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EVALUATION OF A TRIAXIAL SQUID MAGNETOMETER DESIGNED FOR USE AS--ETC(U)
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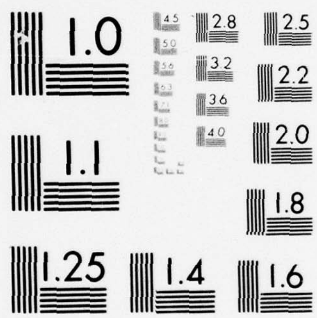
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NRL Memorandum Report 3757

Evaluation of a Triaxial SQUID Magnetometer Designed for Use as an ELF Magnetic Antenna

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and

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April 1978

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A triaxial SQUID magnetometer system has been proposed for use in a submarine towed ELF receiving antenna system. This report describes the testing of the magnetometer system to determine the magnetic orthogonality among the channels of the system, the instrument noise level and responsivity. The other parameters of the system, mostly electrical in nature, had been determined previously.

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SUMMARY

This report describes a series of tests made to evaluate the performance of a triaxial SQUID magnetometer system designed for use as part of a compact, omnidirectional ELF antenna system. The mutual magnetic orthogonality among the three channels was determined to be no greater than 2×10^{-4} radians and the instrument noise level of each of the three channels was determined to be on the order of or less than 2×10^{-14} Tesla rms/$Hz^{1/2}$. These results are consistent with the specifications required of the SQUID system and, thus the SQUID portion of the antenna will not limit overall performance of the antenna.

The measurements were made in the Spacecraft Magnetic Test Facility at the Goddard Space Flight Center, Greenbelt, MD. and at the Low Field Facility, MIT National Magnetic Laboratory, Cambridge, MA.

EVALUATION OF A TRIAXIAL SQUID MAGNETOMETER DESIGNED FOR USE AS AN ELF MAGNETIC ANTENNA

I. INTRODUCTION

A triaxial SQUID magnetometer system was purchased for evaluation of the feasibility of using this type of instrumentation in a compact, omnidirectional ELF receiving antenna.[1-5] Most of the performance characteristics of the SQUID system were verified by the manufacturer during the pre-delivery acceptance testing. However, because of the very elaborate testing facilities needed, the manufacturer was not required to measure the magnetic orthogonality among the three channels or to determine the instrument noise level of the individual channels, without a superconducting shield mounted in the dewar system.*

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*In operation, a superconducting shield cannot be located around the antenna as it would shield the antenna from the signal to be measured. With the superconducting shield removed, Johnson noise from the conducting portions of the dewar can couple into the SQUID system and possibly degrade the performance characteristics of the antenna.

Note: Manuscript submitted March 13, 1978.

After the SQUID system had been used in the field for preliminary evaluation of its performance, it was brought back to NRL for the additional evaluation. In particular, it was desired to measure the following characteristics.

(1) the magnetic orthogonality among the three field sensing coils, one for each channel,

(2) the effective instrument noise level of the SQUID magnetometer <u>and</u> the dewar,

(3) a careful measurement of the response of each channel, that is, the output signal for a given change in input field.

II. BACKGROUND

Orthogonality

The response of a SQUID magnetometer to ambient magnetic field changes is a function of the angle of the magnetic field relative to the normal to the plane of the field sensing coil. During the initial design consideration for the ELF antenna system (Ref. 1) a configuration using three (nominally) orthogonal SQUID sensors was proposed: the outputs from these sensors would be squared and then added to form a rotational invariant quantity. It was shown that to implement this rotationally invariant data processing scheme for a platform with a stability of 10^{-3} radians or less[3], the mutual orthogonality among the three field sensing coils ought to be less than 10^{-4} radians. During the pre-acceptance testing by the manufacturer, it was shown that the mechanical orthogonality among the coils was better than 10^{-4} radians. However, the manufacturer did not have access to a facility to test the magnetic orthogonality, and to construct such a site would have been financially prohibitive. However, such a facility does exist at the Goddard Space Flight Center in Greenbelt, Md. where magnetic orthogonality could be measured to (nearly) the precision required.

