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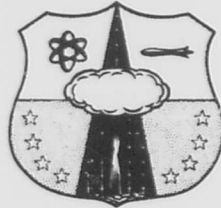
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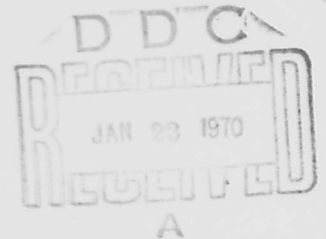
# DEVELOPMENT OF PROTOTYPE MAGNETIC FIELD INSTRUMENTATION

Robert M. Knox



AIR FORCE SPECIAL WEAPONS CENTER  
Air Force Systems Command  
Kirtland Air Force Base  
New Mexico

IIT Research Institute  
Chicago, Illinois  
Contract F29601-67-C-0037



TECHNICAL REPORT NO. AFSWC-TR-68-25

November 1969

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FOREWORD

This report was prepared by the IIT Research Institute, Chicago, Illinois, under Contract F29601-67-C-0037. The research was performed under Program Element 6.57.01F, Project 1357, Task 03.

Inclusive dates of research were May 1967 to November 1968. The report was submitted 27 October 1969 by the Air Force Special Weapons Center Project Officer, Lt W. G. Gallemore (SWVIA).

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This report has been reviewed and is approved.

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## ABSTRACT

Two prototype magnetometer systems have been developed and constructed for use in measuring pulsed magnetic fields. The IITRI model 100 magnetometer is a low-level, moderate bandwidth system that uses an optical carrier for transmitting the magnetic field information to a remote location. The IITRI model 200 magnetometer is a wide bandwidth, moderately sensitive system that uses an FM modulated microwave carrier data transmission link. Both instruments are portable and designed for field use. Extensive tests were conducted using electromagnetic field simulators and environmental test chambers. Results of these tests are included in this report as well as complete specifications for the two magnetometers.

(Distribution Limitation Statement No. 2)

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## SECTION I INTRODUCTION

The purpose of this program was to develop two new types of magnetometer systems for measuring fast-rising pulsed magnetic fields. The suggested systems were the outgrowth of an earlier program that was directed at finding new concepts or techniques for magnetic field measurement. A fundamental approach, arising from early studies, was to impose the magnetic field information on a high-frequency carrier. Thus, two systems were proposed; one using a microwave carrier and one using an optical carrier. The latter technique is presently bandwidth limited by the modulation rate for the optical source, which is a GaAs optical diode in the IITRI model 100 magnetometer.

The microwave carrier technique presently offers the greatest potential for wideband operation. A unique method of carrier modulation is employed in the IITRI model 200 magnetometer. The present system exceeds 50 MHz bandwidth and future versions are envisaged with bandwidth several times that figure.

This report describes both magnetometer systems in some detail. A description is given of the simulator instrumentation available for evaluating the magnetometers. Detailed test results are given for the preliminary contractor tests conducted at IITRI and the final acceptance tests conducted at Kirtland Air Force Base, New Mexico. The report ends with a statement of conclusions.

## SECTION II

### MODEL 100 LOW-LEVEL MAGNETOMETER SYSTEM

#### 1. Introduction

The overall design goals for the Model 100 Magnetometer were to develop a self-contained sensor unit that would be adequately shielded from electric fields, and capable of transmitting the pulsed magnetic field information to a remote location via a fiber optic data link. The desired H field measurements were in a frequency range of 100 Hz to 5 MHz, and an amplitude range of 1.0 millioersted to 0.1 oersted.\* The minimum acceptable signal-to-noise ratio at 1 millioersted was 15 dB. This range of amplitudes plus the desired signal-to-noise ratio at 1 millioersted required a minimum system dynamic range of 55 dB. Experimental studies have indicated that it was not within the state-of-the-art of fiber optic telemetry links to achieve this dynamic range over the desired bandwidth with a single data link 30 feet long; therefore, two fiber optic data channels of approximately 35 dB each were used. With the addition of a range switch, it was possible to increase amplitude range of the sensor system. One fiber optic channel covers the range of signals of 0.5 millioersted to 50 millioersted; the other channel covers the range of 5.0 millioersted to 500 millioersted. The complete specifications of the model 100 magnetometer system are shown in Table I.

The magnetometer is powered by rechargeable nickel-cadmium batteries that provide 8 hours operating time between charging. It consists of four subsystems: the probe, the amplifier, the gallium arsenide optical link, and the photomultiplier receiver. A block diagram of the complete system is shown in Figure 1. Photographs of the model 100 are shown in Figures 2a and 2b.

#### 2. Probe

Initial experiments were performed with a probe consisting of a Hall-effect sensor measuring the low frequency portion of the H field and using the attendant stray lead inductance for sensing the higher frequency field components. Difficulty was experienced,

\* Unless otherwise designated, all magnetic field levels are rms.

TABLE I

MODEL 100 SPECIFICATIONS

Directionality	The instrument will measure a positive or negative magnetic field component. The positive magnetic field direction is indicated by an arrow on the sensor probe.
Sensitivity (millioersted, rms)	$\pm 0.5$
Dynamic Range (dB)	60
Range 1 (millioersted, rms)	$\pm 0.5$ to $\pm 50$
Range 2 (millioersted, rms)	$\pm 5.0$ to $\pm 500$
Low Frequency Response (Hz)	110
High Frequency Response (MHz)	6
Minimum Signal-to-Noise Ratio (dB)	15
Electric Field Isolation (dB below E/377 at $3 \times 10^3$ Volts/Meter)	>40
Power Source	Rechargeable batteries with greater than 8 hour operation per recharge. A.C. line, 60 Hz, 115V. Transformer isolated.
Sensor	
Receiver	
Operating Temperature Range (°F)	60 to 90
Storage Temperature Range (°F)	10 to 120
Humidity Range (%)	10 to 100
Altitude Range (ft)	Sea Level to 10,000

