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*Final Report*

# IMPLEMENTATION OF POYNTING VECTOR MEASUREMENTS

A Report of Work in the Period
1 January 1965 to 7 July 1966
Under Contract NBy-32219
with
U. S. Naval Civil Engineering Laboratory
Port Hueneme, California 93041

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*UNIVERSITY of PENNSYLVANIA*
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*31 August 1966*


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FINAL REPORT

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POYNTING VECTOR MEASUREMENTS

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U. S. Naval Civil Engineering Laboratory
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and

University of Pennsylvania
The Moore School of Electrical Engineering
Philadelphia, Pennsylvania

This report was prepared by:

W. W. Cowles

31 August 1966

Moore School Report No. 67-05

The following members of the Moore School staff contributed to the work reported herein: Dr. N. Farhat, Dr. W. W. Cowles, and Dr. R. M. Showers. The contributions of J. McMennamin and E. Buckley are also gratefully acknowledged.

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R. M. Showers

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Electrical Engineering

TABLE OF CONTENTS

## LIST OF FIGURES

## SUMMARY

This report covers the design, construction, and field testing of an experimental device ~~cable~~ Capable of measuring the magnitude of the Poynting vector associated with an electromagnetic field. With mechanical manipulation, it can determine the direction of the Poynting vector. It is based upon theory which has been described previously.

Tests of the final device demonstrate that it is capable of measuring this quantity with reasonable accuracy. The major limitations on its use result from the necessity for obtaining an accurate phase calibration of the two separate channels used for amplifying the signals received respectively on the rod and the loop antenna. Interaction between the rod and the loop does not seem to be a significant problem.

The device has unique characteristics and a number of applications for it are indicated. Recommendations on improvements in the device which are desirable for general field use are included.

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# IMPLEMENTATION OF POYNTING VECTOR MEASUREMENTS

## 1.0 INTRODUCTION

In December of 1964 a report was issued[3] which described the basic theory of the "Poynting sensor" and experimental data taken in the laboratory under idealized conditions, which essentially verified it and indicated that the concept of the device was correct. A number of methods that could be used in implementing a practical device were also described in that report.

In September of 1965 an amendment to the original contract was issued covering the development of one of these devices which would demonstrate the usefulness of this technique for field use. Two successive amendments were granted covering the period until July 7, 1966 covering an extension in time incurred as a result of unexpectedly long delivery dates on some of the critical parts and the necessity for additional work beyond that originally anticipated on the calibration technique which turned out to be one of the more serious problems in the implementation.

By far, the major amount of effort has been spent on the development of the necessary components along with the adaptation of other components, in particular, AN/PRM-1 radio interference and field intensity meters. This work was necessitated by the critical nature of many of the circuit elements with respect to the problem of maintaining accurate control of phase. Field tests have shown that the device does behave essentially as predicted. Details of all of this work and the results are contained in the remainder of this report.

## 2.0 DEVELOPMENT OBJECTIVES

In the work which has been carried out in the period covered by this report, the major objective was to illustrate the practical feasibility of the construction and use of a device for correctly measuring the Poynting vector. Previous tests have indicated that it would be necessary for this device to be completely and conveniently portable, that it would have to be completely battery operated, and that it would have to meet certain minimum stability requirements. It was determined that these requirements could be met without building a complete unit by utilizing already available RF and IF channels and constructing only those components necessary to make the necessary phase and product measurements along with adaptors as required. In addition to being able to use this device to demonstrate the correctness of the principles of measurement of the Poynting vector, it was also desired to determine those technological characteristics of the various elements of electronic circuits required which were of significance in a final prototype design. Finally, it was desired to demonstrate applications of such a measurement technique with the device in a variety of field conditions.

The device which has been constructed and tested, in general, meets all of these requirements. Admittedly, further design and development work is necessary before a completely satisfactory prototype can be built. On the other hand, there seems to be little question that the requirements can be met with a sufficiently careful development program.

## 3.0 DESIGN AND DEVELOPMENT OF MEASUREMENT DEVICE

### 3.1 Overall Configuration

The block diagram of Fig. 3.1 shows the basic configuration of the device. It consists of a two-channel superheterodyne receiver with a single local oscillator to assure preservation of the relative phase angle between the two signals. One channel is excited by a rod antenna, which responds to the E field parallel to it. The other

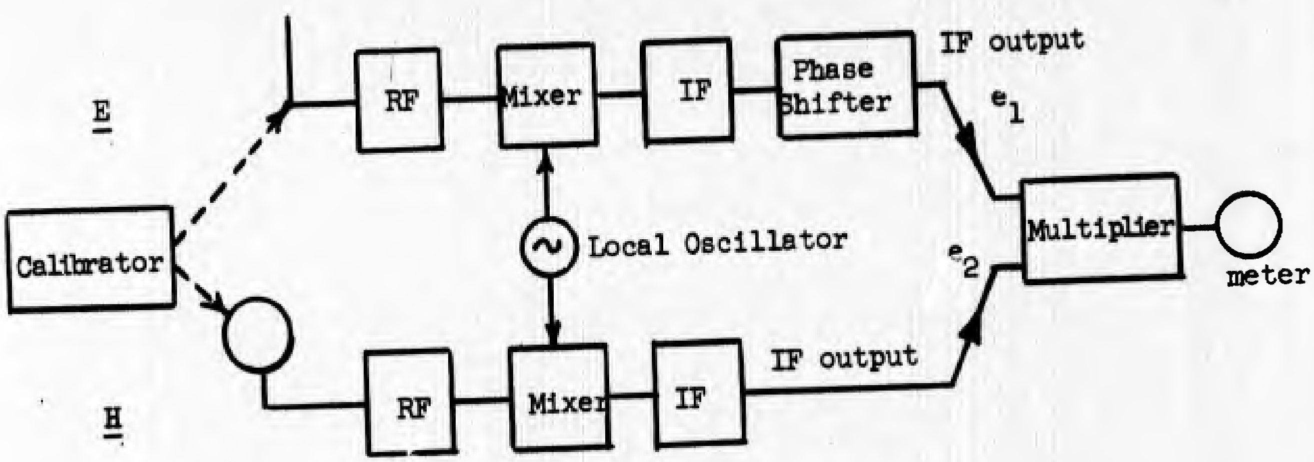



Figure 3.1 Block Diagram of the Poynting Sensor

channel is fed by a loop, which responds to the normal component of the H field. The receivers serve to amplify the respective signals. The IF voltages fed to the multiplier are thus proportional to the respective incident E and H fields. The phase shifter is intended to balance out any difference in phase angle between the two channels, so that the time phase angle between the IF outputs, $e_1$ and $e_2$, is identical with the phase angle of the incident fields. The multiplier develops the instantaneous product, $e_1e_2$, which is averaged and fed to a dc indicating instrument. For incident field components which vary sinusoidally with time, the meter reading is thus proportional to the product $|\underline{E}||\underline{H}|\cos \phi_{EH}$ (where $\phi_{EH}$ is the time phase angle of the incident field components, E and H). This product has been shown to be proportional to the total power density in the wave. (The measured power corresponds only to that component of the wave having a polarization compatible with the sensor orientation.

The complete sensor is thus equivalent to an ac wattmeter. It possesses the same directional properties, in that power flow in one direction will produce an up-scale deflection, while power in the reverse direction will be shown by a down-scale deflection. The "polarity markings" for positive power may be interchanged either by reversal of one of the sensing antennas or by a $180^{\circ}$ change in the phase shifter setting.

The calibrator shown in Fig. 3.1 is required to enable the operator to find the correct setting of the phase shifter. The phase shifter setting is very critical. A setting $90^{\circ}$ in error will result in measurement of reactive power, or stored energy, rather than real power. A setting $180^{\circ}$ in error would correspond to measurement of power flow in the opposite direction. Since the field components in the near field region of an antenna are mostly reactive, accurate setting of the phase shifter is of prime importance. For example, in the near field of a source, the phase angle between the

$\underline{E}$ and $\underline{H}$ fields might be $89^{\circ}$. In this case, the real power is about 1/50 of the product of the magnitudes of the field components. Accordingly, a one degree error in phase shifter setting would result in significant error in power measurement.

### 3.2 Implementation

The original proposal for this investigation envisaged the construction of a laboratory model of the "Poynting sensor" to demonstrate the feasibility of design and construction. The intent was to use two Stoddart PRM-1 receivers with minor modifications and an external attachment for the multiplier device. The availability of a good, amplitude independent phase shifter would presumably make the project feasible. The original plan was to simply interconnect the phase shifter together with a small transistorized, battery operated, commercial amplifier. It was proposed that two squaring networks, such as are used in the Ballantine true rms voltmeter, be used as the basic elements of a quarter-square multiplier.

### 3.3 Design of the Multiplier Unit

The complete multiplier unit is shown in Fig. 3.2. The schematic is given if Fig. 3.3. The device consists of two channels, which are fed from the IF outputs of the PRM-1's, which contain amplifiers and attenuators. In addition, the phase shifter is included in one channel and provision is made for adding and subtracting the voltages in the two channels and for multiplying them.

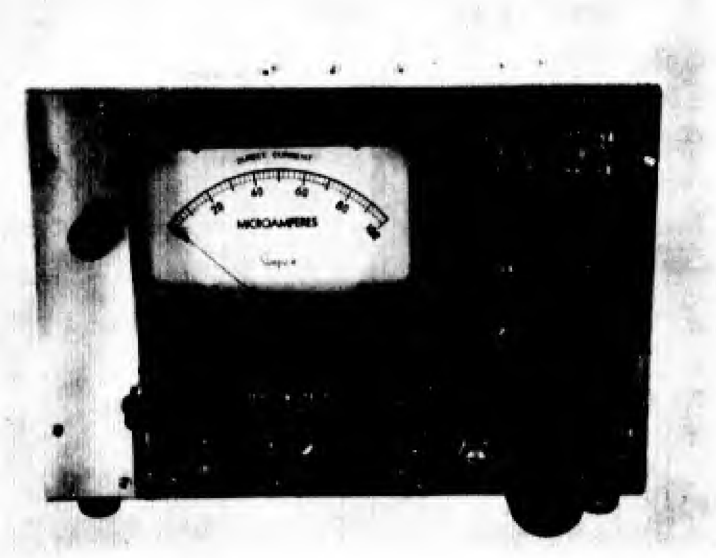
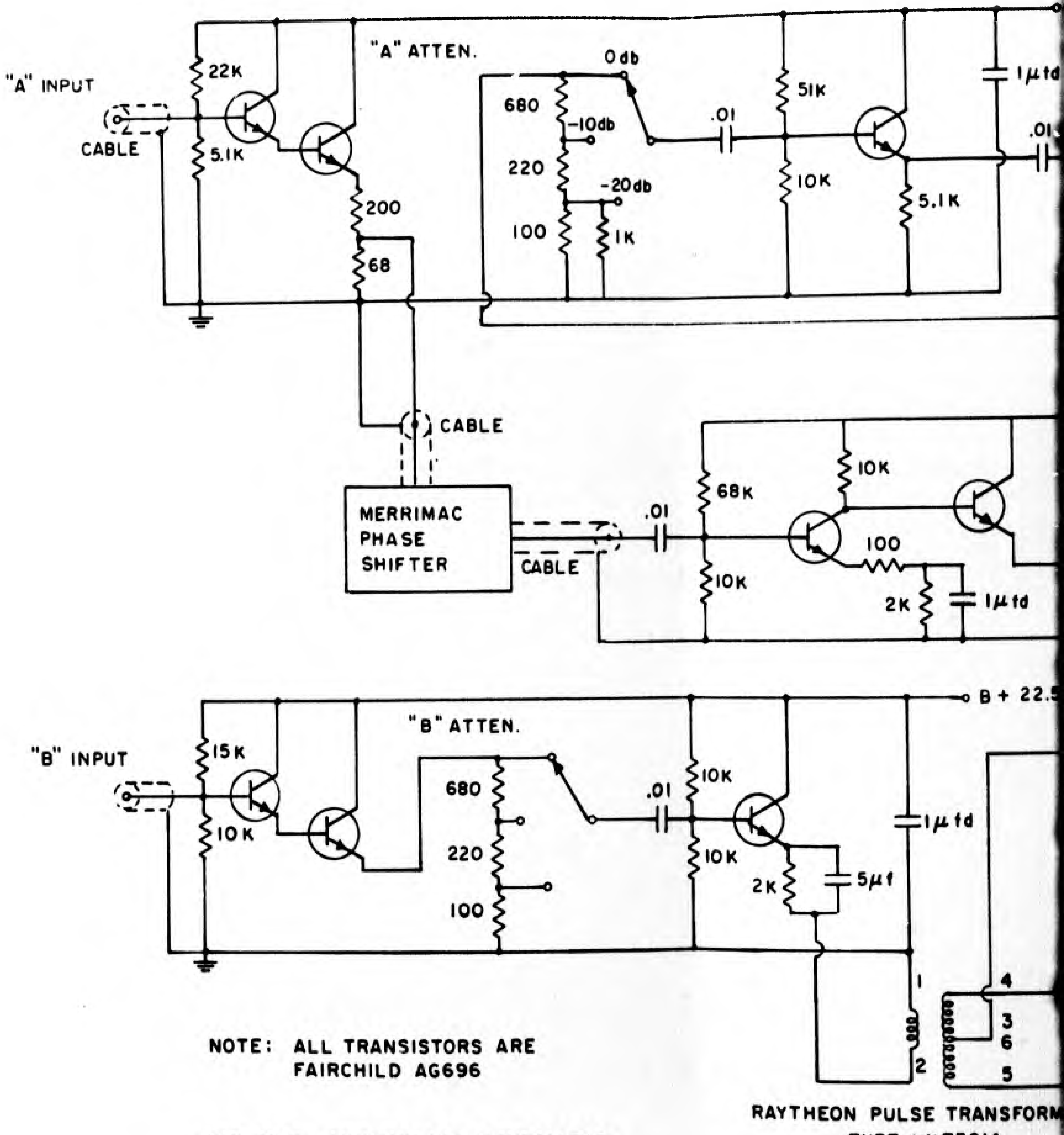