Noise

Since the magnetic field sensitivity of the SQUID system is several orders of magnitude below environmental background noise in the 30-130Hz band, (the band of interest for ELF reception) the measurement of instrument noise is quite difficult to perform. During the preacceptance testing, a superconducting shield was placed in the dewar surrounding the antenna to shield the antenna from environmental noise and also, unfortunately, from any Johnson noise that might be generated in the dewar walls and coupled into the antenna. To determine whether the Johnson noise in the dewar degrades the antenna performance, the entire system with the superconducting shield removed, must be measured in a facility where the ambient background noise is known to be of the order or less than 10^{-14} tesla rms/$Hz^{1/2}$. This level of background field noise could be achieved in a very large superconducting shield, but such a shield would have to have a room temperature access region of the order of one foot in diameter. However, the Low Magnetic Field Facility at the MIT National Magnetic Lab. provided the ideal site for the noise measurements.

Responsivity

During the pre-acceptance testing of the SQUID magnetometer by the manufacturer, the response of each of the channels were determined by the following procedure:

(1) the magnetometer, without superconducting shield, was operated on the least sensitive range,

(2) the system was taken to a remote "magnetically quiet" site,

(3) a loop dipole of known size was excited by ac current and the magnetic field at the site of the SQUID magnetometer was determined and the responsivity of the SQUID calculated,

(4) the DC response was determined by flipping a bar magnet of known magnetic moment.

There were two difficiencies to these tests. First the measurements were made on the least sensitive range setting while in operation under water the SQUID would operate on the most sensitive range. Secondly, these measurements were made over a surface of finite conductivity and any variation in skin depth with frequency might effect these ac measurements.

At the Magnetic Test Facility at Goddard, once the earth's magnetic field has been cancelled to an accuracy of a nanotesla, a known field dc or ac can be applied in any prescribed direction with an amplitude known to plus/minus a nanotesla. Since this field is at the center of a Braumbek coil and the coil system is above the surface of the earth, any possible effects of a frequency dependent skin depth measurement would be negligible.

III. RESULTS

A. Goddard Tests - Magnetic Orthogonality

The Goddard Facility consists of three sets of 138 m diameter mutually orthogonal coils, in a Braunbek configuration to maximize the field uniformity at the center of the system (see Fig. 2). This facility can compensate for the earth's magnetic field to at least 1 nanotesla; furthermore, it can provide magnetic fields in any direction, varying from 0 to 55,000 nanotesla, with at least one nanotesla accuracy and with a uniformity of 1 part in 10^5 over a centrally located 2 meter cube. Orthogonality of the Goddard magnetic axes was specified to be 10^{-4} radians of arc but had not been checked to this degree of precision.

The sensing coils of the triaxial SQUID magnetometer in the low sensitivity (10^{-13}T) mode were mounted at the center of the test area and aligned ($\sim 10^{-2}$ radians) with the 138 m diameter coils. The earth's magnetic field was nulled, and a calibration field was applied to each axis in turn. The SQUID outputs were measured with a DVM and several sets of readings (field on, field off, field reversed) were averaged in order to accurately determine the sensitivity of the SQUID magnetometer. These results are indicated in Table I.

The following procedure was utilized to check the magnetic orthogonality of the SQUID sensing coils. With the SQUID axes aligned to at least 10^{-2} radians with the Goddard coils, fields of 9000 mT were sequencially applied to each of the three perpendicular directions. For each applied field, changes in the outputs of the SQUID axes orthogonal to the applied field direction were measured (i.e., for a vertical applied field(UD), the east-west(EW) and the north-south(NS) SQUID output signals were noted before and after applying the field.) Magnetic fields aligned with the SQUID coils could not be determined, since they exceeded the dynamic range of the system. We assume that these fields are 9000 mT to within a part in 10^4 for the 10^{-2} radian alignment.

For convenience, we will call N, E and U the three Goddard Field directions, and 1, 2 and 3 the three SQUID axes directions. Initially 1 is aligned with N, 2 with E and 3 with U. If the misalignments in the SQUID axes are denoted by e_{xy}, e_{xz}, e_{yz}, etc., and the misalignments in the Goddard Field directions are n_{NE}, n_{NU}, n_{UE}, etc. then it can be shown that to first order in e and n that for a 9000 mT field applied in turn to N, E and U (see Appendix A)

$$\text{(a)}\quad \frac{H_1^N h_1^E + h_2^N H_2^E + h_3^N h_3^E}{81 \times 10^6} = n_{NE} \pm e_{x,y} \qquad \text{(radians)}$$

$$\text{(b)}\quad \frac{H_1^N h_2^U + h_2^N h_2^U + h_3^N H_3^U}{81 \times 10^6} = n_{NU} \pm e_{x,z} \qquad (1)$$

$$\text{(c)}\quad \frac{h_1^E h_1^U + H_2^E h_2^U + h_3^E H_3^U}{81 \times 10^6} = n_{EU} \pm e_{y,z}$$

where $(H_1^N,\ h_2^N,\ h_3^N)$, (h_1^E, H_2^E, h_3^E), (h_1^U, h_2^U, H_3^U) are the measured components of the fields applied in the NS, EW, and UD direction respectively. [Note the signs on the right hand side of Eq. (1).] The measured field components and all the quantities indicated in Eq, (1)[(a),(b),(c)] are shown in Table I.