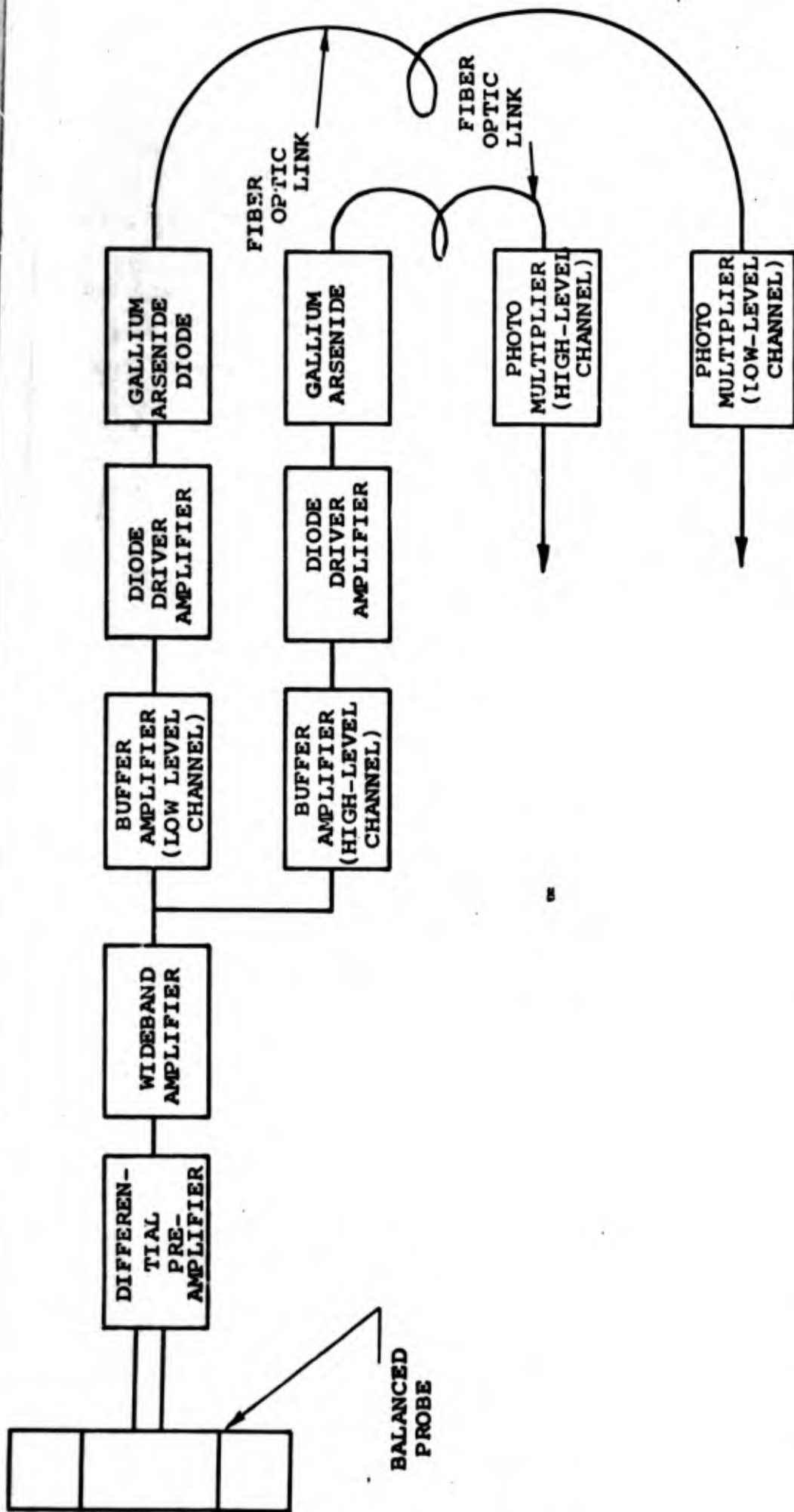


Fig. 1 BLOCK DIAGRAM OF "H" FIELD SENSING SYSTEM WITH FIBER OPTIC READ-OUT

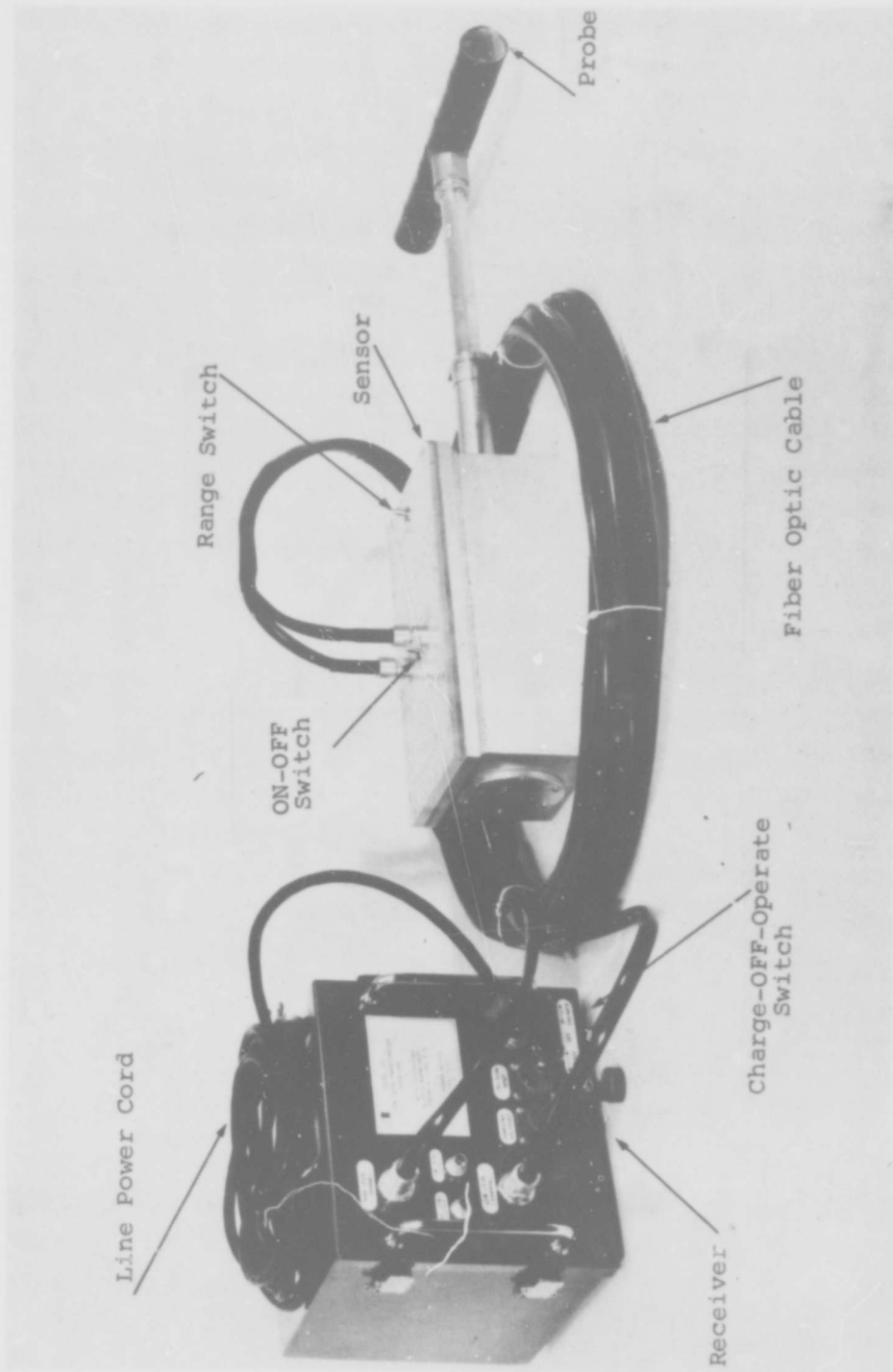


Fig. 2a PHOTO OF MODEL 100 WITH IDENTIFICATION OF PARTS

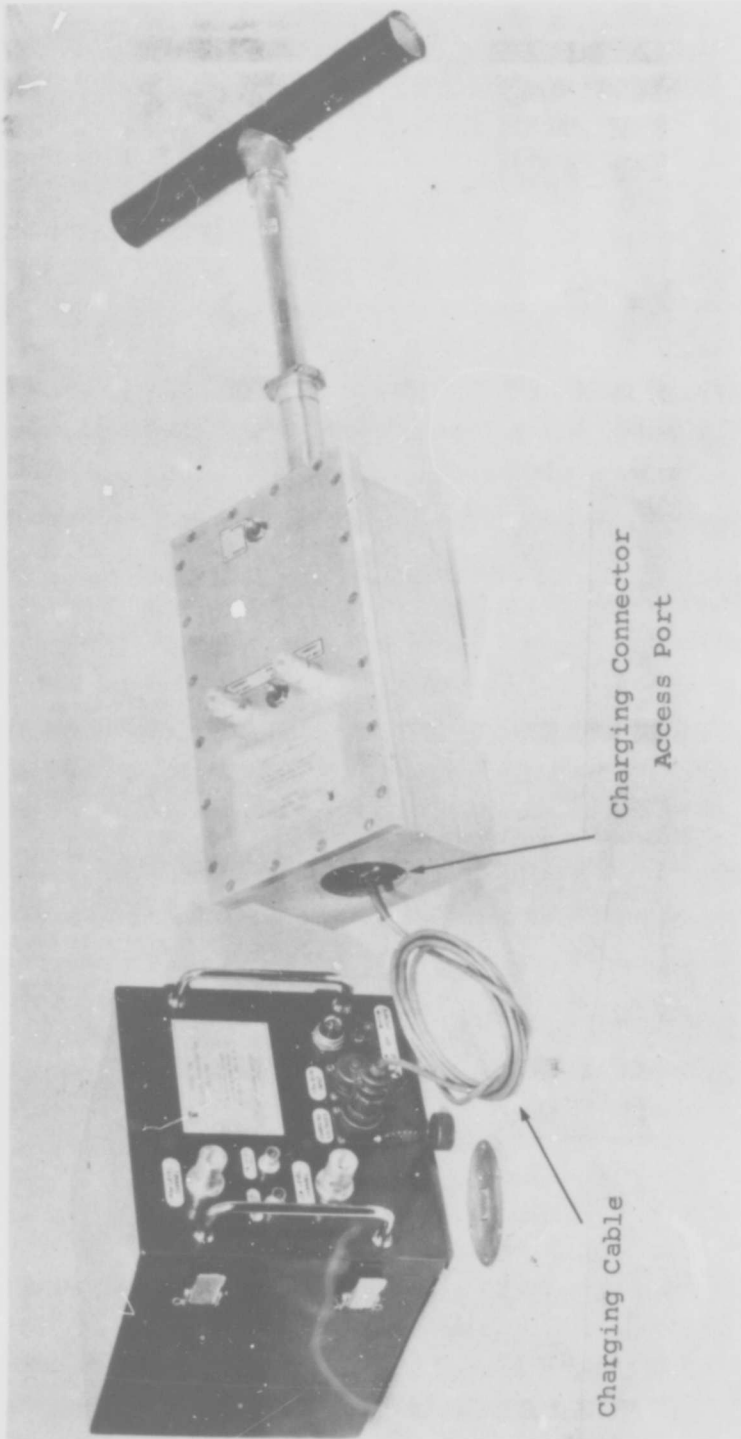


Fig. 2b PHOTO OF MODEL 100 (BATTERY CHARGING)

however, in obtaining a smooth cross-over frequency free from peaks and dips, and it was found that simple compensation networks in the probe or amplifier were not adequate for good transient response. Because of these difficulties, effort was expended in developing a probe that used a highly damped winding where the integration would be done by the winding inductance and load resistance. In this way, the current flowing through the load resistor would be proportional to the magnetic flux cutting the winding rather than the rate of change of flux. This principle is essentially the one used in conventional wide band current probes. It was found that by using a ferrite rod\* adequate frequency response and sensitivity could be achieved to meet the design specifications. A probe was constructed which employs a balanced output and a Faraday type shield for prevention of electric field pickup. The Faraday shield is a cylinder with a lengthwise slit dielectrically insulated to form a capacitor. The open ends are shielded by a two-sided copper-clad dielectric on which the copper is etched into finger-like strips with a common ground point soldered to the cylinder. The strips on one side of the dielectric are orthogonal to the strips on the opposite side. The inductance of the sensor winding is 8.8 mH. The total load resistance including the winding resistance is 5.6 ohms. This combination gives a low-frequency cut-off of about 100 Hz. The high-frequency output of the probe is flat to about 15 MHz where it rises about +10 dB because of resonance effects. Over the band of interest the output is flat to within +1 and -3 dB.

### 3. Amplifier

The amplifier for the system is composed of three sections: a preamplifier section, amplifier section, and buffer section. The preamplifier section is a differential amplifier that has at least 30 dB common mode rejection over the entire 5 MHz bandwidth. The main function of the differential amplifier is to convert the probe output from balanced to unbalanced where most of the gain can be obtained from a single-ended amplifier.

\* General Ceramics "H" type material

The amplifier section provides additional gain and also divides the signal into two channels. One channel has 20 dB greater gain than the other and serves as the low level channel for the 0.5 to 50 millioersted range. The lower gain channel is used for the 5 to 500 millioersted range.

The buffer section provides isolation between the two channels when the low-level channel is overloading while the higher fields are being measured.

#### 4. Optical Diode-Fiber Bundle Telemetry

The two channels of the amplifier section feed into drivers for two separate gallium arsenide optical diodes.\* They are biased and driven so that the maximum dynamic range is achieved from each channel. The frequency response of the diodes begins to drop at about 4 MHz, but compensation in the drivers keeps the response flat out to about 10 MHz. The overall 3 dB bandwidth of the amplifier-diode system is about 20 Hz to 8 MHz. The fiber optic bundles that transmit the diode light signal to the photo tubes are 1/8 inch in diameter. Except for the ends of the cables, the entire length of the two cables are encased in a single sheath of plastic tubing for convenience in handling.

#### 5. Receiver System

The receiver system consists of two photomultiplier tubes.\*\* These tubes convert the optical signal back to an electrical signal suitable for oscilloscope monitoring. Each is followed by an emitter-follower amplifier stage that provides a low-output impedance so that long coaxial cables may be used for oscilloscope monitoring without degrading the high-frequency response.

#### 6. Conclusions

The model 100 Low-Level Magnetometer is a sensitive, moderately broadband, 2-channel magnetometer specifically designed for measuring the magnetic field component of a propagating

\* Texas Instruments Type TIXL-03

\*\* RCA Type 7102

electromagnetic plane wave. It can operate satisfactorily in the presence of the electric field environment of such a plane wave. It is designed for minimum field perturbation through the use of optical signal transmission.

The magnetometer will measure equally well time-periodic magnetic fields that are in the specified range (100 Hz to 5 MHz).

The model 100 is composed of two units; a sensor unit and a receiver unit. The time history of the magnetic field is displayed on an oscilloscope connected to the receiver unit (the oscilloscope should have sufficient bandwidth and a sensitivity range of 10 mV/div). The receiver is connected to the sensor by a nonmetallic glass fiber optic cable. The purpose of the dielectric cable is to eliminate the field-perturbation effects of a conducting cable.

The receiver contains a battery charger, and an auxiliary cable is provided to connect the receiver to the sensor for charging.

The results of all testing programs (see Section V and VI) indicate that, as shown in Table I, the model 100 meets or exceeds all specifications originally set forth and provides a unique combination of sensitivity and bandwidth in a magnetic field measuring instrument.

## SECTION III

### MODEL 200 BROADBAND MAGNETOMETER

#### 1. Introduction

The primary purpose of developing the model 200 magnetometer was to achieve extremely wide bandwidth for measuring fast rising pulsed magnetic fields. This requirement was coupled with the need for a large dynamic range, good sensor isolation, and good sensitivity. The objective was 50 MHz minimum upper frequency response. The range of field measurement was 0.1 to 100 oersted. With the exception that the sensitivity and low frequency response are slightly higher than desired, all original specifications were met. The specifications of the instrument are shown in Table II. The bandwidth limitation lies somewhat in the state-of-the-art of amplifiers rather than in the basic system concept. The probe bandwidth is known to be 100 MHz but the differential amplifier in the receiver is also only 100 MHz wide. Thus, considering only these two parts of the system, the bandwidth could not exceed 70 MHz. In addition, some bandwidth limitation is expected from the microwave detectors.

The discussion that follows will show that the use of a microwave carrier offers great potential for wide bandwidth. The limitations imposed on the model 200 are those of presently available commercial components. A block diagram of the basic system is shown in Figure 3 and a photograph is shown in Figure 4.

#### 2. Probe Sensor

The field probe is a ferrite-loaded many-turn coil that is identical to that used in the model 100. Higher frequency response is achieved by increasing the load resistance of the probe to 50 ohms. The measured magnetic field is introduced as frequency modulation on a microwave carrier in the following manner. The carrier signal source is a YIG-tuned transistor oscillator in which the frequency of oscillation is magnetically tunable in accordance with the electron spin resonance (ESR) frequency of a YIG sphere, which is

TABLE II

MODEL 200 SPECIFICATIONS

Directionality	The instrument will measure a positive or negative magnetic field component. The positive magnetic field direction is indicated by an arrow on the sensor probe.
Sensitivity (oersted, rms)	$\pm 0.20$
Dynamic Range (dB)	54
Range 1 (oersted, rms)	$\pm 0.2$ to $\pm 10$
Range 2 (oersted, rms)	$\pm 2.0$ to $\pm 100$
Low-Frequency Response (Hz)	1600
High-Frequency Response (MHz)	65
Minimum Signal-to-Noise Ratio (dB)	15
Electric Field Isolation (dB below E/377 at $10^5$ Volts/meter)	>40
Power Source	
Sensor	Replaceable long-life batteries. A.C. line, 60 Hz, 110V, transformer isolated.
Receiver	
Operating Temperature Range (°F)	60 to 90
Storage Temperature Range (°F)	10 to 120
Humidity Range (%)	10 to 100
Altitude Range (ft)	Sea Level to 10,000

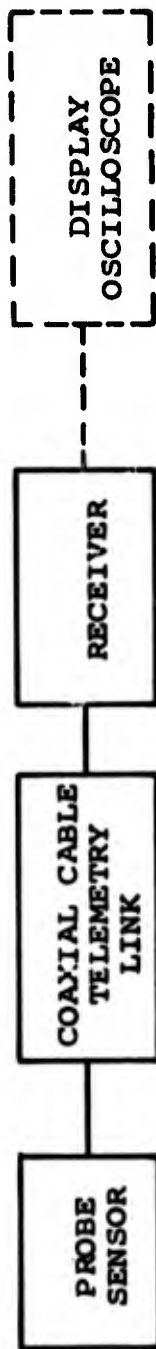


Fig. 3 MODEL 200 BROADBAND MAGNETOMETER

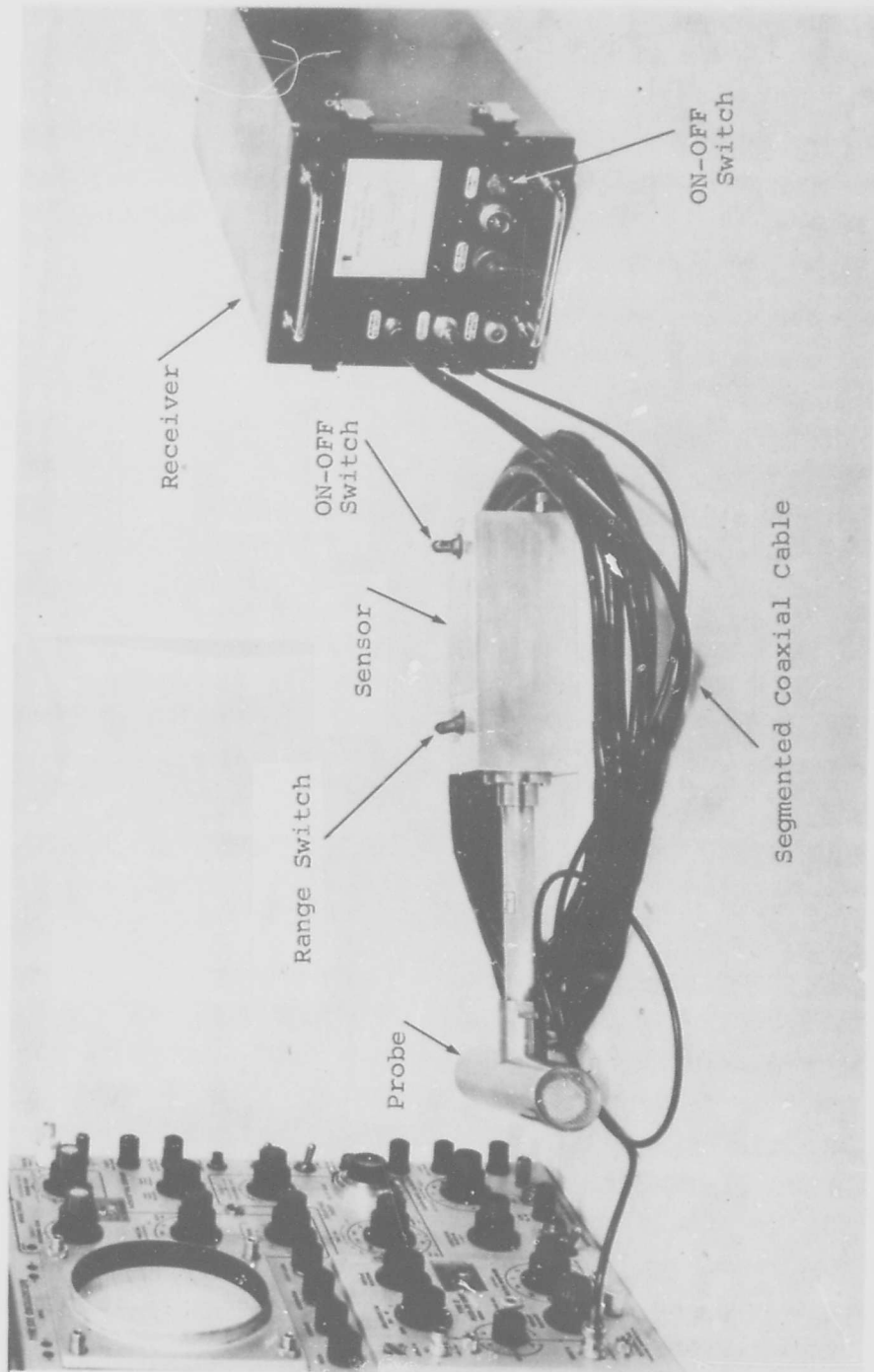


Fig. 4 PHOTO OF MODEL 200 WITH IDENTIFICATION OF PARTS

the resonant circuit for the oscillator. A bias magnet sets the frequency of oscillation at 1.5 GHz. The pulsed magnetic field to be measured is reinduced in the YIG sphere by a miniature Helmholtz coil. The YIG sphere is at the center of the uniform region of the Helmholtz pair. A switch and resistive divider network provide a 20 dB range switch in the line from the probe. An isolator is also provided in the probe sensor box to provide uniform loading characteristics for the transistor oscillator. The complete block diagram for the probe sensor is shown in Figure 5.

