stage gives high input impedance of 10^{11} Ohms
- No-signal supply current, 150 μA typical
- Bias current, 10 pA
- Slew rate of 0.7V/μsec
- Wideband noise, 2 μV rms (max)
- Overload recovery in 15 μsec (max)
- Small signal bandwidth of from 0.6 MHz to 1 MHz
- Ideal for portable battery-powered instruments

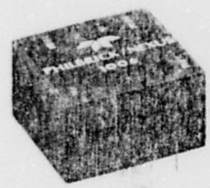
DESCRIPTION

The Philbrick/Nexus type 1006 Micropower FET operational amplifier is designed for operation over a wide range of power supply voltages, from as low as + 2V up to + 16V, with a maximum quiescent current of 200 μA. These unique provisions allow long battery life in portable instrumentation, with no compromise in specifications.

The FET input circuitry provides a high input impedance of 10^{11} ohms, low bias currents of 10 pA, and low wideband noise for both voltage and current. These characteristics, along with a very low power supply drain, makes this amplifier especially attractive for use in medical electronics and other high impedance applications.

Since the 1006 is internally trimmed to less than 1 millivolt of voltage offset, the amplifier may be used without the need for zeroing potentiometers in most applications.

Other features which show the versatility of the 1006 are (1) full output power to above 50 kHz, (2) overload recovery within 15 μsec, (3) settling time of 6 μsec. This combination of features show that the 1006 may be used in high-speed applications which up to now have been impractical for a low-voltage operational amplifier.



TYPICAL OPERATION*

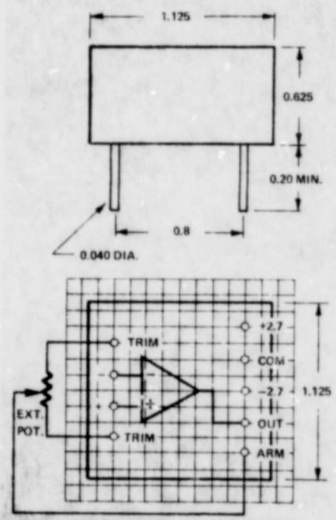
Supply Volts	$\pm$ 2.7 V nominal, $\pm$ 2 V min, + 16V max
Supply Current	150 μA quiescent
Gain	15,000 at 2.7V supply
Offset Voltage TC	15 μV/^{o}C
Bias Current	10 pA
CMRR	66 dB
Bandwidth	Small-signal bandwidth from 0.6 MHz to 1 MHz
Input Impedance	5×10^{11} Ohms
Output	$\pm$ 2 V, $\pm$ 2.5 mA

* +25^{o}C, $\pm$ 2.7 Volt unless noted

OPERATION

CONSTRUCTION

Type 1006 is fully encapsulated as a solid epoxy block, for complete mechanical protection under the most adverse conditions of vibration, acceleration, and other environmental hazards. This also insures almost completely isothermal operation of the internal components, as a further aid toward superior stability.



VIEW TOWARD PINS (GRID SPACING 0.1)

CASE DESIG.	WEIGHT (GM)	VOLUME (CU.IN.)	MATING SOCKET
A-1	30	.78	NSK-7

CONNECTIONS

Pin spacing is laid out for standard 0.1" printed circuit board hole spacing. Pin connections are as shown above, looking toward the pins.

BIAS CURRENT

The low 50 pA max bias current rating makes bias current correction unnecessary for most practical applications. Use of a FET transistor input circuit not only provides a low bias current, but also contributes a high input impedance, rated at 10^{11} Ω for both common-mode and differential input circuits.

OFFSET VOLTAGE

Offset voltage is rated at 1 mV max, with a temperature coefficient of 50 μV/^{0}C max. This voltage may be nulled with an external 1,000 Ω potentiometer connected to trim terminals provided on the amplifier.

This potentiometer trim is optional for many applications, when the small offset voltage may be neglected. No external short is required when omitting the external trim circuit.