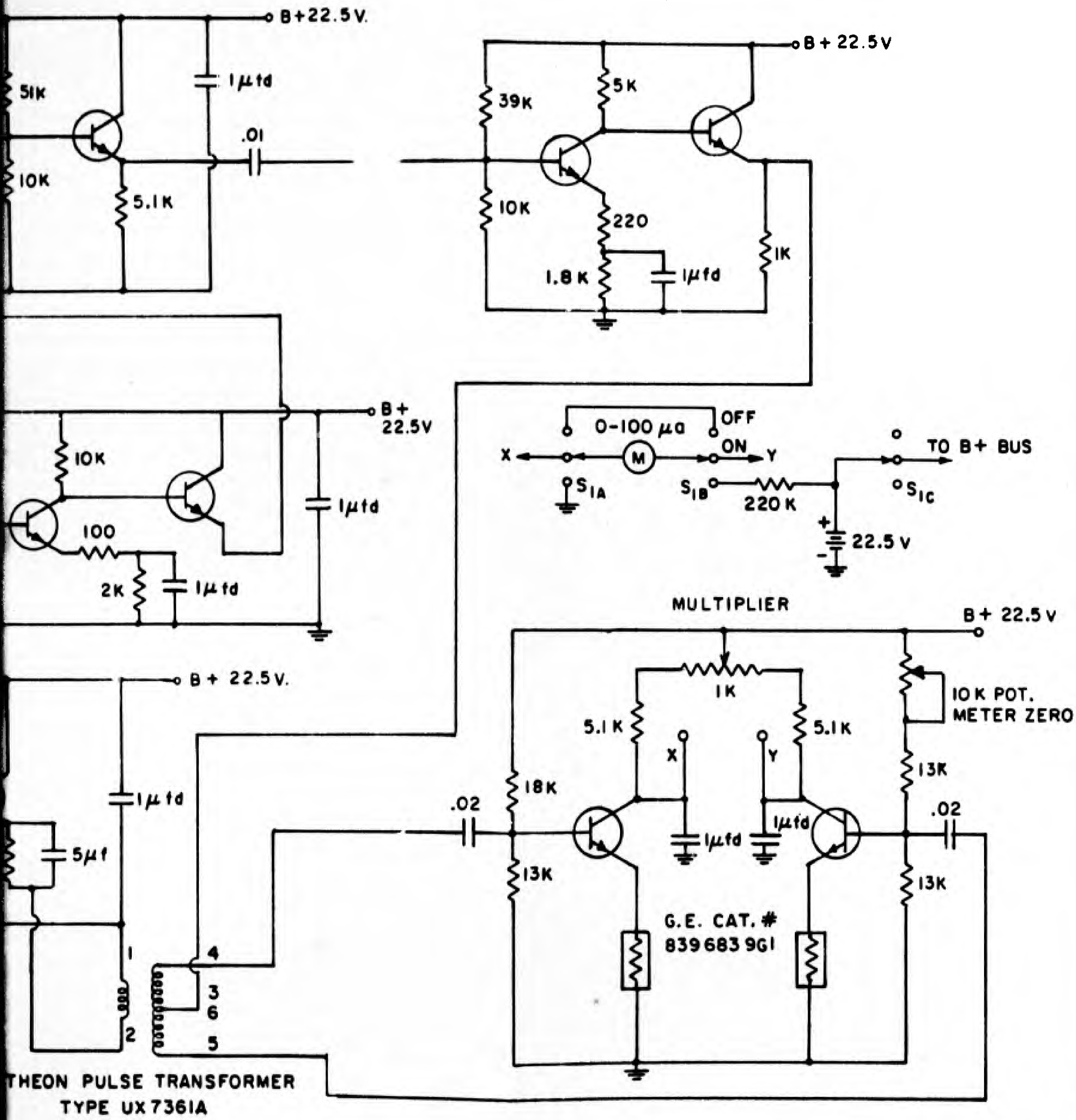

Figure 3-2   Multiplier Unit




NOTE: ALL TRANSISTORS ARE FAIRCHILD AG696

FIG. 3-3 MULTIPLIER SCHEMATIC.

A


B+22.5V.
51K
1μfd
.01
10K
5.1K
B + 22.5V
39K
5K
10K
220
1.8K
1μfd
1K
B+
22.5V
10K
100
2K
1μfd
1μfd
0-100 μa
OFF
ON
X
M
Y
TO B+ BUS
S1A
S1B
220 K
S1C
22.5 V
MULTIPLIER
B+ 22.5 V
B + 22.5 V.
1K
10 K POT.
METER ZERO
5.1 K
5.1 K
X
Y
13K
1μfd
18K
.02
1μfd
1μfd
.02
5μf
13K
13K
G.E. CAT. #
839 683 9G1
1
4
3
6
2
5
THEON PULSE TRANSFORMER
TYPE UX 7361A

B

### 3.3.1 Amplifiers and Attenuators

Amplifiers are used chiefly to provide impedance matching. Both channels are provided with attenuators to allow maximum flexibility in measurement.

The design of the attenuators is an important feature of the unit. Phase shift in the attenuators is undesirable, since a readjustment of the phase shifter would be required whenever the position of one of the attenuators was changed. The attenuators shown are simple resistive voltage dividers operating at an impedance level of 1000 ohms. The output impedance of the compound emitter follower driving the attenuator is about 25 ohms. These attenuators appear to have a negligible phase shift compared with other inaccuracies in the instrument. The PRM-1 attenuators, by contrast, were found to display phase changes as large as 15°. Phase changes were also found in commercial wideband matched attenuators.

### 3.3.2 Phase Shifter

One channel included the Merrimac resolver type phase shifter. The device operates in a manner very similar to the standard ac induction phase shifter. A pickup, mounted on the dial shaft, is subjected to a rotating field derived from the input signal with the aid of a 90° phase shifting network. The device provides any phase shift from 0 to 360° with negligible amplitude variation. The phase shifter used was obtained on special order, since the device is normally supplied only for 30 and 60 Mc IF frequencies. Additional transistor stages are provided in this channel; first, to provide a match to the 50 ohm input impedance of the phase shifter, and second to compensate for its insertion loss. (It was originally intended that a commercial amplifier made by Quan-Tech Laboratories would fulfill the latter function, simplifying the design and construction. This amplifier proved inadequate, however, because of output amplitude limitation at the 455 kHz intermediate frequency.) The emitter follower driving the phase shifter also introduces some attenuation in order to achieve a match to the 50 ohm input impedance without excessive battery drain.

The high gain amplifier following the phase shifter is sensitive enough to pick up some stray signal from the power supply circuits. This pickup, while very small, represents a signal of fixed phase added to the phase shifter output. The presence of this small signal, which could be easily eliminated in a new design, is thought to represent a significant portion of the small errors indicated in the test data. A phase error of $\pm 1.5^{\circ}$ can result under conditions when the output of the phase shifter is very small.

### 3.3.3 Multiplier Circuit

A quarter-square multiplier was used. Figure 3.4 shows a general block diagram of such a multiplier. The operation is based on the identity

$$e_1 e_2 = \frac{1}{4}\left[(e_1 + e_2)^2 - (e_1 - e_2)^2\right] \qquad (3.1)$$

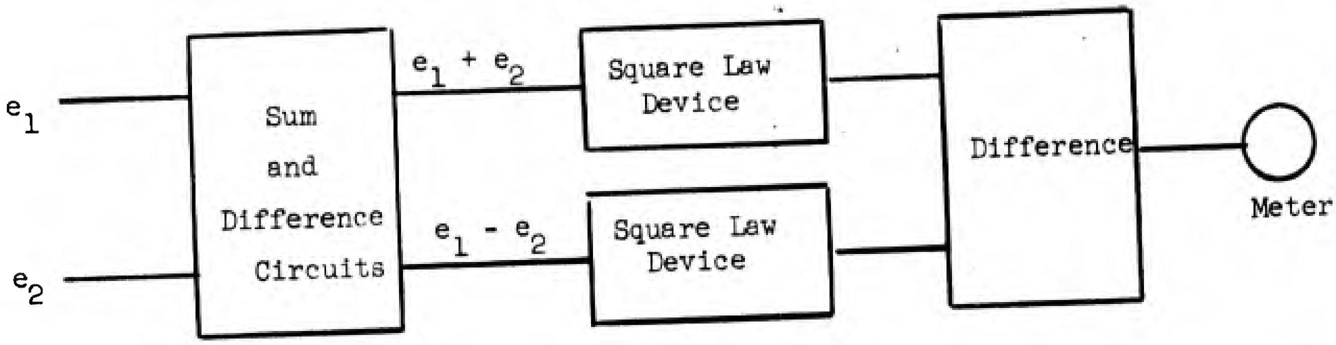



Figure 3.4 Basic Configuration of "Quarter-Square Multiplier"

The sum and difference operation was realized with a small pulse transformer. In general, the requirements on this transformer are broad bandwidth and good balance of the two secondaries at the operating frequency. The sum and difference circuit is shown in Fig. 3.5.