A point of particular interest is that the change in the frequency of oscillation  $\Delta f$  is related by a constant to the change in the magnetic field sensed by the probe

$$\Delta f = \gamma \Delta H$$

where  $\gamma$  is a constant equal to 2.8 MHz/oersted. Thus, the system has an invariant calibration factor and only changes in the gain of the output or oscilloscope amplifiers can cause a change in the system calibration.

### 3. Coaxial Cable Telemetry

A 40-ft length of coaxial cable is used to transmit the frequency modulated carrier to a receiver. In order to prevent conduction of currents induced on the cable by the fields under measurement, the entire length of a 10-ft section of this cable has been formed into a bandpass filter structure. The latter consists of three lengths of cable separated by isolators. This results in a segmented cable that inhibits current flow along the cable conductors at frequencies below one GHz. The remaining 30-ft cable section has a continuous inner coaxial conductor and a segmented filter structure on the outer coaxial conductor. Because of the continuous inner coaxial conductor, this cable length will not be as effective in preventing field perturbation at lower frequencies as the 10-ft cable section. Thus, it should be oriented in a direction of low electric field whenever possible.

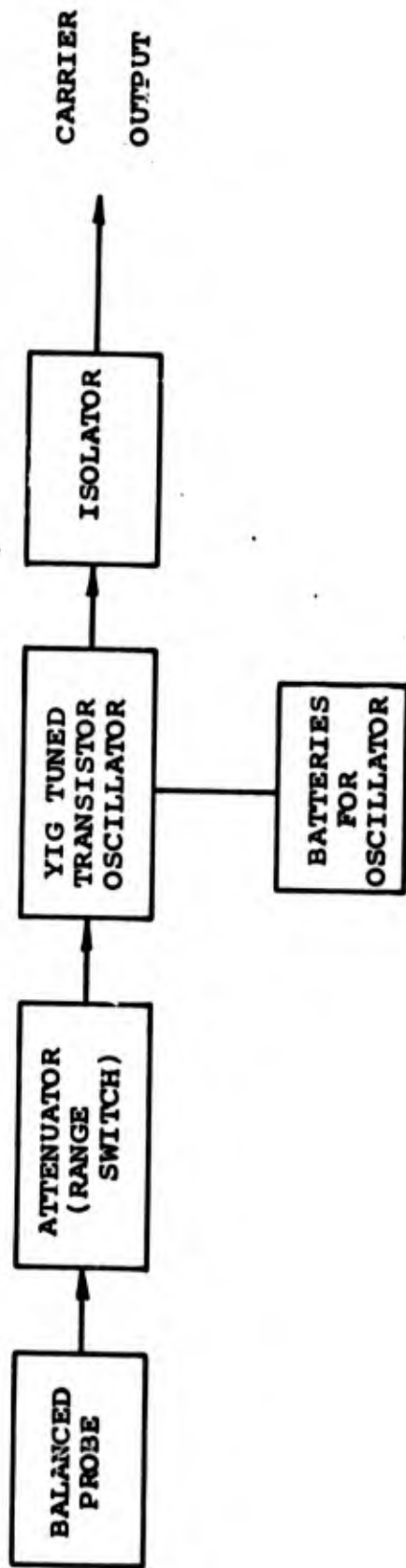


Fig. 5 BLOCK DIAGRAM OF THE MODEL 200 PROBE SENSOR

#### 4. Receiver

A block diagram of the receiver is shown in Figure 6. The purpose of the receiver is to amplify, filter, and limit the carrier; remove the frequency modulation from the carrier; and amplify the pulsed magnetic field information signal. The microwave band-pass filter removes any spurious low-frequency signal that may have coupled into the coaxial cable from the magnetic or electric field environment. The Traveling Wave Tube (TWT) amplifier not only provides gain for the carrier but, because it is operated in a saturation mode, it provides amplitude limiting as well. Approximately 10 dB of amplitude limiting is achieved over the 1.4 to 1.6 GHz operating bandwidth of the system. The attenuator is used to set the power level of the carrier into the TWT amplifier in order to operate in the optimal limiting portion of the gain characteristic. The directional coupler provides a monitor point for setting the power level into the TWT amplifier.

The discriminator is an original IITRI device developed during the course of this program. It uses two 3 dB directional couplers connected by line lengths that are not equal. If the phase length difference ( $\phi$ ) of the two lines is given by

$$\phi = (2n + 1)\frac{\pi}{2} \frac{f}{f_0}, \quad (n = 0, 1, \dots)$$

then the discriminator characteristic is given by

$$V_0 = |V(j\omega)| \{ |\cos(\phi/2)| - |\sin(\phi/2)| \}$$

where

$V_0$  = discriminator output voltage

$|V(j\omega)|$  = magnitude of the input voltage

$f_0$  = center frequency of operation.

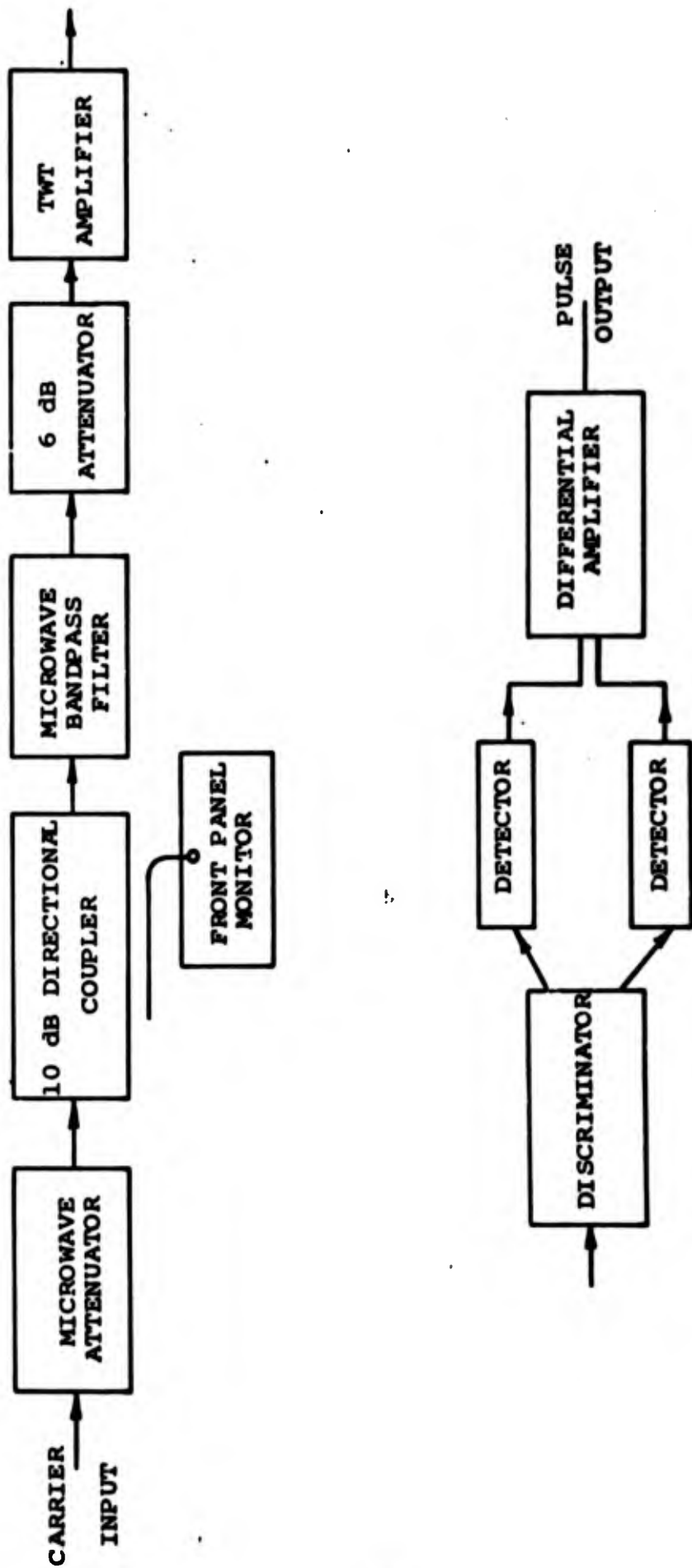


Fig. 6 BLOCK DIAGRAM OF THE MODEL 200 RECEIVER

The above characteristic assumes that linear voltage detectors are used at the output of the discriminator to remove the microwave carrier. When driven rather hard (greater than 3 mw), most microwave square-law detectors do become linear.

A computer plot of this equation for several values of  $n$  and a normalized center frequency of  $f_0 = 1.0$  is shown in Figure 7. Experimental verification for these results has been obtained for the discriminator used in the model 200. The crossover frequency in the model 200 discriminator is about 1.515 GHz and a value of  $n = 6$  was used, which gives maximum sensitivity consistent with the 200 MHz bandwidth requirements.\*

The discriminator characteristic requires that the detector outputs be subtracted from each other. Thus, a broadband differential amplifier was used. The output of this amplifier goes directly to an oscilloscope. The amplifier used has 100 MHz bandwidth and provides 10 dB gain. It is a relatively new instrument and represents the state-of-the-art in commercially available differential amplifiers.\*\*

The primary bandwidth limiting components in the receiver are the differential amplifier and the detectors. The discriminator is capable of much broader bandwidth operation. Thus, assuming that the magnetic field probe bandwidth could be increased, the entire system could be made broader if the detectors and differential amplifiers had greater bandwidth. The state-of-the-art could be advanced on these components, and a magnetometer system exceeding 100 MHz and possibly 200 MHz (with less sensitivity, of course) should be achievable.

\* The use of an attenuator means that for a field of 100 Oersted only 10 Oersted is coupled into the YIG sphere. A study showed that for the resulting frequency variation of 28 MHz an information bandwidth of 100 MHz would be adequate for signals up to 100 MHz. Because the field can be either positive or negative, a total information bandwidth of 200 MHz is required.

\*\* Tektronix Model #P6406

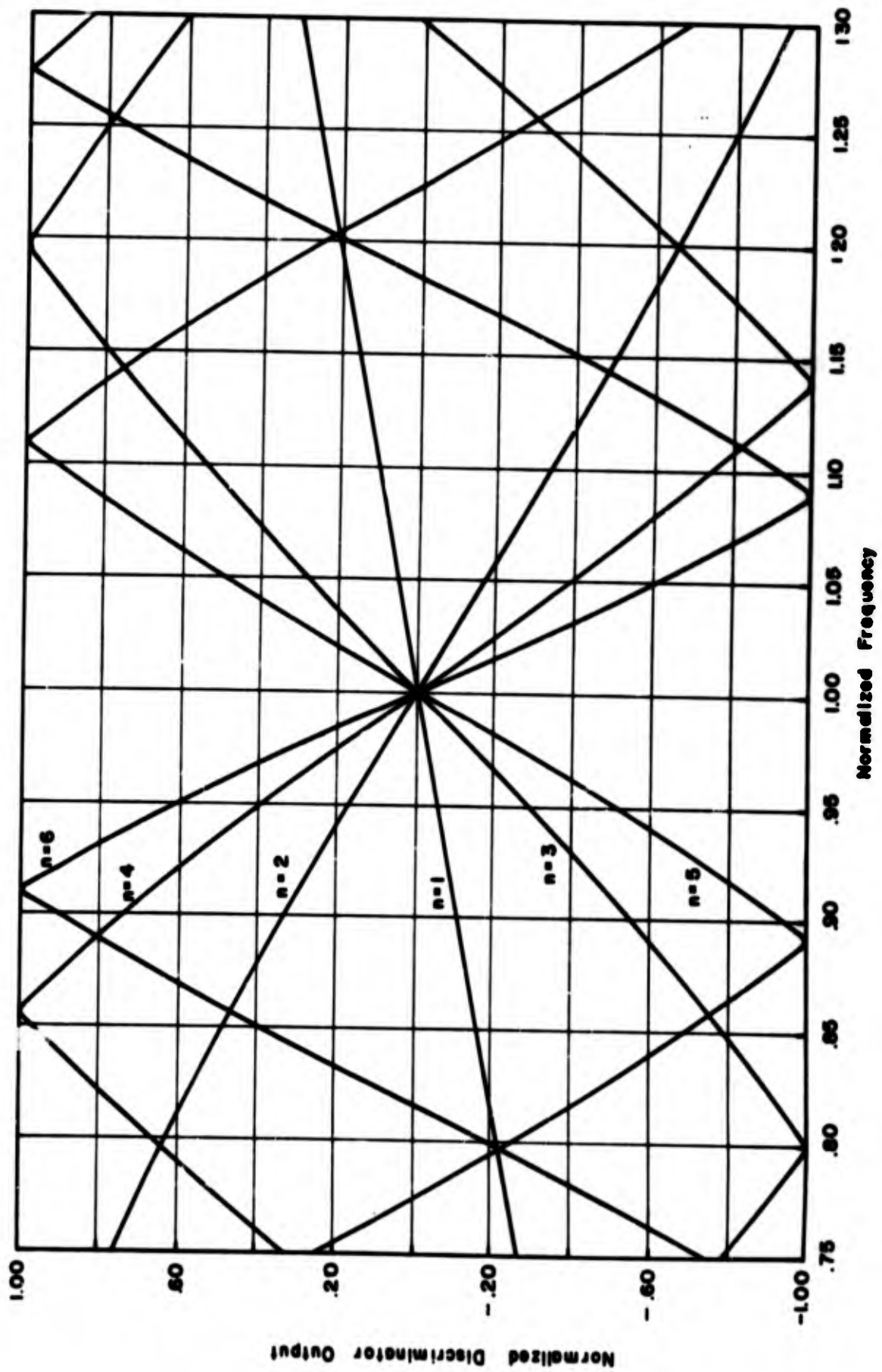


Fig. 7 Normalized Discriminator Characteristics

## 5. Conclusions

The model 200 Broadband Magnetometer is a moderately sensitive, broadband, two-channel magnetometer specifically designed for measuring the magnetic field component of a propagating electromagnetic plane wave. It can operate satisfactorily in the presence of the electric field environment of such a plane wave. It is designed for minimum field perturbation through the use of a segmented coaxial cable connecting the sensor to the receiver.

The magnetometer will measure equally well time-periodic magnetic fields that are in the specified frequency range (1000 Hz to 50 MHz).