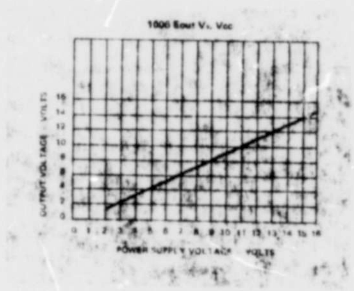
SUPPLY POWER

Type 1006 will operate normally at any supply voltage in the range from $\pm$ 2V to $\pm$ 16V. A power supply of $\pm$ 2.7V is recommended for micropower applications. At this supply voltage, the no-signal current is not more than 200 μA.

SUPPLY VOLTAGE REJECTION

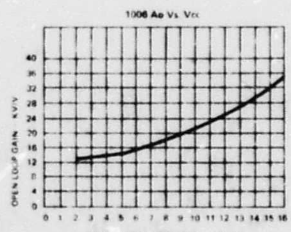
The curves shown on these pages illustrate the performance of Type 1006 over the supply voltage range. These curves show the variation in five important parameters as the supply voltage varies from $\pm$ 2 to $\pm$ 16 Volts:

... Output Voltage
... Open Loop Gain
... Common-mode voltage range
... Common-mode rejection (dB)
... Bias Current



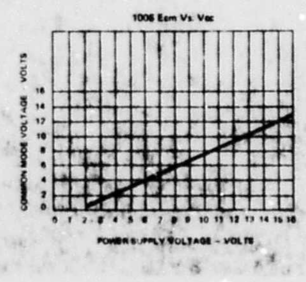
SPECIFICATIONS

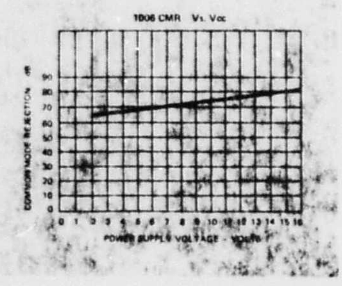
OUTPUT	Typical	Guaranteed
Full Load Output Voltage (1)	± 2V	±1.5 V min
Output current	2.5 mA	1 mA min
Maximum Capacitive Load (2)	—	0.005 μF max
Output Impedance Open Loop	1 k	1.5 kΩ min.
INPUT		
Common Mode Rejection Ratio(1)	66 dB	60 dB min
Common Mode Voltage Range	—	± 0.5 V min
Input Impedance, Common Mode	10^{11} Ω	——
Input Impedance, Differential	10^{11} Ω	——
Voltage Offset	300 μV	1 mV max
Voltage offset vs supply volts	400 μV/V	——
Voltage offset vs Common Mode	500 μV/V	——
Voltage offset vs temperature	15 μV/°C	50 μV/°C max
Bias Current	10 pA	50 pA max
OPERATION		
Gain, full load (1)	15,000	10,000 min
Frequency for unity gain (1)	0.6 MHz	——
Maximum full-output frequency (1)	75 kHz	50 kHz min
Slewing Rate, Full Load (1)	0.7 V/ μsec	0.5 V/μsec min
Overload Recovery Time	—	15 μsec max
Wideband Noise (3)	1.3 μV rms	2 μV rms max
Operating Temperature	—	−25°C to +85°C
Storage Temperature	—	−55°C to + 125°C
POWER		
Supply Voltage	—	± 2V to ± 16V
No-load current	150 μA	200 μA max
Full-output current	—	1.2 mA max

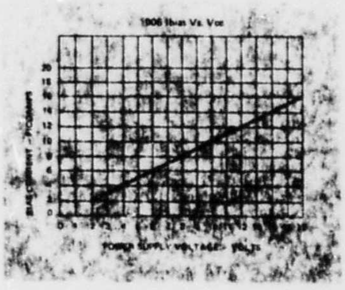


* At +25°C, ± 2.7V supply, except where indicated

(1) 1.5 k load, including feedback resistance
(2) Without instability; (3) 0.16 kHz to 1.6 kHz; (4) −25°C to +85°C







APPENDIX D

SURVEY OF ELECTRIC FIELDS IN AND NEAR A PRIVATE DWELLING

DATE: 6 March 1972

TO: PME 117-21

FROM: A. R. Valentino AR Valentino

SUBJECT: Survey of Electric Fields In and Near a Private Dwelling

REFERENCES: (a) IITRI Memorandum to PME 117-21, "A Comparison of SANGUINE Electric and Magnetic Fields to Those Due to an Electric Blanket," 9 February 1972.