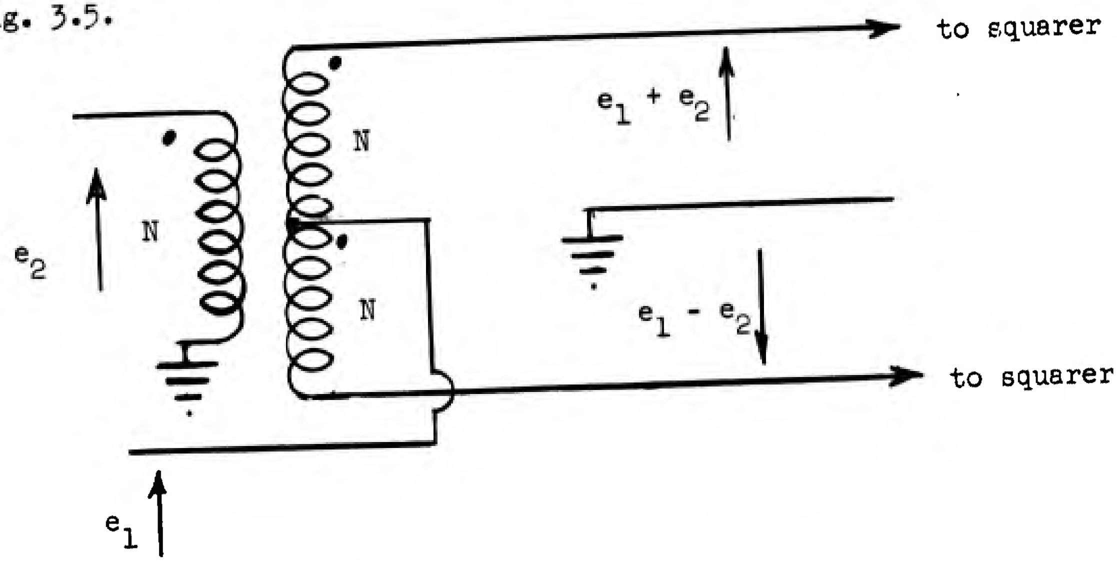



Figure 3.5 Sum and Difference Circuit

For the multiplying function itself, consideration was given originally to the use of the squaring network used in the Ballantine rms voltmeter. This uses a series of diodes with properly adjusted bias voltages. After some consideration it was decided not to use it because of the requirement of an extra power supply to bias the diodes, together with the requirement of a rectified push-pull drive signal. These circuit complexities presented serious design problems, particularly for an instrument for which portable battery operation was a requirement. After further study it was decided to develop a circuit making use of the nonlinear properties of Varistors.

Varistors, in general, are described by a power law $i = aV^n$, where a wide range of the exponent, n, is possible. The selection of a particular Varistor was based on catalog information showing the volt ampere curves. The unit which most closely approached a square law characteristic (i.e., $n \approx 2$) was chosen.

The Varistors in the multiplier circuit are approximately matched. The Varistor manufacturing tolerance is quite large. Matching was achieved by selection of two units from a group of nine. The transistors driving them may be considered as emitter followers. The Varistors are thus driven at a low impedance maintaining the square law variation. The collector currents of the transistors are, of course, substantially equal to the emitter currents. Thus, a high impedance current output is obtained from the collectors. A balancing potentiometer allows variation of the relative sizes of the collector resistances. This facilitates matching of the Varistors. The potentiometer should be adjusted so that the varistor with the larger coefficient of the square-law term has the smaller collector resistor and vice versa.

This is easily done experimentally, as follows. The same signal is applied to the inputs of both square-law devices (here the base terminals of the emitter followers). The balance meter is then adjusted to maintain a zero reading of the indicating meter. Unfortunately, the balance and zero adjustments interact, so that several trials are necessary to obtain the correct adjustment. Accurate matching over the same 50 to 1 dynamic range mentioned in section 3.1 is required if a full-scale reading is to be maintained in a field with an $89^{\circ}$ angle. The circuit described here does not have this range. It could be obtained by increasing the sensitivity by the use of a more sensitive meter movement (perhaps with a range switch) or, alternatively, by the use of lower impedance Varistor units. The latter scheme would increase the battery drain considerably.

A further limitation of the maximum allowable signal is overload of the amplifiers in the multiplier unit. Severe overloads will, of course, result in damage to the transistors. Moderate overloads will result in the generation of second order distortion products which will produce confusing readings of the meter. Table 3.1 shows the signal inputs at the multiplier terminals which will produce amplifier overload.

Table 3.1 Multiplier Overload Voltages

| | Attenuator Position | | |
|---|---|---|---|
| | 0 db | 10 db | 20 db |
| Channel A | 2.25 | 5.5 | 5.5 |
| Channel B | 5.5 | 7.5 | 7.5 |

Voltages shown are peak.

Slight overloads are detectable by checking for zero shift with a single input. (The product should be zero if either input is zero regardless of the magnitude of the other.)

Two other tests of the multiplier unit were made immediately after the design and construction were completed. The multiplier inputs were connected in parallel, with separate blocking capacitors, and driven by a 455 kc oscillator (see Fig. 3-6). The test data shown in Table 3.2 are for a combined amplitude linearity and attenuator check. The phase shifter was set to give a maximum multiplier deflection and clamped in this position. The test data shown in Table 3.3 are for the phase shifter. Here, the signal amplitude was kept constant and the attenuators left in the maximum gain position. The phase shifter dial was turned to obtain readings corresponding to cosines of various angles. The data show the actual angle required as well as the theoretically correct angle. This test demonstrates the accuracy of the multiplier and phase shifter combination.

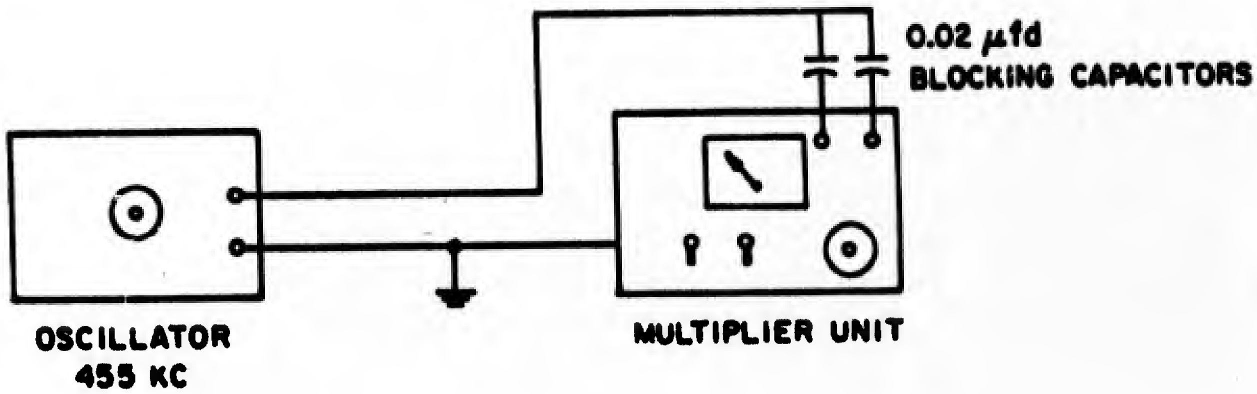



FIG. 3-6 TEST CIRCUIT ON MULTIPLIER UNIT

Table 3.2 Results of Linearity and Attenuator Test

| Multiplier Reading | | | Attenuator Settings (db) | |
|---|---|---|---|---|
| Correct | Actual | Input Voltage p-p | A | B |
| 100 | 100* | 0.3 | 0 | 0 |
| 25 | 25 | 0.15 | 0 | 0 |
| 31.62 | 32 | 0.3 | 0 | 10 |
| 31.62 | 33 | 0.3 | 10 | 0 |
| 10 | 10.3 | 0.3 | 10 | 10 |
| 10 | 11.2 | 0.3 | 20 | 0 |
| 10 | 11.0 | 0.3 | 0 | 20 |
| 3.162 | 3.3 | 0.3 | 10 | 20 |
| 3.162 | 3.5 | 0.3 | 20 | 10 |
| 1 | 1 | 0.3 | 20 | 20 |

* Denotes reference state

Table 3.3 Phase Shifter Test

| Multiplier Reading | Actual Phase Shifter Setting | Correct Phase Shifter Setting |
|---|---|---|
| 100 | 223* | 223 |
| 0 | 313 | 313 (+90) |
| 0 | 131 | 133 (-90) |
| 50 | 283 | 283 (+60) |
| 50 | 160 | 163 (-60) |
| 70.7 | 267 | 268 (+45) |
| 70.7 | 176 | 178 (-45) |
| 86.6 | 190 | 193 (+30) |
| 86.6 | 253 | 253 (-30) |

*Denotes reference state

The results of these bench tests were very encouraging. The accuracy attained by the instrument was very good indeed, in spite of the fact that it represented nothing more than a laboratory breadboard for a feasibility study. It should be apparent that the feasibility of construction of this section of a "Poynting Sensor" had been clearly established.

## 4.0 INITIAL EXPERIMENTAL EVALUATION

### 4.1 Field Tests

The first series of field trials of the improvised "Poynting Sensor" were conducted in the winter of 1965-66. Except for the addition of the multiplier unit described in the previous section, the equipment was identical with that used in the phasemeter tests reported in the Eighth Interim Report.[1]

The transmitter consisted of a rod antenna driven by a crude amplifier fed by a General Radio oscillator. The frequency was 1 Mc. An attenuator was provided between the transmitter amplifier and driving oscillator to allow reduction of the signal strength as the source-sensor distance decreased. This step is necessary because operation of the PRM-1 receiver attenuators changes the phase angle of the signal presented to the multiplier.

The PRM-1 function switches were set to the "meter zero" position which eliminates the AGC system and unfortunately disables the receiver meter. Elimination of AGC action is necessary to provide linear rather than logarithmic response and to avoid changes in phase resulting from operating point changes. Attempts were made to demonstrate the inverse square law for the radiated power in the near field of this source. One way of determining the "zero" of the phase shifter was by moving the sensor into the "far field" and setting the phase shifter for maximum output on the multiplier, since in the far field, the electric and magnetic components are in phase. Other methods attempted were moving the sensor very close to the source and setting the phase shifter for zero multiplier output or setting the phase shifter for the theoretical angle at an intermediate distance.

Many difficulties were encountered during these trials. Typical data would show an inverse square law to within 50 or 60 meters of the source. At this distance the slope would change to a radically steeper one as shown in Fig. 4-1, which could, perhaps, be interpreted as the inverse fifth power curve to be expected from the product of the magnitudes of the E and H fields at close distances. It was possible, however, to duplicate the phase angle vs distance curve of the Fourth Interim Report[2] fairly closely. The multiplier unit was used as a phase-meter in the following manner. The phase-shifter was tuned to obtain a zero output on the multiplier meter at each distance, the phase-shifter settings were recorded and the resulting curve showed approximately the correct variation of phase with distance. The indication, was, of course, relative only.