The model 200 is composed of two units; a sensor unit and a receiver unit. The time history of the magnetic field is displayed on an oscilloscope connected to the receiver unit (the oscilloscope should have sufficient bandwidth and a sensitivity range of 10 mV/div). The receiver is connected to the sensor by a segmented coaxial cable that is actually a bandpass filter structure. The cable is an open circuit to all frequency outside of the range 1.4 to 1.6 GHz. Thus, this cable will not perturb fields with CW or pulse frequency components under one GHz. The output of the magnetic field probe is used to frequency modulate a YIG-tuned transistor oscillator operating at 1.5 GHz. The frequency modulated carrier is converted, in the receiver, to an amplitude modulated carrier by a discriminator. The carrier modulation is then detected and amplified for display on the oscilloscope.

The system is presently bandwidth limited by the detectors and differential amplifier in the receiver. With an improved differential amplifier and detectors and some sacrifice in sensitivity, it is believed that the overall system bandwidth of the model 200 could be made to exceed 100 and possibly 200 MHz.

## SECTION IV

### SIMULATOR INSTRUMENTATION

#### 1. IITRI Facilities

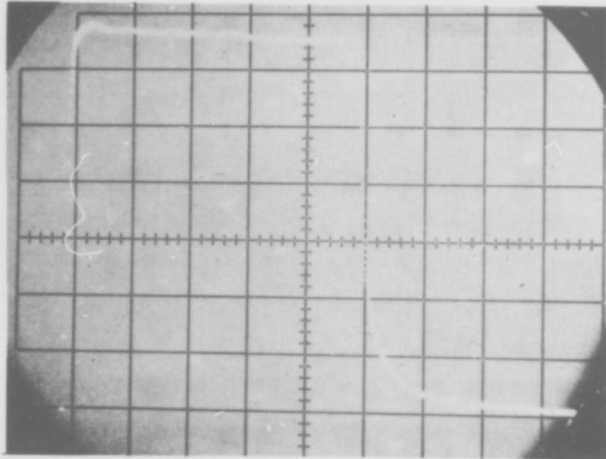
##### a. Pulsed Transmission Line

In order to test the high-frequency response of the Model 200 Broadband Magnetometer it was necessary to establish a transmission line test chamber in which a fast-rising pulsed field was available. The test line is a Transverse Electromagnetic (TEM) line with flat ground planes and center strip (commonly referred to as "triplate" construction). The characteristic impedance is 50 ohms and the ground plane to center strip spacing is 6 inches. The voltage developed between conductors is 2500 volts. The electric field is, therefore,  $1.67 \times 10^4$  V/m and the corresponding field is 44.3 A/m or 0.555 oersted (the units oersted and gauss are frequently interchanged because B and H are numerically equal in cgs units). The length of the test pulse is 1500 ns. The risetime achieved is about one nanosecond and the faltime is 25 ns to the 30 percent level and 125 ns to the 10 percent level. This type of response is achieved by charging a 500-ft coaxial, 50-ohm transmission line to 5000 volts. The discharge of the line is controlled by a mercury-wetted reed switch that is vibrated at 60 Hz.

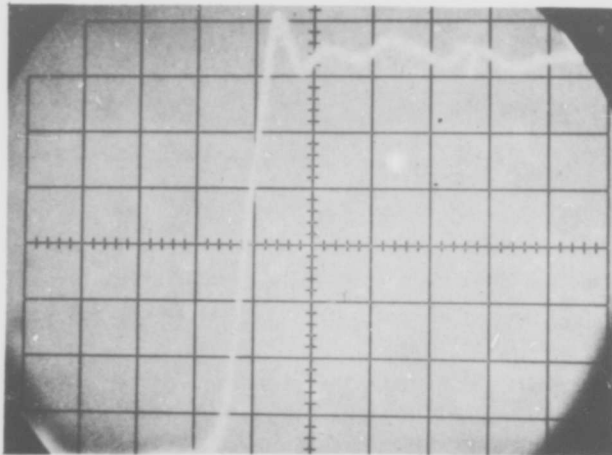
The actual waveform of the voltage on the transmission line is shown in Figure 8. Only a small amount of overshoot and ringing are present in the waveform. The line is terminated in a high-power, 50-ohm load to prevent voltage breakdown and assure that no reflected wave is present on the line.

##### b. Electric Field Instrumentation

A high-level, high-frequency electric field simulator has been developed. This is a single-frequency system in which a parallel plate capacitor forms part of a resonant circuit excited by a 1000-watt transmitter. The operating frequency is



a. Vert: 400 v/cm  
Horiz: 250 ns/cm



b. Vert: 400 v/cm  
Horiz: 1 ns/cm

Fig. 8 Voltage waveform of the 0.5 oersted plane wave simulator used for testing the magnetometer systems

about 3 MHz and voltages to 10,000 volts are developed across two large plates. For a nominal spacing of 10 cm, fields to  $10^5$  V/m can be developed. Thus, this facility has the capability of testing to limits required by the present program.

c. Helmholtz Magnetic Field Calibration

Low-level, low-frequency field calibration can be performed in this facility. The uniform field area is sufficiently large for the entire sensor assembly of either magnetometer. The facility can be operated up to frequencies of 1000 Hz and at field levels up to one oersted.

2. Government Furnished Facilities

a. Helmholtz Coil

The Helmholtz coil is 2 meters in diameter with a separation of 1 meter. The pulsed field capability is 100 oersted. The CW frequency range is 500 Hz to 1 MHz at levels up to 100 mOe.

b. Parallel Plate Capacitor

Fields to  $10^5$  V/m can be generated on a pulsed basis. Fields to 200 V/m can be generated on a CW basis. The frequency range is 500 Hz to 10 MHz. The plates are 2 meters in diameter and separated by one meter.

c. ALECS Facility

This facility is a large volume transmission line with a uniform field region 50-ft long, 75-ft wide, and 45-ft high. A pulsed field is generated up to  $10^5$  V/m with a risetime of 5 to 8 nanoseconds and several hundred nanoseconds pulse duration.

d. Vertical Pulsed Transmission Line\*

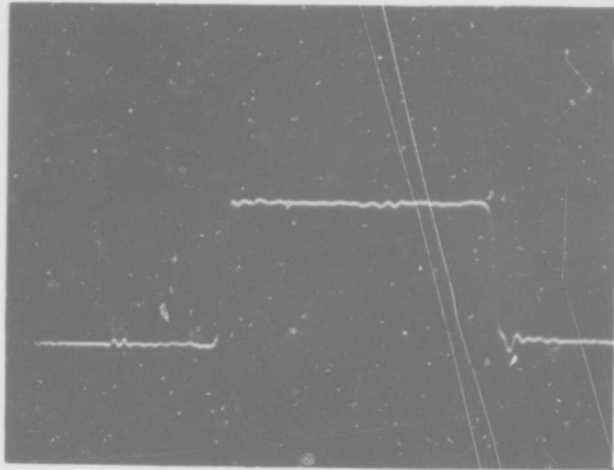
The guiding structures of this facility are vertical from the ground. The guiding wires form a diamond that has maximum dimensions of 20-ft by 20-ft at the center. A repetitive

\* Available through AFSWC contract with EG&G.

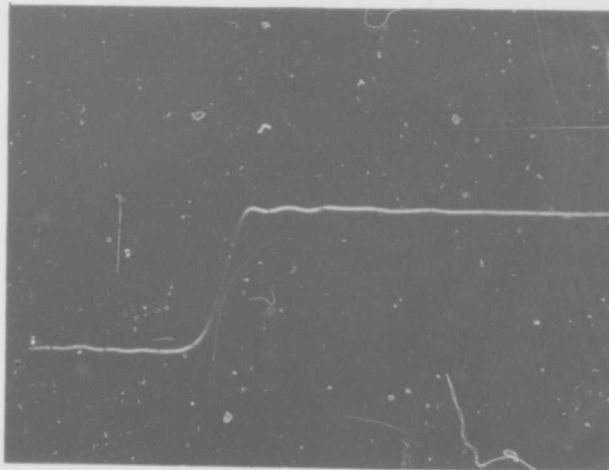
voltage of 280 volts is applied to the line. The waveforms of Figure 9 show the risetime to be approximately 3 nanoseconds.

3. Conclusions

The IITRI facilities described above were sufficient for preliminary contractor testing of feasibility and prototype magnetic field instrumentation. For complete instrumentation evaluation a high-level pulsed plane wave was available at AFSWC. The combination of IITRI and Air Force facilities has permitted rather extensive evaluation of system capability for both magnetometer systems.



a. Vert: 100 V/cm  
Horiz: 20 ns/cm



b. Vert: 100 V/cm  
Horiz: 5 ns/cm

Fig. 9 Voltage Waveform of the Vertical Pulsed Transmission Line Facility

## SECTION V

### RESULTS OF CONTRACTORS TESTS

#### 1. Introduction

Tests were conducted at the facilities of IIT Research Institute to demonstrate that the instrumentation was capable of meeting the required specifications. During these tests, certain deficiencies were noted and were subsequently corrected prior to the final acceptance tests. The specifications shown earlier in Tables I and II indicate the capability of the instruments at the time of the final acceptance tests. The contractor's test results are described below.

#### 2. Model 100 Low-Level Magnetometer

##### a. Calibration and Bandwidth Tests

The basic source of calibration was the Helmholtz coil. This calibration at 300 Hz was transferred to a small diameter 20-turn test coil that could be placed around the sensor probe and used in the frequency range from 100 Hz to 50 KHz. An rms current meter was used to maintain constant magnetic field in the test coil. The low-frequency response of the model 100 was measured with the 20-turn test coil and is shown in Figure 10. The 3 dB lower cutoff frequency is about 110 Hz, which compares favorably with the 100 Hz specification for this instrument.

Midband calibration factors were noted but are not given here since both instruments were given a final calibration prior to the final acceptance tests and these calibration factors are given in Section VI.

A low-inductance, 2-turn coil was calibrated and used as a test coil for measuring the high-frequency response of the model 100, which is shown in Figure 11. At the time of the contractor's tests, the high-frequency response of the model 100 had not been compensated. Therefore, the bandwidth was only 1.8 MHz. Subsequently, the bandwidth was increased to 6 MHz (see Section VI).

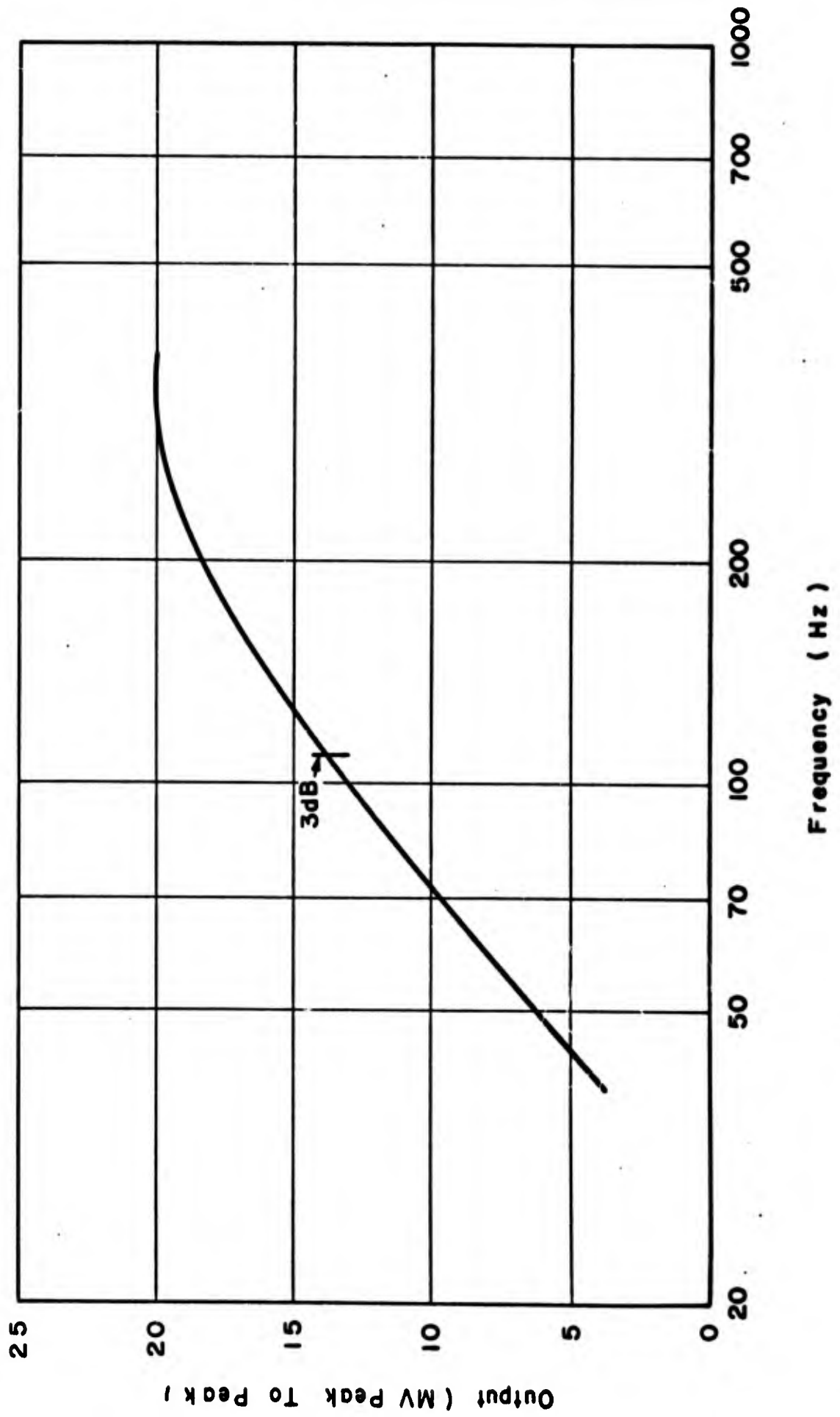
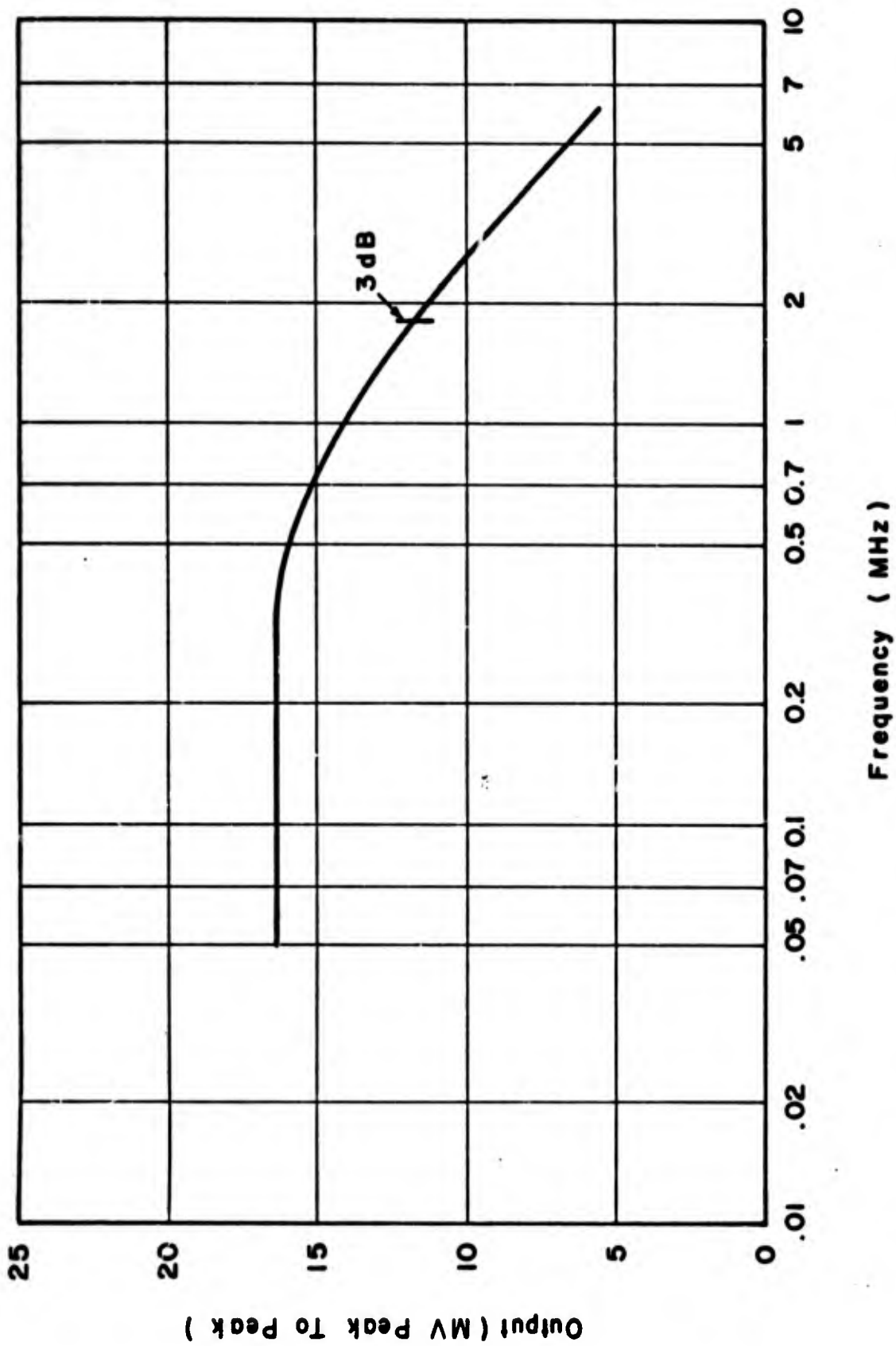