If we assume that the n's are $\sim 10^{-4}$ radians or less in accordance with the facilities specifications, then the maximum SQUID nonorthogonalities based on the data in Table 1 and Eq. 4 would be $1.5\text{X}10^{-4}$ radians for x-y, $1.6\text{X}10^{-4}$ radians for x-z and $1.2\text{X}10^{-4}$ radians for y-z.

As an additional check on the experimental consistency, the SQUID dewar was rotated 90 degrees in the horizontal plane so that NS was now aligned with y, EW with -x, while UD remained aligned with z. The above experiment was repeated with results also indicated in Table 1. In this case, however, Eq. (1)(a) would read

$$\text{(a)} \quad \frac{H_1^N h_1^E + h_2^N h_2^E + h_3^N h_3^E}{81 \times 10^6} = n_{NE} \mp e_{x,y} \qquad \text{(radians)} \qquad (2)$$

Note that the signs have reversed order in Eq. (2). This means that if the + sign were appropriate for the first orientation the - sign is appropriate for the second orientation. Therefore from Eq. (1a) and (2a) we can determine that $n_{NE} = 1.5\text{X}10^{-4}$ radians and $e_{xy} = 0.9\text{X}10^{-4}$ radians.

Unfortunately, since the dewar could not be put on its side we could not effect an interchange of the other axes to unambiguously determine the other misalignments. However because of the consistency of the data for the two orientations nearly independent of rotation, we conclude that both the Goddard coil and the SQUID triaxial magnetometer are aligned to $\sim 10^{-4}$ radians.

In addition to the tests just described several auxillary tests were also performed. An aluminum shield for the SQUID was used to cut down the amplitude of storm generated high frequency noise (sferics) detected when the system was installed at a land based field site. [Underwater operation would not require such a shield because the water will filter out the sferics]. In order to know the amplitude of a detected signal at the field site, the attenuation characteristics of the aluminum shield had to be carefully determined. By applying a time varying field to the Goddard coils we were able to measure the attenuation characteristics of the aluminum shield as a function of frequency from 0.1 Hz to 2000 Hz. These results are shown in Fig. 3.

Also, the SQUID magnetometer was utilized to measure the noise frequency spectrum of the Goddard Test Facility. These tests were used by the operators of the test facility to evaluate the performance of their feedback circuitry and to help them design the next generation of electronics to null the higher frequency components of the ambient field. An example of these results is shown in Fig. 4.

Shielded Room Noise Tests

The shielded room facility at the National Magnet Laboratory (NML) consists of 3 layers of mumetal and 2 layers of aluminum formed into a dodecahedron (see Fig. (5)). It is capable of shielding ambient fields to better than 2×10^{-14} T/ $Hz^{1/2}$ at selected frequencies in the spectrum. The magnetic noise in the room is primarily caused by 60 Hz leakage and vibrations of the room in response to building vibration. This latter noise is at a minimum from midnight to about 6 A.M. when the building is almost empty, machinery is off and the subway (which pratically goes under the building) is not running.

These measurements at the NML would determine if the unshielded SQUID system displayed a noise level comparable to or less than that of the shielded room. Noise levels within the shielded room slightly exceeded the 10^{-14} $T/Hz^{1/2}$ level but by comparing the noise measured with our SQUID belonging to the NML we could set an upper limit on our SQUID and one system noise of less than $2x10^{-14} T/Hz^{1/2}$.

The SQUID system was mounted inside the room, suspended from the walls to decouple it from the floor, and a series of noise spectrum measurements were taken in the early morning hours when the room was quiet. These results were in good agreement with the room noise spectrum determined in a previous independent study. Our results are indicated in Table II.