The other encouraging result was the behavior of the device during a freak winter thunderstorm. The meter deflected upscale

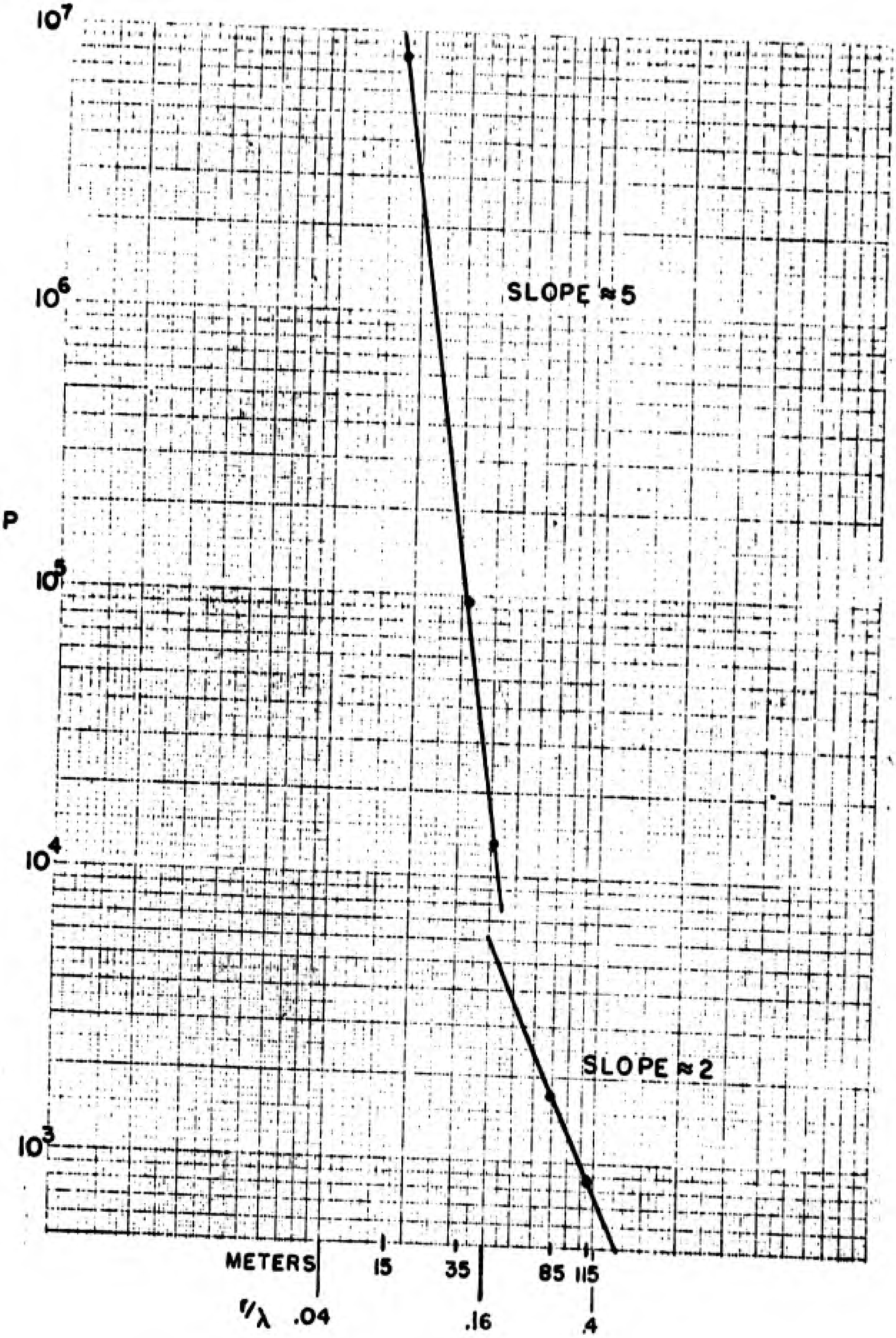



FIG. 4-1 MEASURED POWER VS. DISTANCE

during some lightning strokes and downscale during others, indicating the directional properties of the device. Presumably the upscale deflections corresponded to strokes in front of the device and the downscale deflections to strokes behind it.

Further field tests established several sources of difficulty:

1) unexpected receiver nonlinearity

2) lack of satisfactory phase calibration system

3) aberrations in the transmitter field produced by line cord radiation and inhomogeneities in the ground surface from underground structures.

It should be noted that an operating point shift, and thus a change in Miller Capacitance, and a resultant change in phase-shift are associated with an amplitude nonlinearity.

### 4.2 Laboratory Tests and Further Modifications

Studies of the receiver linearity were made in the laboratory. Several input vs output curves were obtained showing severe non-linearity. All of these tests were made with the receiver function switches in the "meter zero" position which eliminates the AGC circuits and substitutes a fixed bias. The difficulty was finally localized by a check of plate currents in the IF amplifiers. First, it was found that the load of the multiplier and particularly the shunt capacity of its connecting cables severely detuned the last IF stage. Secondly, it was determined that nonlinearity was still present in the third IF with settings of the RF gain control near minimum. The PRM-1 receiver achieves gain control by changing the

the grid voltage on the third IF. It was found necessary to modify this factory wiring. The RF gain control was connected to the RF and mixer stages and the third IF was then connected to the fixed bias source formerly connected to the RF and mixer stage. (This arrangement actually corresponds to the original receiver design found in early versions.) The multiplier load problem was minimized to a satisfactory degree by installation of an emitter follower buffer in the receiver. This restored the gain of the last IF to about 80% of normal with the multiplier and cables attached. (The stage was retuned with the multiplier, cable and emitter follower attached).

Final checks of the PRM-1's with these modifications showed linear receiver performance for all gain settings up to about 40 V signal amplitude at the 4th IF plate. In the minimum gain position, the receiver 4th IF plate output is about 20 volts with a 20 millivolt input (step attenuator at 0 dB, function switch in "meter zero"). Further tests were made with both receivers coupled to the multiplier. A signal generator was used to feed the two receiver inputs in parallel and a check was made of the multiplier reading. The multiplier reading was found to be proportional to the square of the signal input within a few percent. This test established the linearity of the complete instrument consisting of the modified receivers and the multiplier unit.

Complete details on the receiver modifications used in constructing the prototype are given in Appendix A.2.

4.3 Phase Calibration

Two possible phase calibration methods were envisaged. The first system, the antenna substitution method, required the switching of one of the receivers from the rod antenna to the loop antenna. The concept was that if both receivers were sensing the same field component, the phase shifter could then be set to give zero phase difference at the multiplier. Then, one receiver could be switched to the other antenna, and the power measured. Alternatively, in this procedure, both receivers could actually be fed by the same antenna.

The second scheme proposed was the use of a calibrating oscillator which could inject into both channels signals with a known phase difference. The phase shifter could then be set with this signal. This method also allowed simultaneous amplitude calibration.

Tests of the antenna substitution method for phase calibration were made by setting up a source field and switching the rod receiver from rod to loop and back again to determine the reproducibility of the phase change. This experiment was performed both with and without receiver retuning. The phase angle was measured by setting the multiplier reading to zero with the phase shifter and recording the reading of the latter. The results obtained were found to vary by $15^{\circ}$ to $20^{\circ}$ for short and long term periods. This system was thus abandoned. Nevertheless, it should be noted that the accuracy of the dummy rod and dummy loop in the PRM-1 as well as the receiver alignment affect the result. Also, the detent of the "Rod-Loop-Cal" switch is strong and the mechanical shock associated with its operation may detune the receivers slightly. (A very slight detuning will result in a large phase change.)

The mechanical difficulties of obtaining direct access to the PRM-1 coupling circuits prevented further experiments on this calibration system. Nevertheless, it is felt that it is worthy of further exploration.

In the second calibration scheme the calibrating oscillator was adjusted to beat with the signal at a subaudible rate. The multiplier itself serves as the beat detector. The signal was then turned off and the phase shifter position for zero multiplier reading with the injection oscillator only was determined. This was compared with the zero position of the signal alone. While both angles were dependent on receiver tuning, and operating frequency, the difference between the two was remarkably constant and stable.

The magnitude of the difference between the signal angle and the calibration angle was dependent on the injection scheme used.

In the first tests, both rod and loop were driven by the Stoddart 91550-1 current probes. One probe was clamped around the loop, the other around the rod. With this arrangement, the difference in phase was reproducible to within 3 or 4 degrees at an operating frequency of 1 Mc. At 1.2 Mc the reproducibility was about $5^{o}$ and at 1.5 Mc about $8^{o}$. These tests were conducted indoors and it is possible that field perturbations in the vicinity may have been a contributing factor. It was felt that part of the difficulty arose from the method of coupling to the rod. The large bulky current transformer, of course, affected the rod impedance significantly.

A small capacitive "gimmick" of insulated wire was wrapped part way around the rod at the base, and taped in place. At an operating frequency of 1 Mc, the difference in phase angle between the oscillator and the signal was reproducible to within $1^{\circ}$. This reproducibility is possible on a long term as well as a short term basis provided that the equipment is handled carefully. The injection system has since been redesigned to use a rigid metal collar, thereby providing greater mechanical rigidity. The rod injection system is shown in Fig. 4-2.

During field tests, we were able to reproduce this figure over a period of 10 days. The angle changed only when a loose connection in the calibrator was discovered and repaired. Presumably the change was a result of a different lead placement in the calibrator after repairs were completed.

In order to make the final field tests of the complete sensor, it was necessary to devise a portable calibrating oscillator. A calibrating oscillator, designed for the Ferris 32B RIFI meter, was modified for this purpose. The attenuator network was replaced and a low impedance emitter follower output, together with control switches, was added. Two switches were provided--a power switch and an output switch. These were necessary because it was found that

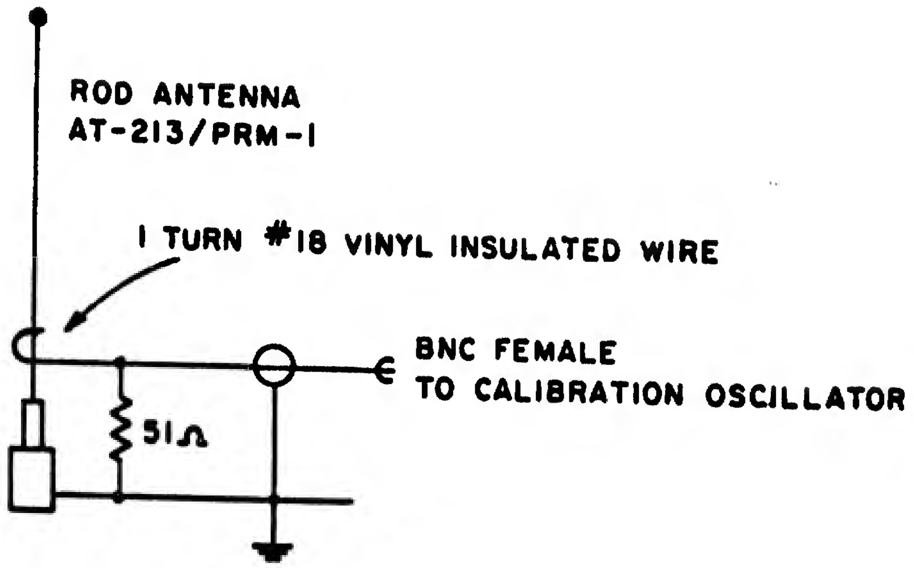



FIG. 4-2 CALIBRATOR ROD INJECTION.

the required warmup time for stable operation was excessive if the oscillator power was turned off between trials.

The output control of this oscillator, which varies the oscillator plate voltage, proved to be a very useful means of fine tuning.

A circuit diagram of the calibrator system used in the field tests is shown in Fig. 4-3.

The design objective of the calibration system is to achieve loose coupling to the antennas, so that the phase-shift of the calibrating signal will be affected in the same manner as that of the signal.

Injection of the calibrating signal into either the rod or loop antenna may be represented by the equivalent circuit of Fig. 4-4.

We desire that $e_3/i_{cal}$ vary in the same manner with tuning and other variables as $e_3/i_{ant}$.

It can be shown quite readily that this result can be most closely approximated by making $Y_{inj}$ as small as possible.

The effect of the coupling may be measured in a qualitative way by determining the change in amplitude and phase of the signal received by the antennas when the calibrator is connected. In the Moore School prototype, the phase of the received signal was found to change by about $10^{\circ}$ when the calibrator circuit was disconnected.