Fig. 10 LOW — FREQUENCY — RESPONSE MODEL 100 MAGNETOMETER



**Fig. II HIGH - FREQUENCY - RESPONSE MODEL 100 MAGNETOMETER  
( Prior to Compensation )**

b. Pulse Tests

The model 100 magnetometer probe was inserted in the IITRI pulsed transmission line in order to evaluate pulse reproduction characteristics of the system. Oscilloscope traces of the pulse response are shown in Figure 12. A risetime close to 200 nano-seconds is observed, which corresponds to a frequency response of

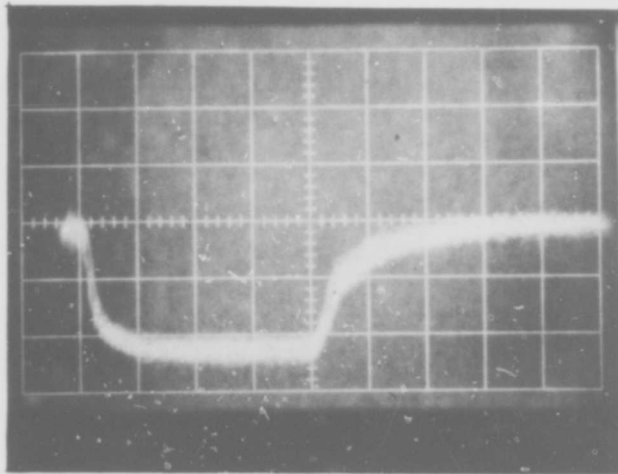
$$f_{co} = \frac{.35}{200} \times 10^9 \text{ Hz}$$
$$= 1.75 \times 10^6 \text{ Hz}$$

which is in close agreement with the measured frequency response of 1.8 MHz.

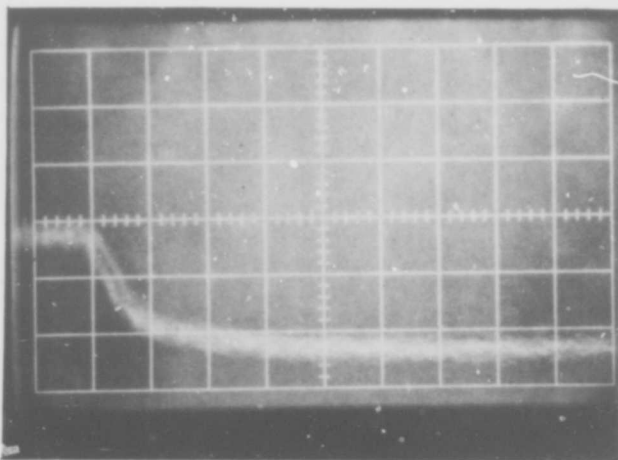
One of the deficiencies of the system was noted when the probe was inverted in the test line. Figure 13 shows the pulse response with the polarity of the probe reversed. A greater amplitude was observed even though the risetime was similar. The system was operating on range H2 at the time, and it was determined that the input stage of the amplifier was saturating. At the time the attenuator was located after the input stage. Subsequently, the attenuator was shifted ahead of the input stage and the difficulty was alleviated.

c. Electric Field Isolation Tests

The capacitor plates in the IITRI electric field test facility are 2-ft square. The probe was placed at the center of the horizontal plates in a vertical direction so as to be most susceptible to electric field. The range selected was H1, which has a calibration factor of 6.0 mV peak to peak for 5 millioersted of magnetic field. The electric field level was 5.3 KV/m, which, for a plane wave, corresponds to 176 millioersted. A signal output of 1 mV peak to peak was noted. It will be assumed that this signal was caused by electric field. However, it is difficult to ascertain whether or not the output may actually

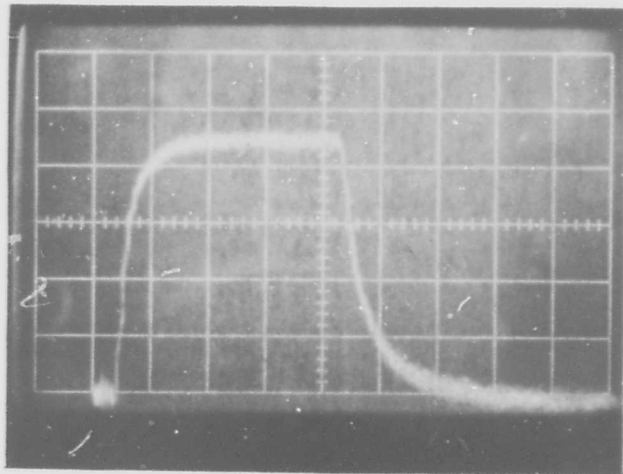


a.     Vert: 5 MV/cm  
       Horiz: 200 ns/cm



b.     Vert: 5 MV/cm  
       Horiz: 50 ns/cm

**Fig. 12**     Pulse Response of the Model 100 Magnetometer  
                  Prior to Compensation of the Upper Frequency  
                  Response



Vert: 5MV/cm  
Horiz: 200 ns/cm

Fig. 13 Pulse Response of the Model 100 With the Probe Direction Reversed from that of the Tests Shown in Fig. 12

have been caused by magnetic field. The probe causes some perturbation of the field, and since the plate area was not too large, a small component of magnetic field may have been induced along the probe direction.

According to the calibration, then, the magnetic field corresponding to 1 mV peak to peak is 0.83 millioersted. The ratio of the signal that would have been induced by a plane wave with intensity equal to the test field to the spurious signal caused by the electric field is

$$\text{Ratio} = \frac{176 \text{ mOe}}{0.83 \text{ mOe}} = 212$$
$$= 47 \text{ dB.}$$

The ratio required in program specifications is 40 dB.

### 3. Model 200 Broadband Magnetometer

#### a. Calibration and Bandwidth Tests

The calibrated 20-turn coil described in paragraph 2a was also used for calibration and measurement of the low frequency response of the model 200 magnetometer. By using an rms current meter to maintain constant current in the coil, the response of the system from 0.7 to 20 kHz was measured. The result is shown in Figure 14 in which a 3 dB cutoff frequency of 1.6 kHz is indicated. This is somewhat higher than the 1.0 kHz program specification. However, this lower cutoff frequency is determined by the probe, and it was decided not to make any modification to the probe which would likely lower the upper cutoff frequency because the latter was the more important of the two cutoff frequencies. In light of the intended usage of these systems, the 1.6 kHz lower bandwidth limit was considered completely adequate.

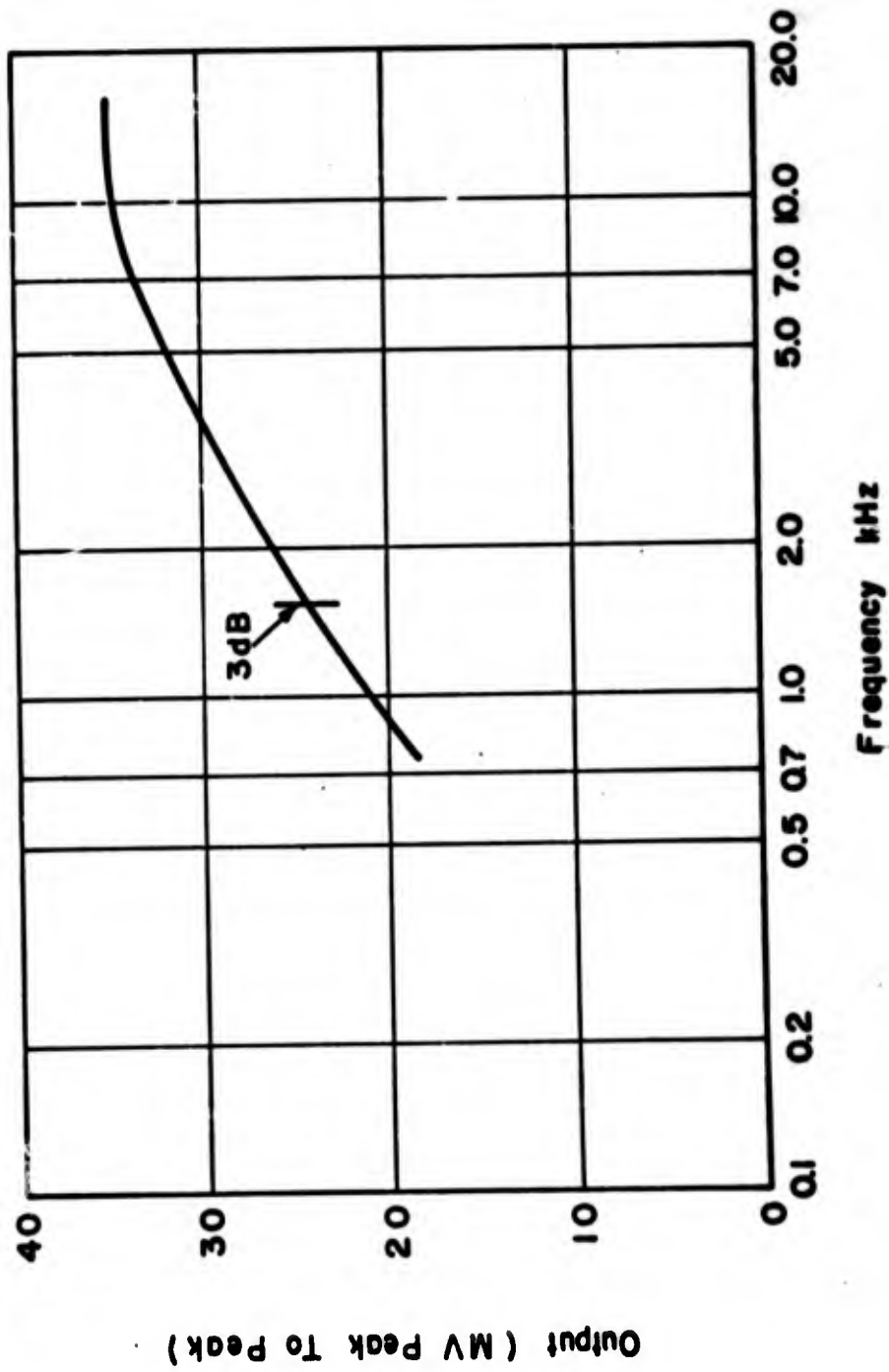


Fig. 14 LOW - FREQUENCY - RESPONSE MODEL 200 MAGNETOMETER

The high-frequency response of the model 200 magnetometer system was obtained by removing the probe and inducing a driving current directly into the small Helmholtz coils around the YIG sphere. This was done because of the difficulty in maintaining uniform characteristics in a driving coil used with the probe at high frequencies. The probe had been tested previously and found to have a bandwidth of 100 MHz or more and so was not considered a limiting factor in the system response. The driving current for the small Helmholtz coils was held constant by monitoring with a broadband current probe. The measured CW high-frequency response of the model 200 magnetometer is shown in Figure 15. At the time of these measurements, 93-ohm terminations were used on the output of the detectors. These were subsequently lowered to 50-ohms with some bandwidth increase resulting (see Section VI). The upper 3 dB cutoff frequency was found to be about 49 MHz, comparing favorably with the 50 MHz specification.

The calibration factor for the model 100 on the low range is 10 mV peak to peak for 0.1 oersted. The noise level on low range was 4 mV peak to peak. Thus, the signal to noise ratio (S/N) at 0.2 oersted is

$$\begin{aligned} S/N &= \frac{20}{4} = 5 \\ &= 14 \text{ dB.} \end{aligned}$$

The specified minimum S/N is 15 dB. Thus, the specification is met at a field level of 0.2 oersted rather than 0.1 oersted.

b. Pulse Tests

The probe of the model 200 sensor was placed in the IITRI pulsed transmission line. The output waveforms are shown in Figure 16. The risetime is approximately 7 to 8 nanoseconds which is consistent with the measured bandwidth of 49 MHz.