(b) IITRI Memorandum to PME 117-21, "Estimate of Body Current Flow Due to Exposure to SANGUINE Electric Field," 8 February 1972.

A survey was made of the 60-Hz electric field in and near a private dwelling. This survey was made to provide some indication of the electric field environment which exists in the average home for comparison with the electric field which would be due to a SANGUINE system. A small, spherical (6 cm diameter) probe which is isolated from ground was used to make these measurements. The probe uses a fiber optic light guide to carry the measured signal so that the measured field is not distorted by metallic cables.

The data obtained is separated into three categories. The first is a collection of measurements of the electric field near appliances and directly attributed to their operation. The second is an indication of the ambient electric field level in a home as represented by the field measured at the center of rooms in the home and remote for operating electrical appliances. The third is a set of measurements made under power lines.

6 March 1972
To: PME 117-21

Table 1 presents the measurements made near appliances. The electric field in the vicinity of an electrical appliance depends upon a number of factors. Among them are: the size and shape of the appliance, the manner in which it is wired, the metallic structures surrounding it, which of the two possible ways the plug is inserted into the power outlet, and whether the appliance is switched on or off. The measurements were made with the appliance in its normal operating location and, when appropriate, measurements were made for the four combinations of on-off switch and plug reversal. The numbers presented in Table 1 represent the maximum measurement made for these four conditions. Table 1 presents a measurement of the electric field at a distance of 30 cm from the appliance.

The electric field was measured at the center of each room in the home and remote from electric appliances to provide a measure of the ambient field. The results are listed in Table 2.

Measurements of the vertical electric fields under power lines are listed in Table 3.

There is an important difference between the high impedance electric fields measured in this survey and that which would be produced by a SANGUINE system. That is, the SANGUINE field (0.07 volts/meter nominal maximum) will exist within the conductive earth. A person making good contact with the earth could experience more body current flow, for a given electric field, in the case where the field exists in the earth and provides a potential difference between his two feet. Discussions of this effect may be found in References (a) and (b). However, it has been estimated (Ref. (a) and (b)) that the body currents for a person in a high impedance electric field of about 100 volts/meter may be comparable to or even greater than those for a person standing near a SANGUINE antenna installation.

DISTRIBUTION: DAMiller
MMAbromavage

Table 1 60-Hz Electric Fields in the Vicinity of Electrical Appliances

(The measurements were made at a distance of 30 cm from the appliance)

APPLIANCE	ELECTRIC FIELD (volts/meter)
Electric Range	4
Toaster	40
Electric Blanket	250
Iron	60
Broiler	130
Hair Dryer	40
Vaporizer	40
Refrigerator	60
Color TV	30
Stereo	90
Coffee Pot	30
Vacuum Cleaner	16
Clock Radio	15
Hand Mixer	50
Incandescent Light Bulb	2

Table 2 60-Hz Electric Fields at the Center of Various Rooms in a Typical Home

ROOM	E-FIELD (volts/meter)
Living Room	3.3
Kitchen	2.6
Bedroom	7.8
Bedroom	5.5
Bedroom	2.4
Dining Room	0.9
Bathroom	1.5
Bathroom	1.2
Laundry Room	0.8
Hallway	13.0

Table 3 60-Hz Vertical Electric Fields under Power Lines
(Fields measured four feet from ground level)

POWER LINE	ELECTRIC FIELD (volts/meter)
33 kv high-voltage line	140
7.2 kv single-phase distribution line	80
7.2 kv two-phase distribution line	21
Home service drop	11