The resistors in the calibrating network were selected to give injection levels compatible with the signals being measured. They must be changed at different signal levels. A development model sensor would, of necessity, incorporate suitable means of varying

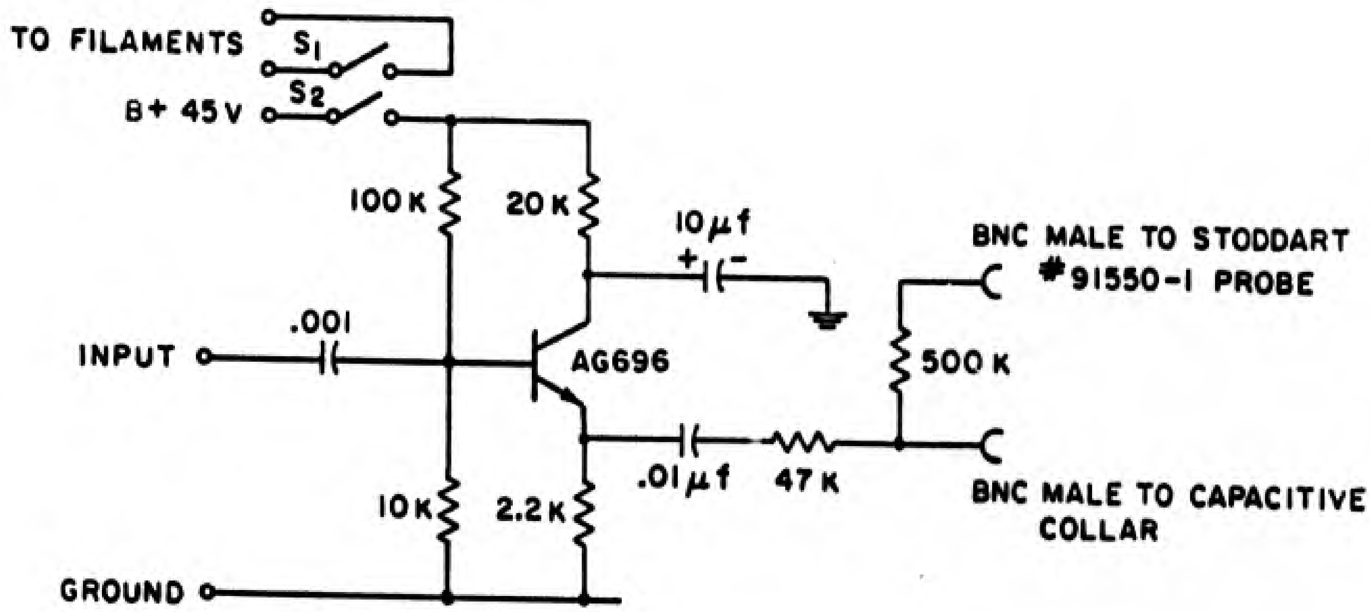
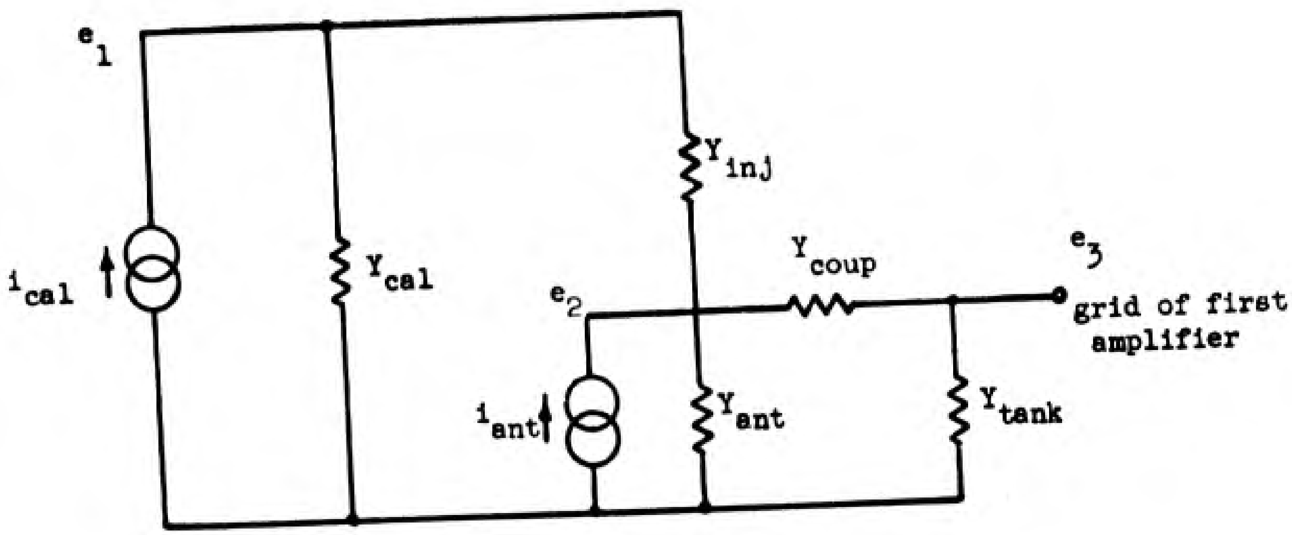



FIG. 4-3 SCHEMATIC OF CALIBRATOR OUTPUT CIRCUIT FOR USE WITH FERRIS 32B OSCILLATOR.




$i_{cal}$ = calibrator current

$Y_{cal}$ = calibrator source admittance

$i_{ant}$ = antenna current induced by field

$Y_{ant}$ = antenna admittance

$Y_{coup}$ = coupling admittance

$Y_{tank}$ = tuned circuit admittance

Figure 4-4. Calibrator Injection into an Antenna the injection levels without changing the injection phase. Note that independent variation of the rod and loop injection is required, although usually the range of relative variation need not be too great--perhaps 10:1. A complete description of the calibration method used in the trials is included in Appendix A-2.

# 5.0 FINAL FIELD TESTS

## 5.1 Improvement in Test Range Facilities

The earlier tests had been conducted on a newly acquired test site located about 25 miles from the Moore School building. Because of limitations on time, the facilities used were temporary and consisted of a "portable" ground plane about 6' by 6' in size, under which were housed a General Radio oscillator and a one-tube amplifier. In the new facilities used for the tests to be described, the "ground plane" was 20' and 25' wire mesh mounted directly on the ground, and the rod antenna used to set up the "test field" was mounted directly on the ground plane and fed by a linear amplifier located in a box below ground level as shown in Fig. 5-1. The amplifier schematic is shown in Fig. 5-2. The amplifier was driven by an oscillator and attenuator located below ground level and at a distance of about 35' from the antenna (see Fig. 5-3).

Various tests performed on this range have been very successful in matching theoretical predictions.

Figure 5-1  Test Facility

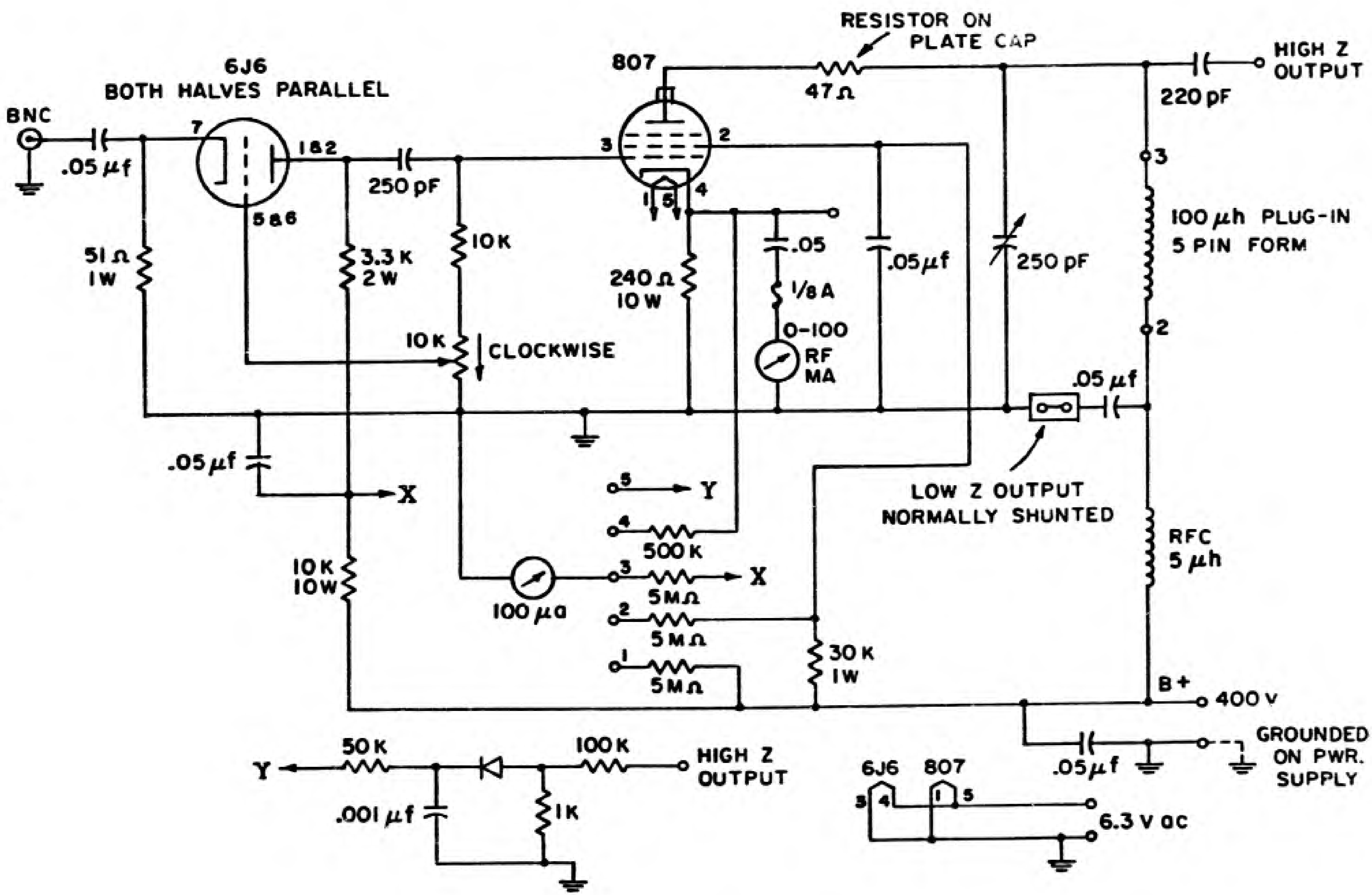



FIG. 5.2 LINEAR RF POWER AMPLIFIER

## 5.2 Procedure

The attenuator provided between the transmitter oscillator and amplifier permitted adjustment of amplifier output as the sensor-course distance changed. This would have been quite unnecessary if the receiver attenuators could have been used.

The proper initial phase-shifter setting was established using the theoretical phase angle of the field at a known distance. This angle was added to that measured by setting the phase shifter to obtain a zero multiplier reading with the source. This angle is then compared to thd zero setting for the calibrator. In this way it was determined that the correct phase-shifter setting for power measurement was obtained by determining the "calibrator zero" and adding $50^{\circ}$.

## 5.3 Results

An inverse square-law curve was obtained using this setting of $50^{\circ}$. The data were obtained by starting with the sensor 100 meters from the source. The sensor was then brought in closer and measurements made of the relative power. The sensor, consisting of the two receivers, multiplier and calibrator,was mounted on a rubber-tired cart made of wood except for the wheels, axle, and fastenings. The complete instrument is shown in Fig. 5-4. The measured data for the inverse square law are shown in Fig. 5-5.

It was found unnecessary to recalibrate at every distance. Only two recalibrations were required, which may be taken as an indication of the phase stability of the receivers. This also explains the near success of the previous tests made without a calibration procedure.