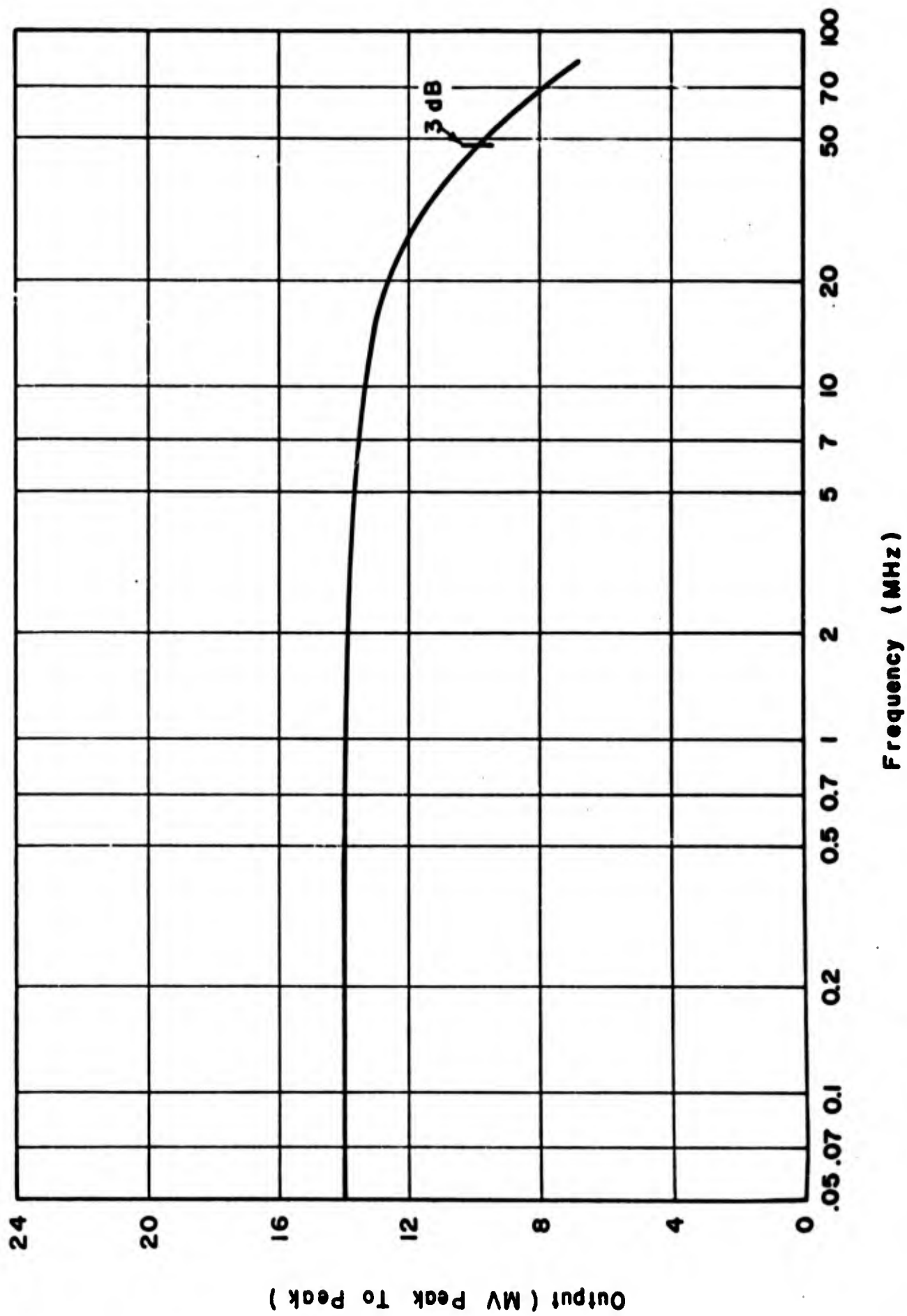
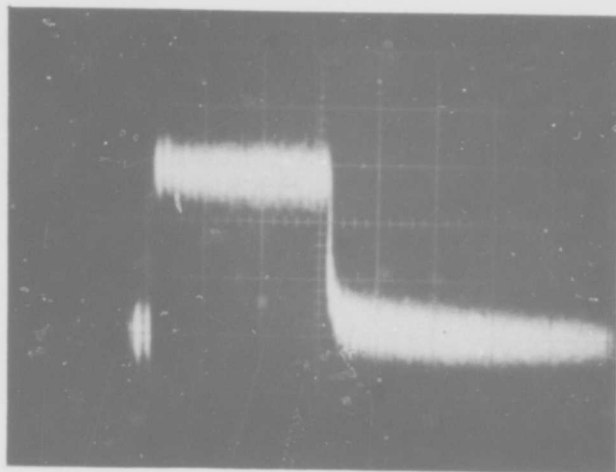
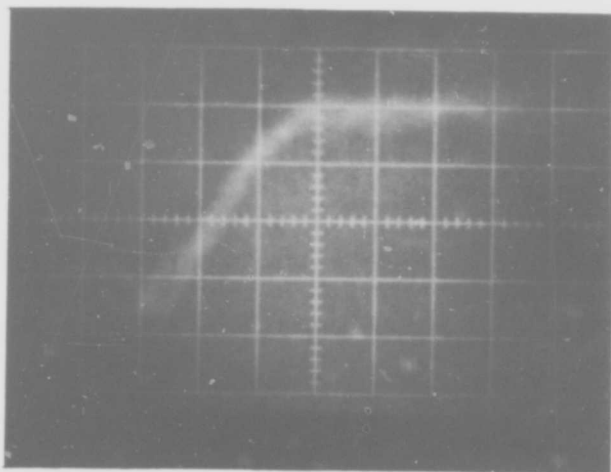


Fig. 15 HIGH - FREQUENCY - RESPONSE - MODEL 200 MAGNETOMETER



a. Vert: 10 MV/cm  
Horiz: 500 ns/cm



b. Vert: 10 MV/cm  
Horiz: 5 ns/cm

Fig. 16 Pulse Response of the Model 200 Magnetometer

Some comment is in order at this point about the use of the filter cable. The system receiver was inside a screen room. The arm that supports the probe must necessarily be aligned with the electric field. This causes currents to flow along the sensor and cables. Experiments showed that spurious waveforms were produced at the output when a continuous cable was connected directly from the sensor to the receiver. This was caused by direct coupling from the cable shield into the receiver or oscilloscope. Two techniques both of which successfully suppressed the spurious signal, were employed. If the continuous cable was grounded to the screen room through a feed through, then the currents flowed onto the screen room and no spurious pulse was observed. Alternately, the spurious signal was removed by using the filter cable structure between the sensor and receiver when the cable was not grounded to the screen room. In this test, the filter cable itself was not exposed to the electric field environment.

Later measurements, performed in a high field environment (see Section VI), indicate that the filter cable does make the system more vulnerable to electric field influence. The use of the filter cable to isolate the sensor is considered in more detail in Section VI.

c. Electric Field Isolation Tests

The model 200 probe and sensor were inserted between the plates of the IITRI electric field simulator so that the probe was aligned with the electric field and centered on the plates. When the filter cable was used, there was no signal due to direct coupling along the cable shield into the receiver or oscilloscope. The spurious signal due to electric field was 2 mV peak to peak on the low range. The calibration factor is 10 mV peak to peak for 0.1 oersted on this range. The field level, considering again a plane wave, corresponds to 0.176 oersted. The spurious signal output corresponds to 0.02 oersted. The ratio of the signal that would have been

induced by a plane wave with intensity equal to the test field to the spurious signal caused by the electric field is

$$\text{Ratio} = \frac{0.176}{0.02} = 8.8$$

$$= 19 \text{ dB.}$$

This is considerably short of the 40 dB required by program specifications. This is one of the important deficiencies detected by the contractor tests which was remedied prior to the final acceptance tests. The additional isolation from electric field was obtained by inserting an additional grid shield on each end of the tubular Faraday shield around the probe. The electric field isolation subsequently achieved is reported in Section VI.

#### 4. Conclusions

Contractor tests were conducted on both magnetometer systems to the limits of the facilities available at IIT Research Institute. The following deficiencies were noted:

1. The model 100 saturated at approximately 100 millioersted on range H2.
2. The upper cutoff frequency of the model 100 was about 3 MHz less than the 5 MHz specification.
3. The sensitivity of the model 200 (defined by a 15 dB S/N ratio) was about 0.2 oersted instead of 0.1 oersted.
4. The electric field isolation of the model 200 was 19 dB rather than the required 40 dB.

Item 1 was subsequently corrected by placing the range switch attenuator ahead of the input amplifier stage. Range H2 now covers the full range from 50 to 500 oersted. Compensation was added to the model 100 in order to provide an upper 3 dB cutoff frequency of 6 MHz, thus satisfying program specifications.

No attempt was made to increase the sensitivity of the model 200 because this could only be achieved at the expense of bandwidth (by doubling the number of turns on the Helmholtz coils around the YIG sphere). Maintaining bandwidth was considered a more important requirement than achieving an additional 6 dB in sensitivity. Improvement of the electric field isolation to satisfy program requirements was achieved as described in Section 3 above and the results are reported in Section VI.

SECTION VI  
RESULTS OF FINAL ACCEPTANCE TESTS

1. Introduction

The government furnished facilities described in Section IV, all located at or near Kirtland Air Force Base, New Mexico, were used in conducting the final acceptance tests.

Environmental tests were subsequently conducted, and both systems were considered satisfactory as regards the following specifications:

Operating Temperature Range	60 to 90° F
Storage Temperature Range	10 to 120°F
Humidity Range	10 to 100%
Altitude	Sea Level to 10,000 ft
Shock	Normal Handling

The test results presented in the following subsections substantiate that, with only very minor exception, both magnetometers satisfy the original program specifications. In some instances the original specifications have been exceeded.

2. Model 100 Low-Level Magnetometer

a. Calibration and Bandwidth

The model 100 magnetometer was given a final calibration prior to the final acceptance tests. The midband calibration factors for all four ranges are shown in Table III as measured at IITRI. Throughout all of the final acceptance tests, excellent agreement (within normal reading errors and well within the  $\pm 10\%$  program requirement) between IITRI and AFSWC calibration was achieved. These results will be reported as the various tests are described below.

One of the modifications made to the model 100 prior to the final acceptance tests was to compensate the upper frequency response. The upper frequency response, measured at IITRI prior

Table III

MODEL 100 LOW-LEVEL MAGNETOMETER  
MIDBAND CALIBRATION (20 kHz)

3-ft, 93-ohm output cable  
93-ohm termination on scope

Channel Range	Magnetic Field millioersted	PP Voltage Out
Low            1 (0.5 - 5)	0.5	6.0
	1	12.0
	5	60.0
Low            2 (5 - 50)	5	6.0
	10	12.0
	50	60.0
High          1 (5 - 50)	5	6.0
	10	12.0
	50	60.0
High          2 (50 - 500)	50	6.0
	100	12.0
	455	55.0

to the final acceptance tests, is shown in Figure 17. The upper 3 dB cutoff frequency is 6 MHz which exceeds the required 5 MHz specification. The final acceptance tests did not include a CW frequency response measurement. However, subsequent pulse risetime measurements tend to substantiate this CW measurement.

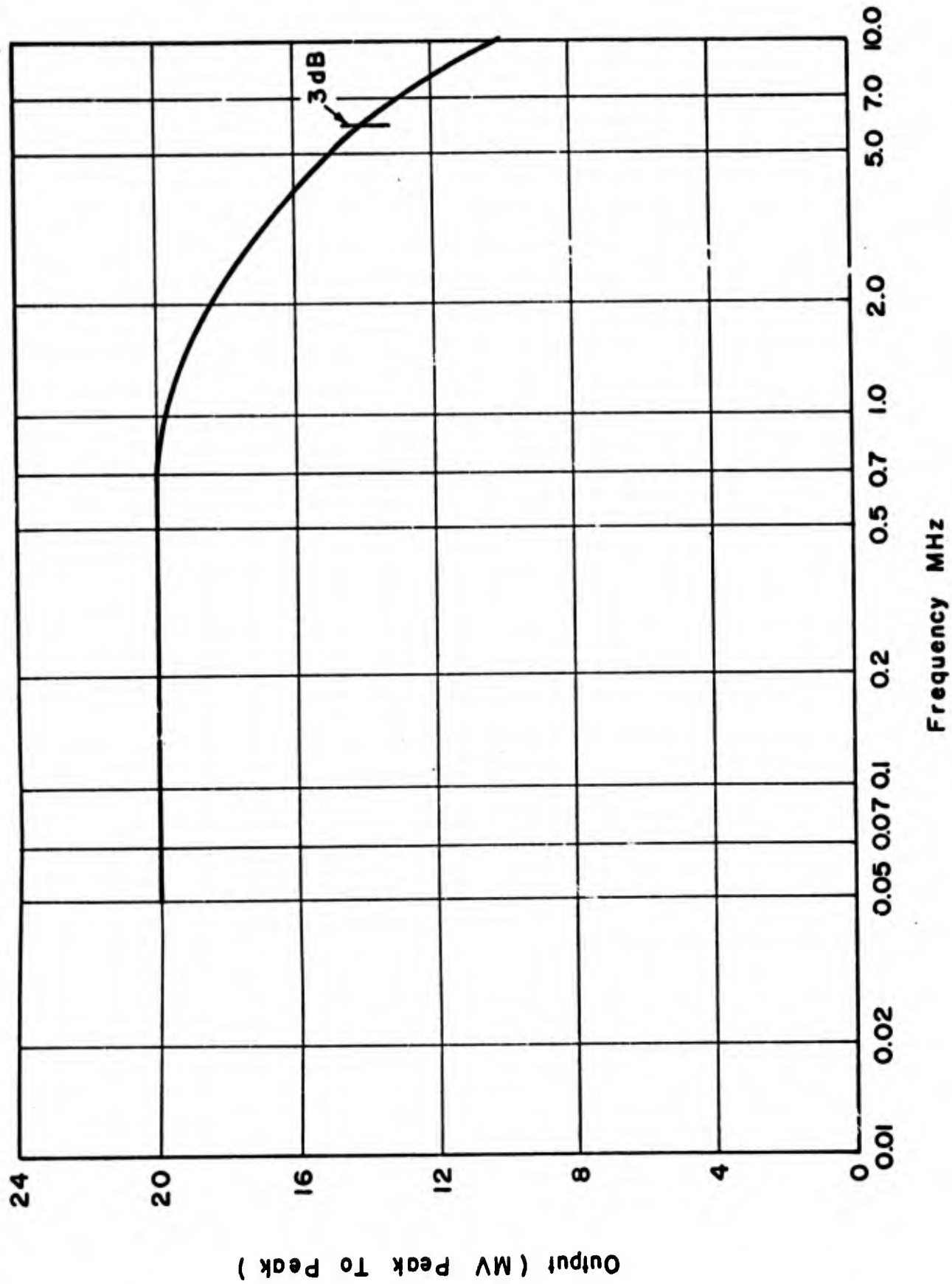


Fig. 17 HIGH - FREQUENCY - RESPONSE MODEL 100 MAGNETOMETER

The low-frequency response given previously in Figure 10 is still applicable because the compensation did not influence low-frequency response.