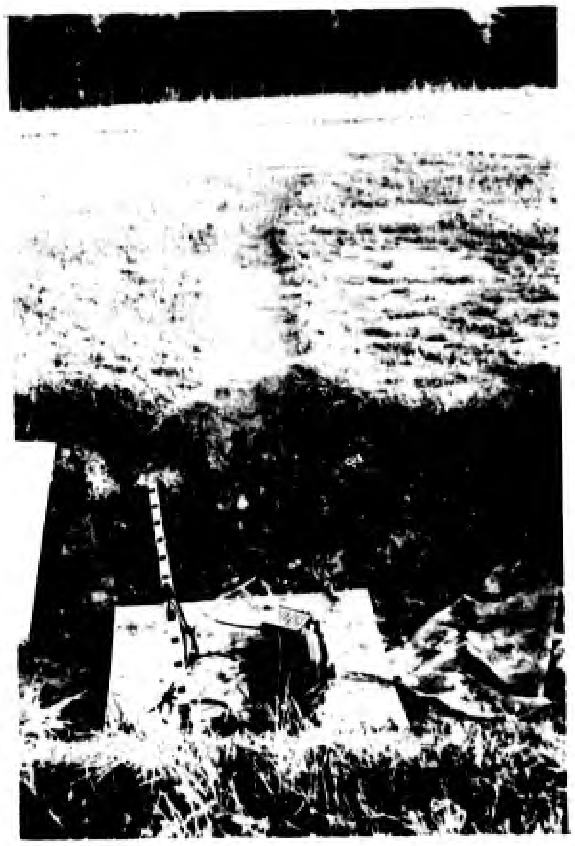


Fig. 5-3

Driving Oscillator
and Attenuator

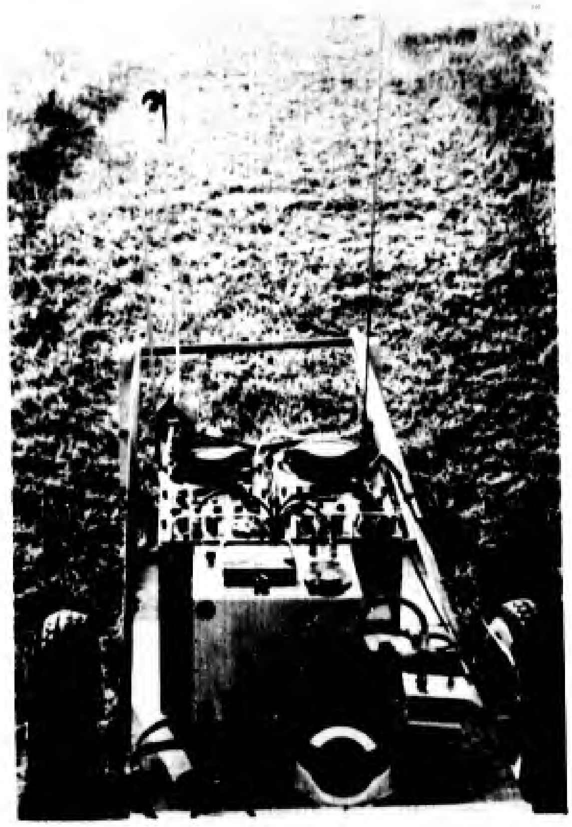


Fig. 5-4

Poynting Sensor

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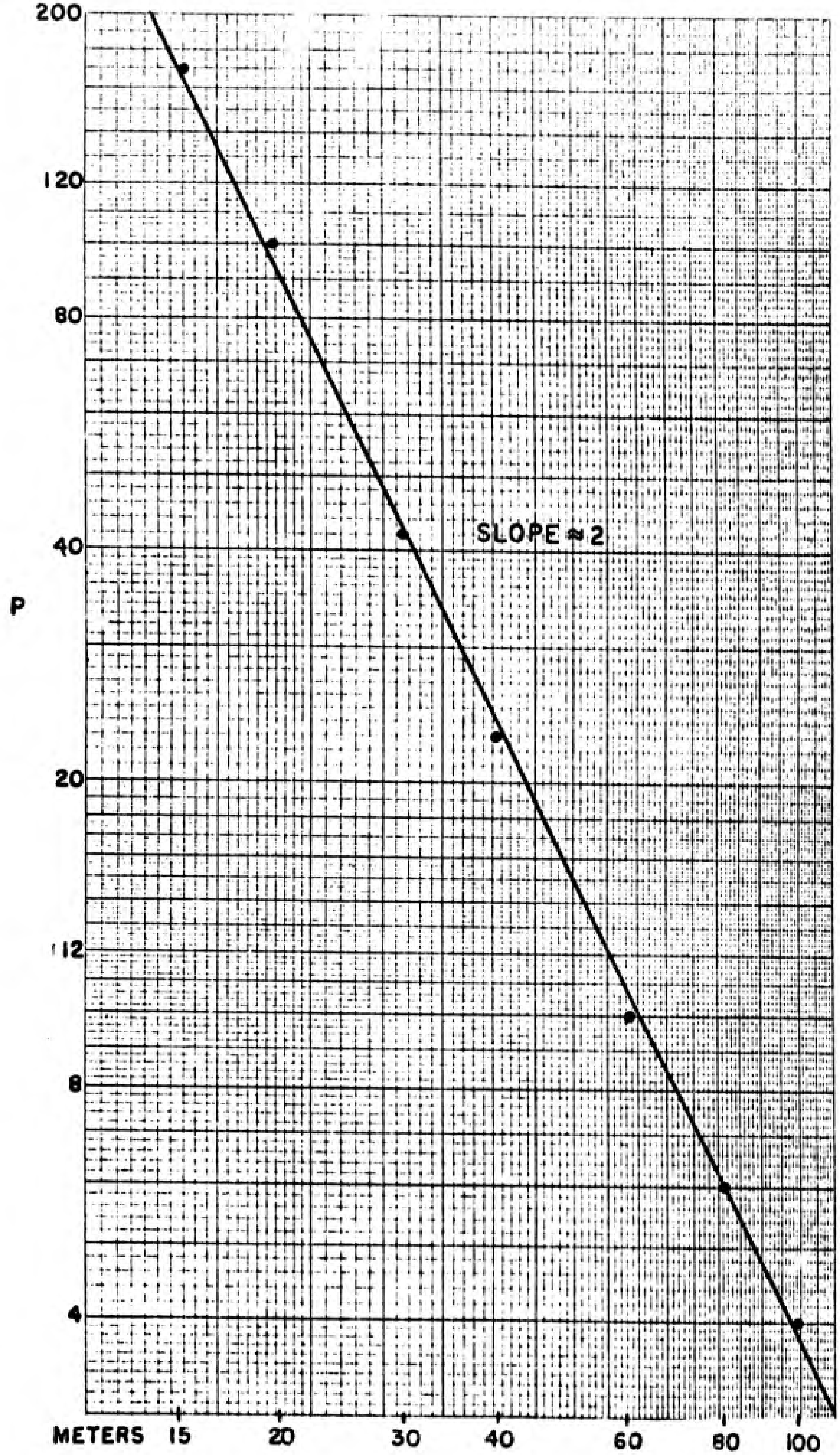



FIG. 5-5 MEASURED POWER VS. DISTANCE

Several other tests were made. A transmission line consisting of a single wire approximately 6' above the ground and about 50 meters long was fed with the transmitter and terminated at the other end by a 1000 ohm resistor to ground. The first attempts to measure the field of the wire indicated that the relative magnitudes of the E and H fields were sufficiently different that the relative magnitudes of the loop and rod calibration signals had to be readjusted. The 47 K resistor in the loop circuit was replaced by a 470 K resistor. To determine the proper phase shifter angle, the rod antenna was set up again and the field measured at a known distance. The new correction angle to be added to the calibrator zero angle was found to be $61^{\circ}$. Power measurements were made approximately under the line. The relative power transmitted along the line was measured as 76 on the meter. The volt-amperes were 84. (The volt-ampere reading is obtained by setting the phase shifter for a maximum multiplier reading.) The power flow transverse to the line was approximately 1.7 and the volt-amperes about 2. (The latter readings are rather inaccurate, since the smallest multiplier-scale division is 2.)

Additional qualitative tests were made to determine the sensor response to broadband signals. The device was tuned to a broadcast station. The meter indication was found to increase with depth of modulation. A Tesla coil was used as a broadband noise source with the sensor tuned to a broadcast station. The reading increased with the noise source in front of the sensor and decreased with the noise source behind the sensor. The noise source was also used with the transmission line system. The results were identical. In both these cases, the phase-shifter setting was determined with the original signal source (the broadcast station or the sine wave transmitter). The Tesla coil signal was simply added to the narrow-band signal.

The proper phase calibration procedure for a broadband source has not, as yet, been evaluated carefully. However, it does appear that the device responds properly to a broadband source.

## 6.0 CONCLUSIONS AND RECOMMENDATIONS

The successful completion and testing of the final device clearly demonstrates the practical feasibility of the measurement of the "Poynting Vector." The field tests clearly support the contention that the device is capable of measuring the actual power component of a complex electromagnetic field.

Although exhaustive field tests were not carried out due to time limitations, the device can be indicated for use in the following applications:

1. Measurement in the near field of radiated power of any type of source. In addition to the "point" type of source, this application should be considered to include exploration of the field of large aperture antennas.

2. Immediate characterizations of an unknown source as being primarily electric or primarily magnetic in nature. (In additdon to measuring electric and magnetic components, the phase angle can be determined.)

3. Measurement of magnitude and direction of power flow in the case of a distributed source (such as a power line).

4. Measurement of direction of arrival of signals or noise. In this connection, note that not only does the device specify whether the wave flows forward or backward, but that the combined E-H sensor has a unique directivity not characteristic of other antennas.[2,3]

At the present time, the technique should be considered to be a laboratory tool. No claim is made here that the potential applications are of such importance as to justify large scale production of this device. Its primary value is in its usefulness in analysis of electromagnetic fields. Furthermore, its limitations have not been thoroughly explored. For example, its usefulness is reduced, but certainly not eliminated, as one goes up in frequency, since for many sources, the induction (or near) field range is shorter at higher frequencies. Also, the device itself undoubtedly causes some distortion of field components which are being measured. The practical effects of this distortion are unknown. (Some studies of the field distortion effects were included in refs. 2 and 3).

Since the prototype device is still rather cumbersome, an improved, more portable instrument is desirable. Additional development is needed to:

1. improve the flexibility of the phase calibration procedure,
2. incorporate all separate units into a single cabinet with convenient arrangement of controls and elimination of those considered unnecessary,

3. provision of the possibility (admittedly at reduced sensitivity) of locating the sensors (rod and loop) on the end of a cable so as to permit convenient field exploration,

4. eliminate or reduce phase shift changes introduced by changes in the position of RF or IF attenuators.

Design considerations for a Poynting Vector measuring device are discussed in further detail in Appendix A-I.

## 7.0 REFERENCES


1. "Study of Methods of Implementing Poynting Vector Measurements," Eighth Interim Report, July 31, 1964, under contract NBy-32219, Univ. of Pa., by Nabil Farhat, K. S. Foo, and R. M. Showers.

2. "Feasibility Studies of Poynting Vector Measurements," Fourth Interim Report, 31 July 1963, under contract NBy-32219, Univ. of Pa., by R. A. Bartfeld, R. G. Mulholland and P. B. Swarup.

3. "Study of Methods of Implementing Poynting Vector Measurements," Final Report, 31 December 1964, under contract NBy-32219, Univ. of Pa., by W. W. Cowles, N. Farhat and K. S. Foo.

APPENDIX A.1

## Design Considerations for a Poynting Vector Measurement Device

### A.1.1 Introduction

The purpose of this section is to review some of the critical design features of a Poynting vector measurement device in order to provide a guide for future developments. It is assumed the general design follows the arrangement given in Fig. 3.1. Comments on various parts of the device follow.

### A.1.2. RF and IF Channels

Reasonably good quality channels typical of the communication receiver practice should be adequate. Both channels, RF as well as IF sections, should be designed or checked for linear response. AGC cannot be used. Linear response is required if the multiplier output is to be proportional to the product, $|E||H|$. Furthermore, use of AGC inherently involves a change in operating point, which will change the Miller capacitance of the tuned stage sufficiently to induce a spurious phase shift.

A stable phase characteristic is required but should not be too difficult to obtain. Even though the calibration generator will permit correction for long term drift in phase, the phase characteristics of the receiver must be quite stable over a period of a few minutes to permit time for a field measurement to be made after calibration. The short term phase stability represents one contribution to the overall error. Requirements for total phase error are derived in the latter part of this section. No serious difficulty was experienced in the trials at the Moore School using the Stoddart PRM-1 receivers. The fact that the early trials, made without provision for phase calibration, were almost successful is indicative of the phase stability of these receivers. The recent trials made with the calibrator indicate a change of a few degrees in the course of a couple of hours (after warm-up, of course). It should be noted that the phase angle of importance here is the difference between the phases of the two channels. Thus, with identical components, and identical environments, drifts should be self-compensating.

Wide dynamic range is a second general requirement of great importance. As pointed out in section 3.1 of this report, consider a situation in which the time phase angle is $89^{\circ}$, when the ratio of power to volt-amperes is about 1:50. Thus, for reasonable accuracy of measurement, the amplifiers and multiplier circuitry should be capable of linear response with a signal amplitude at least 50 times larger than that required for full-scale output of the wattmeter with a $0^{\circ}$ phase angle. The required linear range increases rapidly as the phase angle approaches $90^{\circ}$. Results of the experiments indicate that measurement in a field with an $89^{\circ}$ phase angle would be a reasonable target for a development model.

A.1.3 Attenuators

Both channels must be equipped with RF and/or IF attenuators. Since the relative phase angle between the E and H signals must be preserved, these attenuators must either be designed to have no change in phase shift with attenuation or, alternately, provision must be made for correcting for attenuator phase-shift during calibration. The latter procedure is inconvenient.

The capacitive attenuators provided in the PRM-1 receivers are not suitable. Phase changes of the order of 10 or 15 degrees occur with attenuation changes. This is presumed to be a result of the fact that the PRM-1 attenuators are directly connected to tuned circuits where small charges in susceptance can produce large phase changes.

Attenuators, operating at the 455 Kc IF frequency, were included in the multiplier unit constructed at the Moore School. These attenuators consisted of a compound emitter follower with an output impedance of the order of 25 ohms, driving a resistive voltage divider with a total resistance of 1000 ohms (see the circuit diagram of Fig. 3.3). These attenuators were found to change the phase angle by less than a degree. Presumably, a capacitively compensated voltage divider should be even better. The only requirement would seen to be adequate buffering between the attenuators and the tuned circuits to avoid the variable reactive loading.

It is recommended that the attenuators be designed to provide 10 db steps, rather than the more conventional 20 db steps, because of the large dynamic range required and the absence of AGC circuits. The attenuators in the multiplier unit would then be superfluous.

### A.1.4 Local Oscillator

Preservation of the relative phase angle of the E and H signals clearly requires the use of a common local oscillator for both channels.

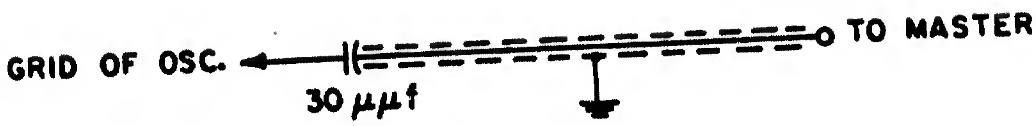
Adequate buffers are required to prevent significant cross-talk between channels (see Fig. A.1-1). No serious difficulty is expected in meeting these requirements.

### A.1.5 Detectors, Multiplier and Phase Shifter

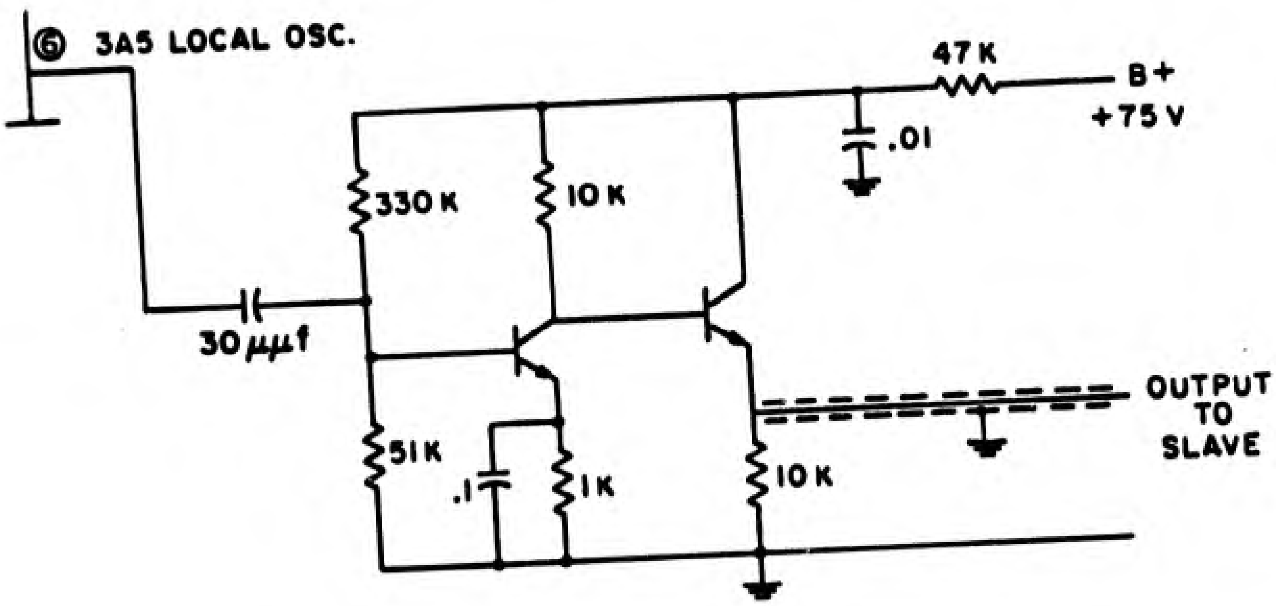
Operating convenience requires conventional detectors and dc meters to monitor the actual amplitude of the E and H signals. Detectors and meters should be provided in both channels. In addition to allowing separate measurement of the E and H field components, these can be used to detect overload in either channel. Overload of either or both channels may occur without deflection of the multiplier meter, since the response of the latter will be zero if the time phase angle is $90^{\circ}$. The detector and meter circuits would also be useful for simultaneous measurement of the amplitudes of E and H. The detectors should be isolated from the signals fed to the multiplier to avoid introduction of distortion products from the detector into the multiplier input.

An audio amplifier stage and earphone connection is also desirable to assist in identification of the signal. A single audio channel, capable of being switched between the two detectors, would be adequate.

A single phase shifter is required to balance out the phase difference between the E and H channels in the receiver. This phase difference arises from differences in the coupling networks and loading of the rod and loop antennas and from minor variations in receiver tuning, tracking and alignment.




(a) PRM-1 SLAVE RECEIVER MODIFICATION.




(b) PRM-1 MASTER RECEIVER MODIFICATION.

FIG. A.1-1 RECEIVER LOCAL OSCILLATOR MODIFICATIONS.

The Merrimac resolver type phase shifter which was used proved fully satisfactory in all tests. Presumably, this device could be ordered with impedance levels compatible with the interconnecting circuits, to minimize coupling losses. The amplifers required to compensate for the phase-shifter insertion loss should be untuned, as in the Moore School prototype, since balance of total phase shift in the two channels is important. Additional tuned circuits in one channel might very well introduce difficulties.

The quarter-square multiplier is also an obvious choice for the development model. The transformer sum and difference circuit should be completely satisfactory if a good, well-balanced transformer is used. The "Varistors" used as square-law devices in the prototype were quite satisfactory. Use of these devices provides a remarkably simple circuit. Other square-law devices are available, of course.

The field effect transistor is a second possibility. This device, when properly biased, displays a square-law characteristic. The use of the field effect transistor in a quarter-square multiplier has been studied.* A noteworthy feature of the FET in this application is that the equivalent of "cathode degeneration" allows adjustment of the square-law coefficient of the device, thus making balance possible.

Another method is the use of RF ammeter thermocouple elements. The dc outputs of the thermocouples could be directly connected in

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* "The Quarter-Square Multiplier Using M.O.S. Transistors," Joel Court, Master's Thesis submitted to the University of Pennsylvania, Aug. 1966.

series opposition with a dc meter movement and should be quite reliable. This system also has the virtue of extreme simplicity.

A two-range meter should be provided. This, in conjunction with the attenuators in the two channels, should provide adequate precision of measurement. The prototype constructed at the Moore School has only a single range dc indicating instrument. As a result, when the signals are nearly $90^{\circ}$ apart in phase, and of sufficiently small amplitude to avoid overload, the meter deflection is quite small, less than 5 per cent of full scale. A high sensitivity range on the meter would avoid this situation.

A.1.6 Power Supply

The device must be capable of battery operation in the field. Transistorized circuitry should make a reasonable battery life possible. Operation from a standard ac power supply should also be possible. Transistor voltage regulators should be used to obtain stable operating potentials without excessively frequent readjustment by the operator.

A.1.7 Calibration

While the basic principle of injection used in the prototype appears sound, additional development work appears advisable at this point. The principle behind this calibration method is the following. First, the calibrating oscillator is tuned to the exact frequency of the measured signal. The multiplier unit is used as a beat detector. Second, relative phase shift of the receivers is measured by nulling the multiplier with the calibrating signal along. Finally, a correction angle, determined by prior calibration tests, is added to the phase shifter setting which corresponded to the null output. Then, the phase shifter is correctly set for power measurements, and the signal power may be measured.

Additional development work should make possible considerable improvement over the system of the prototype, particularly in respect to operating convenience.

1. The calibrating oscillator should be coupled to the antenna circuits inside the receiver. Good electrical design and mechanical construction should allow light coupling and at the same time assure long-term stability.

2. A means of varying the relative outputs of the rod and loop injection signals without a change in phase is very desirable. This would allow selection of relative injection levels compatible with the respective signal amplitudes.

3. The overall output of the calibrator generator should be controllable over the entire range of the receiver. This would allow the measurement of unknown signals. In experiments with the prototype, it was necessary to turn off the signal source after beating with the calibrator, so that the phase angle of the calibrator above could be measured. If a wide range of output was available from the calibrator, and the receiver attenuators were free of phase shift, this step would be unnecessary. The calibrator amplitude could simply be increased until it dominated the signal completely and the beat disappeared. Then, the phase angle could be determined with

the calibrator, the calibrator could then be turned off and the signal power measured, all <u>without</u> access to the signal source.

As in the prototype, a fine frequency control for the calibrator is required. To allow field power measurements at any frequency, it will be necessary to obtain a curve of the angle to be added to the phase shifter setting corresponding to zero output, with the calibrator as a function of frequency.

## APPENDIX A-2

## Construction and Operation of the Prototype Sensor

This section is a more complete description of the experimental equipment and procedures used in the tests made at the Moore School. It is intended to include sufficient information to allow repetition of these experiments by interested parties.

The modifications made to the AN/PRM-1 receivers:are described in the first section; the second section describes the calibrating system, and the third section covers the operating instructions. The last section describes the basic test procedures for the multiplier unit itself.

### A.2.1 Required Modifications to the PRM-1 Receiver

The local oscillator of one receiver, the "slave," is disabled by removal of the 3A5 local oscillator tube. The oscillator tank circuit is not disconnected. It provides some filtering of the injected signal derived from the other receiver. The circuit of Fig. A.2-1(a) is installed in the slave receiver with the capacitor connected to the oscillator grid pin. The shielded cable may be brought through the receiver front panel by removing the ground binding post.

The local oscillator of the "master" receiver is equipped with a buffer amplifier to provide drive to the slave receiver as well. The buffer amplifier is connected to the local oscillator plate terminal. The buffer amplifier power supply connection is made directly to the main receiver B+ bus(red wire on oscillator subchassis). Again, the shielded cable may be brought through the ground binding post hole in the panel. The output waveform of the buffer amplifier is not sinusoidal because the transistors operate near their frequency limit and at low quiescent current. The buffer amplifier is shown in Fig. A.1-1(b). The card on which the amplifier is mounted is designed to be attached to one of the cover screws of the IF attenuator for mechanical support.