A series of CW tests using the Helmholtz coil facility were performed at a frequency of 465 Hz, which is a frequency in the mid-band range of this magnetometer. The results of these measurements are tabulated in Table IV.

Tests were also run to determine the maximum field levels that could be obtained on each range before saturation effects were noted. The following approximate saturation levels were recorded.

Range	Upper Calibration Field Level (Peak mOe)	Lowest Saturation Field Level (Peak mOe)
L1	7	9.3
L2	70	90
H1	70	90
H2	700	900 (Est. - Not Measured)

Table IV

MIDBAND CW CALIBRATION TESTS OF THE  
MODEL 100 MAGNETOMETER IN THE A.F. HELMHOLTZ COIL

Test Frequency - 465 Hz

Field Amplitude Peak mOe)	Magnetometer Range	Output Volts (Peak)	Field Calibration (Peak mOe)
2.0	L1	8.5	2.0
7.0	L2	3.0	7.05
70.0	L2	27.5	65.0
7.0	H1	3.0	7.05
70.0	H1	31.5	74.0
70.0	H2	3.0	70.5
280.0	H2	12.5	294.0

The noise level on range L1 was approximately 1 mV peak on the 5 mV scale (Tektronix 454 oscilloscope). At the lowest calibrated field level, 0.7 mOe peak, the signal to noise ratio is

$$S/N = \frac{5.0}{0.7} = 4.3$$

$$= 12.6 \text{ dB.}$$

The system thus meets program specifications which require a 15 dB signal to noise ratio at 1.4 mOe peak.

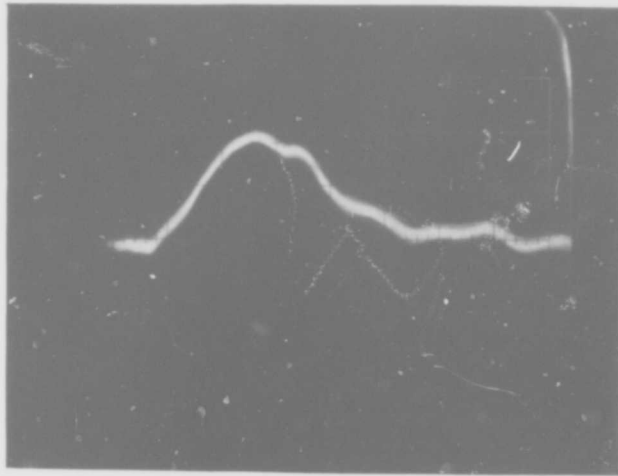
b. Pulse Tests

The model 100 magnetometer sensor was placed in the vertical pulsed transmission line facility (Section IV, 2, d). The separation of the guides at the probe position was 4 meters and the impressed voltage waveform was that shown in Figure 9. The expected field levels were then

Electric: 70 V/m peak

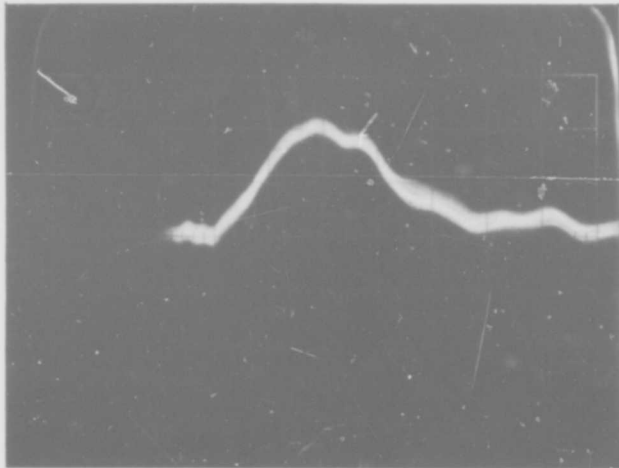
Magnetic: 2.33 mOe peak.

The waveform recorded from the model 100 magnetometer by using a Tektronix 454 oscilloscope is shown in Figure 18. For this test, the probe was vertical and the body of the sensor was aligned with the direction of propagation. A second measurement was performed with the probe once again vertical but the axis of the sensor was transverse to the direction of propagation, a direction that aligns the sensor with the electric field and would produce maximum scattering. The waveform recorded in this case is shown in Figure 19. There was no detectable change, indicating that the sensor did not perturb the field. Similar results were achieved at 3 meters separation. However, at 2 meters separation, the instrument did cause field perturbation and the amplitude of the pulse did depend on sensor position and orientation.



Vert: 5 mV/cm  
Horiz: 50 ns/cm

Fig.18 RESPONSE OF THE MODEL 100 MAGNETOMETER  
IN THE VERTICAL PULSED LINE AT A SEPA-  
RATION OF 4 METERS WITH THE SENSA-  
TION AXIS ALIGNED PARALLEL TO THE DIRECTION OF  
PROPAGATION



Vert: 5 mV/cm  
Horiz: 50 ns/cm

Fig. 19 RESPONSE OF THE MODEL 100 MAGNETOMETER  
IN THE VERTICAL PULSED LINE AT A SEPA-  
RATION OF 4 METERS WITH THE SEN-  
SOR AXIS ALIGNED TRANSVERSE TO THE DIRECTION OF  
PROPAGATION AND PARALLEL TO THE ELECTRIC  
FIELD

The risetime in Figures 18 and 19 is approximately 60 ns, which corresponds to a bandwidth of

$$\text{BW} = \frac{0.35}{60 \times 10^{-9}}$$
$$= 5.8 \text{ MHz.}$$

which correlates well with the CW bandwidth measured at IITRI. The magnetometer was on range L1 and a peak amplitude of 10 mV corresponds to 2.35 mOe field (by IITRI calibration). This is in agreement with the calculated magnetic field level.

c. Electric Field Isolation Tests

The entire model 100 sensor was placed between the plates of the electric field simulator so that the probe was aligned with the electric field. This represents a worst case because the probe would normally be aligned with the magnetic field direction if known. No signal was observed above the noise on range L1 for an electric field level of 3000 V/m (corresponding to 100 mOe). The noise on this range is 15 dB below 1 mOe. Thus, the signal caused by the electric field is certainly in excess of 55 dB below the corresponding magnetic field level ( for a plane wave).

Thus, the model 100 was considered to have satisfactorily met the electric field isolation specification of 40 dB.

3. Model 200 Broadband Magnetometer

a. Calibration and Bandwidth

The model 200 magnetometer was also given a final calibration prior to the final acceptance tests. The midband calibration factor for range 1 was determined at IITRI. However, the midband calibration for range 2 was determined during the final acceptance tests. Both calibration factors are shown in Table V. As with the model 100, good agreement was observed between the IITRI calibration and AFSWC calibration.

The high-frequency response of the model 100 magnetometer was remeasured after replacing the 93-ohm terminations on the detectors in the receiver by 50-ohm terminations. The modified, and final, bandwidth determination is shown in Figure 20. A modest improvement results, and a flat region of unexplained origin is apparent. The 3 dB cutoff frequency is about 65 MHz. The low-frequency response remains the same as shown in Figure 14.

Table V

MODEL 200 BROADBAND MAGNETOMETER  
MIDBAND CALIBRATION (20 kHz)

3-ft 93-ohm output cable  
93-ohm termination on scope

---

Low-Range output 10 mV pp for 0.1 oersted  
High-Range output 11 mV pp for 1.0 oersted

---

The model 200 magnetometer was placed in the Helmholtz coil facility and subjected to a low-frequency, low-level magnetic field. This was done at several frequencies in order to verify the low-frequency response of the system. The field level was held constant at 0.175 oersted, and the magnetometer measurement is shown in Figure 21. The lower 3 dB cutoff frequency was 1.65 kHz, which compares with 1.60 kHz determined in earlier IITRI tests (see Figure 14). The 10 kHz measured output was 0.183 oersted, comparing favorably with the AFSWC calibration of 0.175 oersted.

The voltage output at 10 kHz was 6.5 mV peak and the noise level was 1.5 mV peak. The signal to noise ratio for 0.175 oersted was then

$$\begin{aligned} S/N &= \frac{6.5}{1.5} = 4.33 \\ &= 12.8 \text{ dB.} \end{aligned}$$

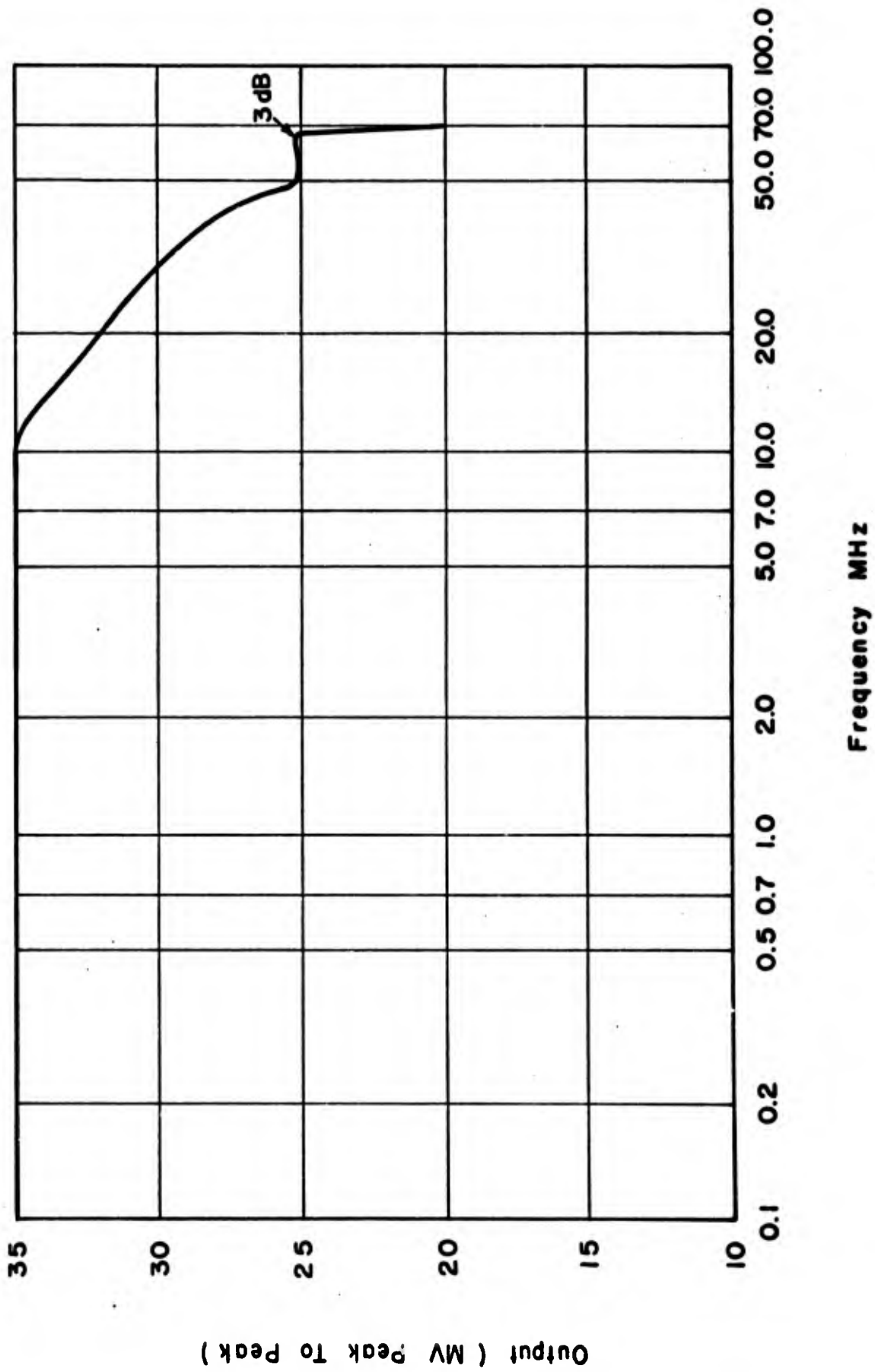


Fig. 20 · HIGH - FREQUENCY - RESPONSE MODEL 200 BROADBAND MAGNETOMETER

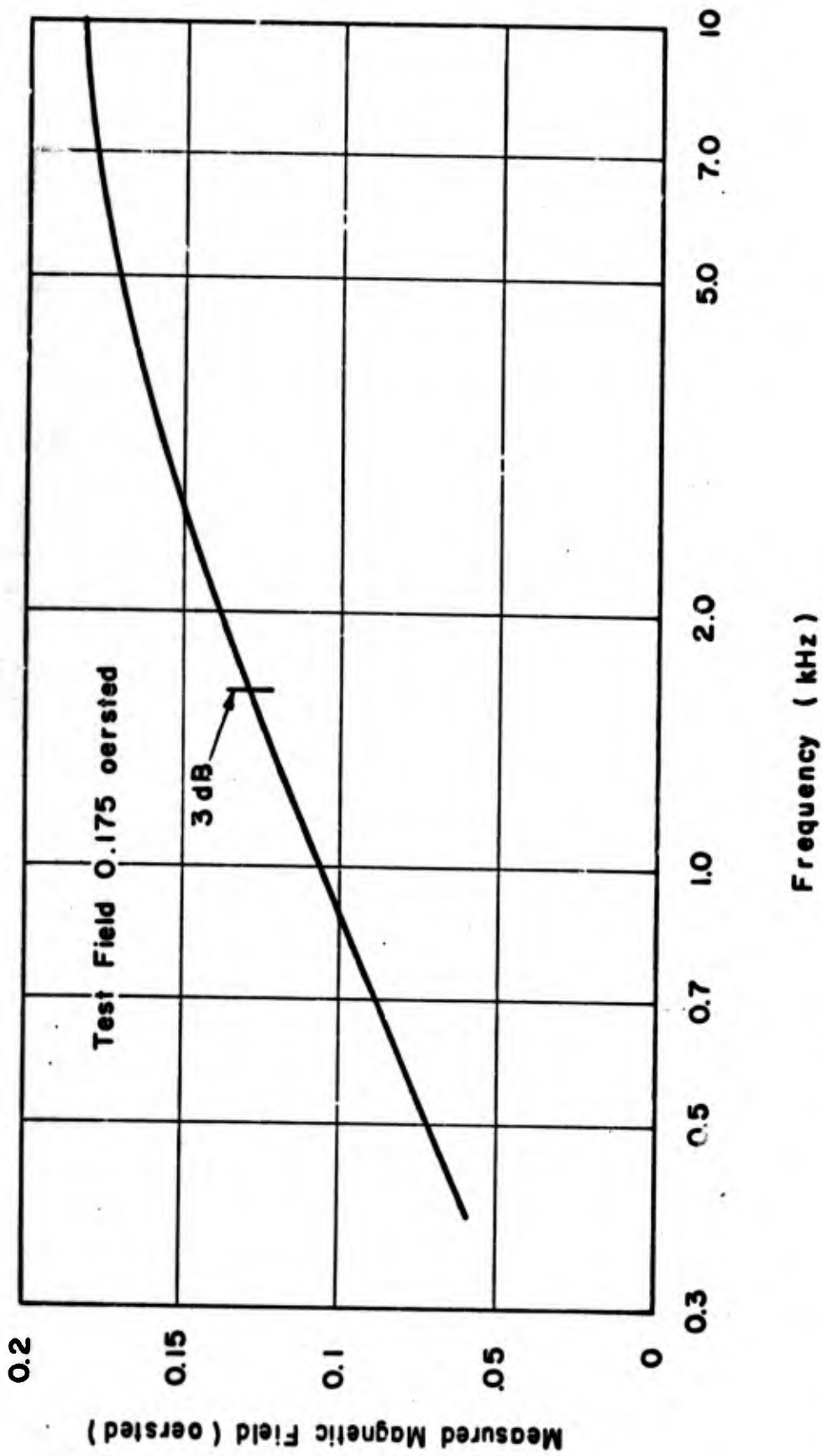


Fig. 21 LOW - FREQUENCY - RESPONSE MODEL 100 MAGNETOMETER

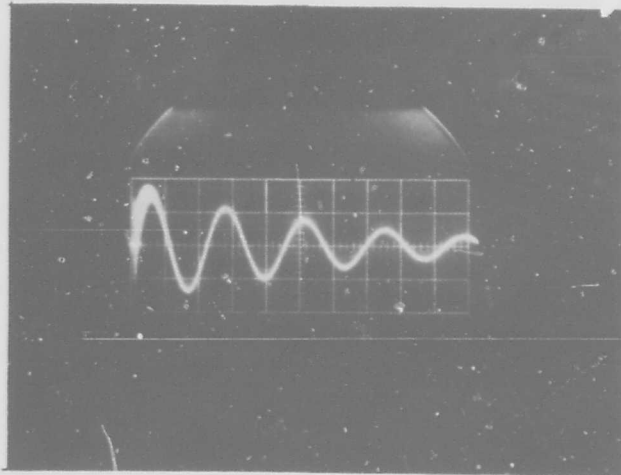
By scaling to 0.20 oersted, the signal to noise ratio would be 14 dB. Allowing for measurement error, the final minimum signal to noise ratio was stated as 15 dB at 0.20 oersted (see Table II)

b. Pulse Tests

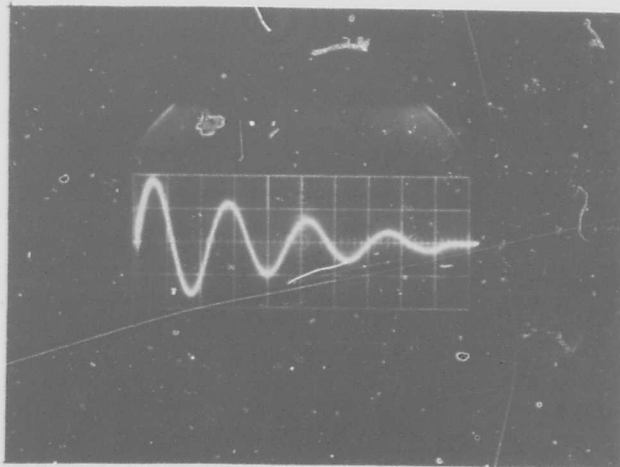
Higher field testing was conducted in the Helmholtz coil by using a single-shot pulse. This permitted, for the first time, operation of the model 200 on range 2 (1 to 100 oersted). The waveform of the test field is shown in Figure 22 (this is the waveform of the current in the Helmholtz coil). In Figure 22a is shown the waveform of a 49 oersted (peak) field and in Figure 22b is shown the waveform of a 5.68 oersted (peak) field. Both of the Helmholtz coil calibration factors (as well as the subsequent magnetometer calibration factors) are based on the amplitude of the first negative peak.

The magnetometer output waveform corresponding to the 49 oersted field (Figure 22a) is shown in Figure 23. The first negative peak corresponds to 45 oersted by using the calibration factor given in Table V for range 2. This calibration factor was actually determined from the attenuation factor of the range attenuator as shown in the results of Figure 24. The test field was identical in both cases (the first negative peak was 5.68 oersted) and is shown in Figure 22b. By comparing Figures 24a and b, it was determined that the attenuator ratio was 11:1. From this the range 2 calibration factor (11 mV peak to peak for 1.0 oersted) was determined from the range 1 calibration factor (10 mV peak to peak for 0.1 oersted). The field level from these calibration factors was then determined to be: Range 1, 5.64 oersted; Range 2, 5.65 oersted compared with the AFSWC calibration of 5.68 oersted.

Additional pulse testing of the model 200 was conducted in the Air Force ALECS large scale transmission line plane wave simulator. The primary benefits accruing from these tests were risetime determination and the evaluation of the influence of electric field on the coaxial transmission cable between the sensor and receiver.



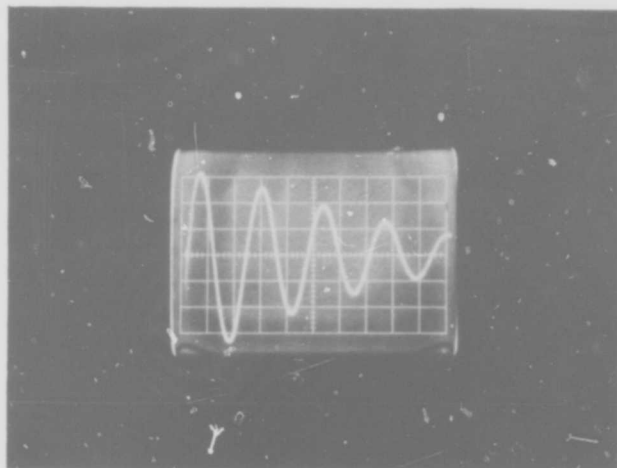
a. Vert: 20 V/cm (35 Oe/cm)  
Horiz: 200  $\mu$ s/cm



b. Vert: 2 V/cm (3.5 Oe/cm)  
Horiz: 200  $\mu$ s/cm

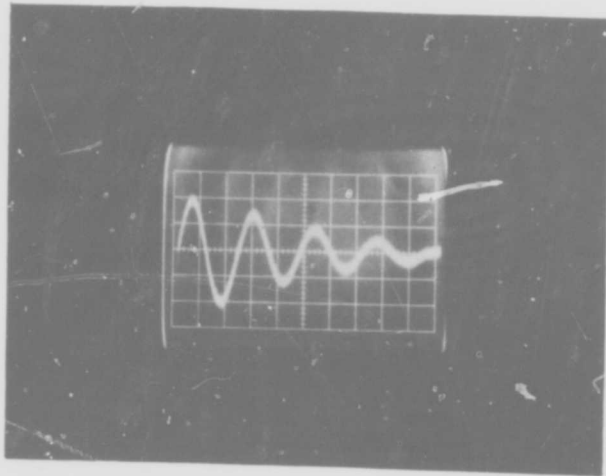
Fig. 22

WAVEFORMS OF THE TEST FIELDS USED  
IN HIGH FIELD PULSE TESTING OF THE  
MODEL 200 MAGNETOMETER

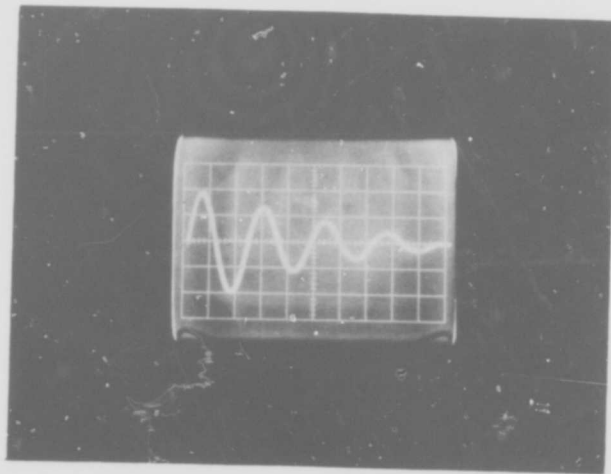


Vert: 50 mV/cm (12.85 Oe/cm)  
Horiz: 200  $\mu$ s/cm

Fig. 23 OUTPUT WAVEFORM OF THE MODEL 200  
MAGNETOMETER (RANGE 2) CORRESPONDING  
TO THE TEST FIELD OF FIG. 22a.



a. Vert: 10 mV/cm (2.57 Oe/cm)  
 Horiz: 200  $\mu$ s/cm



b. Vert: 100 mV/cm (2.82 Oe/cm)  
 Horiz: 200  $\mu$ s/cm

Fig. 24

OUTPUT WAVEFORM OF THE MODEL 200  
 MAGNETOMETER CORRESPONDING TO THE  
 TEST FIELD OF FIG. 22b.  
 a) Range 2, b) Range 1

The measured risetime was 7 nanoseconds which is consistent with the measured CW bandwidth and with the pulse response obtained during contractor tests.

Considerable difficulty was encountered when the segmented filter cable was used in the ALECS facility. The cable has capacitors in the outer shield which apparently admitted high-frequency energy into the interior of the coaxial line. The receiver has a bandpass filter (1.4 to 1.6 GHz) in order to reject such noise (the frequency was approximately 100 to 200 MHz). However, it has been surmised that this spurious signal couples back into the transistor oscillator and causes FM modulation on the carrier. This problem, to a lesser degree, had been noted earlier at IITRI. A series capacitor was inserted in the center conductor of the coaxial cable inside of the sensor that connects the isolator output to the feedthrough in the sensor box. This capacitor forms a high-pass filter, which, unfortunately, is not very effective for very high-frequency energy. The better solution to this problem is to use a bandpass filter structure in the sensor to block all (except inband) energy from coupling into the oscillator.

A standard RG-214/U cable was used in place of the segmented filter cable and the spurious noise was eliminated. This cable, however, offers no isolation of the sensor to prevent field perturbation.

Therefore, in the absence of a filter to reject such noise in the sensor, the segmented cable must be used with caution. In smaller simulator facilities, where no screen room is available, the cable should be used. In larger facilities, where electric field pickup on the cable is troublesome, a solid cable must be used with field perturbation minimized by judicious orientation of the sensor and cable directions so as to not short the electric field.

c. Electric Field Isolation Tests

The model 200 magnetometer was placed in the parallel plate electric field simulator in a position so that the probe was aligned with the electric field. The test field was a pulsed waveform approximately 50 kV/meter in peak amplitude (corresponding to 1.67 oersted magnetic field in a plane wave). The spurious signal caused by electric field was zero when an RG-214/U cable was used but was about 100 mV with the filter cable. This spurious signal was unchanged for either position of the range switch indicating that the spurious signal did not enter the sensor through the probe.

These tests, then, verify the problem shown by the ALECS tests that coupling into the filter cable is presently a system problem. A possible cure and recommendations for use of the filter cable were given in subsection b above.

## SECTION VII

### CONCLUSIONS

Two prototype magnetometer systems have been designed, constructed, tested, and delivered to the Air Force Special Weapons Center. With only minor variations, the final specifications of the two systems either conformed to or exceeded the original program specifications. The only difficulty encountered in final acceptance tests was spurious signal leakage in the filter cable of the model 200 magnetometer. A possible solution to this problem has been recommended herein.

Extension of the bandwidth capability of the model 200 is a realistic possibility. A bandwidth two to four times greater is considered a reasonable extension of the present system.

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) IIT Research Institute 10 West 35th Street Chicago, Illinois 60616		2a. REPORT SECURITY CLASSIFICATION <b>Unclassified</b>	
		2b. GROUP	
3. REPORT TITLE  DEVELOPMENT OF PROTOTYPE MAGNETIC FIELD			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) May 1967 to November 1968			
5. AUTHOR(S) (First name, middle initial, last name)  Robert M. Knox			
6. REPORT DATE November 1969		7a. TOTAL NO. OF PAGES 68	7b. NO. OF REFS
8a. CONTRACT OR GRANT NO. F29601-67-C-0037		9a. ORIGINATOR'S REPORT NUMBER(S) AFSWC-TR-68-25	
b. PROJECT NO. 1357		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
c. Task 03			
d.			
10. DISTRIBUTION STATEMENT This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of AFSWC (SWVIA), Kirtland AFB, NM 87117. Distribution is limited because of the technology discussed in the report.			
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY AFSWC (SWVIA) Kirtland AFB, NM 87117	
13. ABSTRACT (Distribution Limitation Statement No. 2)  Two prototype magnetometer systems have been developed and constructed for use in measuring pulsed magnetic fields. The IITRI model 100 magnetometer is a low-level, moderate bandwidth system that uses an optical carrier for transmitting the magnetic field information to a remote location. The IITRI model 200 magnetometer is a wide bandwidth, moderately sensitive system that uses an FM modulated microwave carrier data transmission link. Both instruments are portable and designed for field use. Extensive tests were conducted using electromagnetic field simulators and environmental test chambers. Results of these tests are included in this report as well as complete specifications for the two magnetometers. (1)			

*frequency*

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	RO - E	WT
Magnetic fields Magnetometer Micro data link Fiber optic data link EMP transients						

UNCLASSIFIED

Security Classification