The output emitter followers which provide the signals to the multipliers are shown in Fig. A.2-1. One circuit is required in each receiver. These circuits also operate from the main 75 V B+ bus. The fourth IF stage should be retuned with both the multiplier and the connecting cables attached to the buffer amplifier. The shielded lead was brought out to the front panel through the "scope" output connector. The lead from the detector circuit, normally attached to this connector, was taped.

The bias circuits for the third IF amplifier and the RF and mixer stage must be interchanged to assure linearity of the third RF. The fixed bias lead from the junction of R-130 and R-133 should be attached to pin 5 of subchassis Z 106. The adjustable bias from the wiper of the "calibrate" potentiometer R-133 should supply pin 6 of Z 101 and Z 102. (This corresponds to the original configuration of the PRM-1 before the factory change shown in the instruction manual dated 6 Feb. 1958.)

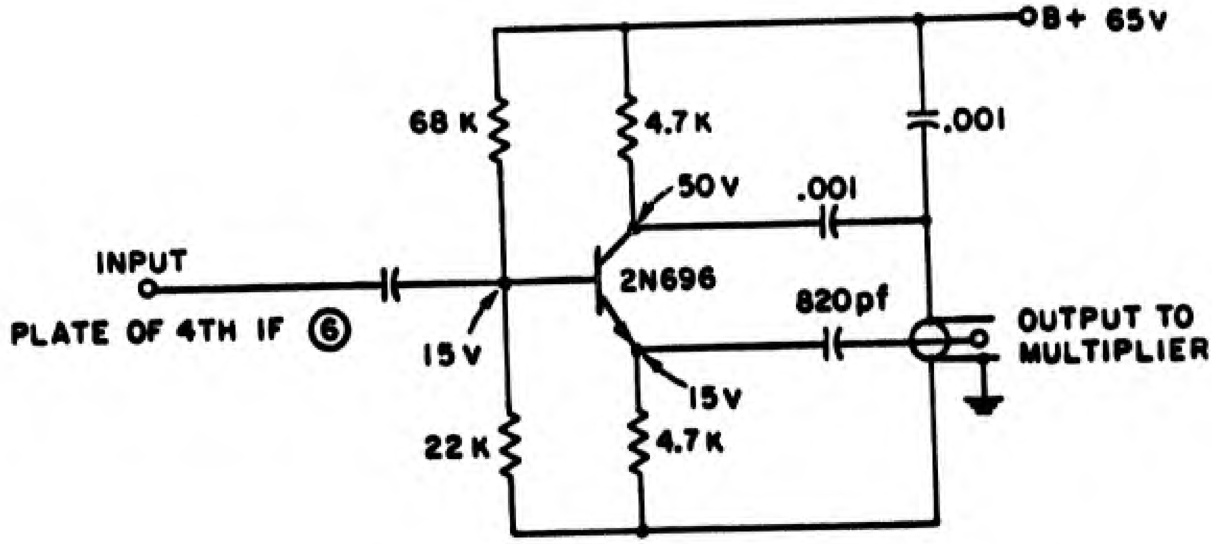


FIG. A.2-1 EMITTER FOLLOWER OUTPUT TO MULTIPLIER UNIT.

One further modification is required to the Stoddart No. 90291-2 rod antenna, mounted in the master receiver in our tests. The capacitive coupling network shown in Fig. 4-2 must be mounted at the antenna base. The cable connects to the calibrating generator. The Stoddart No. 915501 current probe is clamped around the slave receiver loop. The Stoddart No. 91077-2 loop was used to provide a signal level more compatible with that of the rod.

A.2.2 Calibrator

The output circuit of Fig. 4-3 was constructed in a "minibox" with an 8 pin socket for connection to the Ferris sine wave calibrator, model 32B. The Ferris instrument voltage divider was modified to provide a signal of approximately 1 volt to the emitter follower. The 47 K resistor in the calibrator output circuit and the 50 ohm resistor located at the capacitive collar provide a voltage divider determining the magnitude of the calibrator signal. The 500 K resistor in series with the current probe may be replaced with other values to vary the relative magnitude of the loop and rod signals. The presence of the 500 K resistor should assume that the current transformer current is essentially in phase with the rod voltage.

Any available battery powered oscillator should be satisfactory, provided it has adequate stability and some provision for fine tuning. The output control of the Ferris oscillator was found to make an excellent fine tuning control.

A.2.3 Operating Instructions

Assemble the required equipment on a movable cart. Connect the rod antenna with coupling injection network to the master receiver. Connect the loop antenna with current transformer to the slave receiver. Connect the two injection cables to the calibrator. Connect the oscillator injection cable from the master receiver to the slave. Connect the multiplier to the receiver outputs, using the same cables used in readjusting the receiver fourth IF as described in section A.2.1. Perform normal battery checks with the PRM-1's. Check the multiplier battery. Establish the test field. Tune the master receiver with function switch set to FI.

If the unknown field is to be explored over a wide range of distances, the source must be capable of amplitude variation, since the receiver attenuators cannot be changed in the course of measurement. The received signal amplitude should be checked at the maximum and minimum distances at which measurements are to be made to assure that the transmitter output is well above the noise at the maximum distance and can be reduced sufficiently for the minimum distance. Suitable settings for the transmitter output and the receiver attenuator and gain settings are determined by two constraints: (1) Adequate signal for useful multiplier deflection must exist in both receivers under minimum signal conditions, (2) No overloading of the multiplier must occur under maximum signal conditions.

The actual multiplier overload voltages are given in section 3, Table 3.1. Since a voltmeter is not included in the setup, these points may be referred to the FI scale of the receivers. Note that the voltage at the receiver output rises when the AGC is switched off by turning the receiver function switch to "meter zero." For the PRM-1 receivers at the Moore School, the multiplier overload points correspond approximately to the following readings obtained in the FI position:

Multiplier Channel A

| Meter Reading in FI | Multiplier Attenuator Setting |
|---|---|
| 8 db | 0 db |
| 15 db | 10 or 20 db |

Multiplier Channel B

| | |
|---|---|
| 14 db | 0 db |
| 18 db | 10 or 20 db |

These levels should be checked for any other receivers, but are probably nearly correct.

Once it has been established that the transmitter and receiver are set to allow operation within the multiplier range, the calibrating oscillator must be checked. The calibrating oscillator output network should be arranged to provide a signal amplitude adequate for beating with the source signal at all distances involved. The calibrator output may be changed by alteration of the resistors.

Once the test signal, calibrating signal, and receivers have been adjusted to satisfy these requirements, testing may begin. The first step is the determination of $\emptyset_m$, really a calibration of the calibrator. The sensor should be set up in a known field at a distance where the phase angle of E and H is known. (A table of values for the elementary dipole is given on p. 663 of the 4th edition of "Reference Data for Radio Engineers," published by International Telephone and Telegraph Company.)

The following procedure should be followed:

1) Recheck receiver tuning. Check zero adjustment of multiplier. (Remove one input cable. Significant deflection of the multiplier with a single input attached is indicative either of moderate overload, or of the need for adjustment of the internal "balance" control.)

2) Set receiver function switches in meter zero position.

3) Reconnect multiplier.

4) Adjust phase shifter to obtain zero multiplier reading. Record phase shifter settings, $\emptyset_s$.

5) Turn on calibrator and adjust to obtain beat with signal. Start with an audible beat and then adjust fine tuning of calibrator for a subaudible beat, visible on multiplier meter.

6) Turn off source.

7) With calibrator only, again adjust phase shifter to obtain zero output on multiplier, record the setting $\emptyset_c$.

8) Repeat steps 5 to 7 or 1 to 7 several times to establish that the angle, $\emptyset_c - \emptyset_s$, is invariant. If it is not, instability

of some sort is present (possibly the calibrating or source oscillators are drifting).

9) When equipment is functioning properly, determine the correction angle, $\phi_m$, by the following procedure.

Let $\phi_{EH}$ be the theoretical phase angle of the incident field. $\phi_s$ represents the phase shifter setting which will produce a $90^\circ$ difference between the signals applied to the multiplier. Thus, $\phi_{EH} + (\phi_s - 90^\circ)$ is the angle at which the phase shifter should be set to read power.

Then $\phi_c + \phi_m = \phi_{EH} + (\phi_s - 90^\circ)$ will give the correction, $\phi_m$.

The correction angle $\phi_m$ should remain invariant for the frequency of measurement regardless of tuning.

It is then possible to measure power from any source provided the angle, $\phi_m$, is known for the operating frequency.

The steps are as follows:

a) Turn on calibrator, beat with the signal, etc. as in steps 5-7 of the procedure for determining $\phi_m$.

b) Determine $\phi_c$, add the known $\phi_m$, and set the phase shifter to $\phi_c + \phi_m$.

c) Turn off the calibrator, turn on signal and measure power.

### A.2.4 Multiplier Service Information

The complete multiplier may be tested with the circuit of Fig. 3-6. Exact correspondence with the test data of section 3 is unlikely, since two Varistor replacements have been made since this data was taken.

Multiplier battery check; set multiplier function switch to "test." A new battery will give a reading of about 86. Satisfactory results can be obtained with readings as low as 70. The multiplier operates at 22-1/2 volts. A tapped 45 volt battery is used, thus, one standard 45 volt battery may be used twice.

The amplifiers in the multiplier may be checked by signal tracing with an oscilloscope. Simple ohmmeter checks will serve to determine failure of a suspected transistor.

Improper operation of the multiplying circuit proper, indicated by a shift of the pointer from the zero position with a single input below the overload level, or by other aberrations, failure to zero, etc., is probably the result of a transistor or Varistor failure in the squaring circuits.

To test the squaring circuits, the following procedure is recommended:

1) Check function of zero adjust. If zero cannot be obtained, circuit failure is indicated. The defective component should be isolated and replaced.

2) Disconnect the leads from the sum and difference transformer and arrange to apply the same sine wave signal directly to <u>both</u> base inputs (paralleled) of the squaring circuits.

3) Zero the meter.

4) Increase the input signal gradually. The meter should remain at zero or nearly so for signal amplitudes up to 5 volts peak or slightly higher (the clipping level).

5) If the meter does not remain at zero, adjust the balance control to restore the zero reading with signal present. The zero adjust and balance controls interact, so that steps (3) to (5) must be repeated several times.

6) If it is impossible to obtain satisfactory adjustment of the balance control, the Varistors must be replaced. Note: A satisfactory result is obtained if the maximum unbalance, (which may not occur at maximum signal) is within 5 scale divisions on the meter, although better results can be obtained.

In the event that the balance control cannot be adjusted satisfactorily, the Varistors must be replaced with a matched pair.

Varistors may be matched by means of a transistor curve tracer, or alternately by current measurements at several different voltages. Suggested voltages are 7, 10, and 12 volts dc. An exact match is not important, since the balance control will compensate for differences of the order of 5 percent or more. The most significant parameter for matching is the curvature of the volt-ampere curve.

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13. ABSTRACT

This report covers the design, construction, and field testing of an experimental device capable of measuring the magnitude of the Poynting vector associated with an electromagnetic field. With mechanical manipulation, it can determine the direction of the Poynting vector. It is based upon theory which has been described previously.

Tests of the final device demonstrate that it is capable of measuring this quantity with reasonable accuracy. The major limitations on its use result from the necessity for obtaining an accurate phase calibration of the two separate channels used for amplifying the signals received respectively on the rod and the loop antenna. Interaction between the rod and the loop does not seem to be a significant problem.

The device has unique characteristics and a number of applications for it are indicated. Recommendations on improvements in the device which are desirable for general field use are included.

| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
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