A spectrum of room noise was also obtained by recording the SQUID output and analyzing this data with a spectrum analyzer. A typical spectrum is shown in Fig. 5. This analysis once again confirmed the upper limit on the SQUID system noise to be less than $2x10^{-14} T/ Hz^{1/2}$ which is the order of the minimum room noise at selected frequencies. The sensitivity of the flux transformer pickup coil was reduced by approximately an order of magnitude and the noise spectrum was remeasured. At this new sensitivity, the room noise was well below the SQUID system noise for much of the spectrum. In this case the measured SQUID system noise was $1x10^{-13} T/ Hz^{1/2}$ in agreement with the specifications. These results are shown in Fig. 6.

Techniques for measuring the coherent narrow band noise at 76 Hz were tested in the NML shielded environment.

These measurements were performed by recording the SQUID output and a 76 Hz reference. For analysis the tape was played back faster than it was recorded generating a very long effective time constant and therefore a very narrow bandwidth. The resultant coherent noise at 76 Hz was an order of magnitude larger than expected. The measurements were repeated using a 152 Hz reference on tape but a frequency halver on playback to provide the 76 Hz reference. The noise at 76 Hz was reduced by an order of magnitude. To eliminate the possibility of cross talk in the tape recorder, the first set of measurements were repeated with the SQUID output shorted. The 76 Hz noise was now at or below its level when the 76 Hz reference was obtained by halving at 152 Hz. Thus there was significant leakage of 76 Hz from the oscillator into the SQUID electronics which made it imperative not to use any frequency that is being detected as a reference.

IV. CONCLUSIONS:

In order to test the performance of the triaxial magnetometer we used the two best magnetic test chambers in this country. We conclude from these measurements that the axis orthogonality of the magnetometer system is less than 2×10^{-4} radians and that the noise is less than 1.6×10^{-14} T/ $\mathrm{Hz}^{1/2}$. These limits of verification are a reflection of the precison of the existing and available facilities. They do not necessarily reflect the ultimate capability of the system as an ELF magnetic antenna. In fact we conclude that the specifications were met and therefore do not limit the feasibility of the antenna.

In addition very useful information was obtained on the susceptibility of this instrument to electrical pickup, on the performance of its aluminum shield, and on the specifications of the test facilities themselves. This latter information proved very useful to the personnel at these facilities and in some respect justified, especially in the case of Goddard, the generous donation of their time and effort in assisting with these measurements.

V. ACKNOWLEDGEMENTS

We would like to thank Dr. Martin Nisenoff and Dr John Davis for their interest and encouragement on this aspect of the program which represents only a part of the effort in the development of a superconducting magnetic antenna.

We greatly appreciate the assistance of Bill Brown and Chuck Harris of NASA, Goddard both for making the Spacecraft Magnetic Test Site available to us and for operating it during the tests. We also sincerely appreciate the efforts of Dr. David Cohen, for his hospitality and assistance during our tests at the Low Field Lab at MIT.

APPENDIX A

It is desired to estimate the actual errors in orthogonality of a three axis SQUID sensor that is known to be orthogonal to at least 10^{-2} radians. The method used was to align the system to $\sim 10^{-2}$ radians with the three mutually orthogonal coil directions of the Braunbek coil system at Goddard. It will be shown that the "scalar" product of nearly orthogonal ($\sim 10^{-4}$ radians) fields in the SQUID reference frame are to first order simply related to the nonorthogonalities of the SQUID reference frame and the nonorthogonalities of the reference fields. In the following we assume that the reference fields are orthogonal to $\sim 10^{-4}$ radians (their specification). If the Goddard field directions are N, E, U standing for North-South, East-West and Up-Down and the SQUID axes directions are 1, 2, and 3 we will assume initially that 1 is aligned ($\sim 10^{-2}$ rad) with N and 2 with E and 3 with Up, than a field along N will have measured SQUID components as follows:

$$H^N = H_1^N + h_2^N + h_3^N$$

where H_1^N is within a part in 10^4 of H^N and h_2^N and h_3^N are down by at least two orders of magnitude. The SQUID axes are not quite orthogonal. So we can use a Gram-Schmidt procedure to rotate them to an orthogonal coordinate frame. Using this procedure H^N in the SQUID frame can be rewritten in the orthogonalized frame as follows:

$$H_1^N = H_x^N$$

$$h_2^N = \epsilon_1 H_x^N + \epsilon_2 h_y^N$$

$$h_3^N = \epsilon_3 H_x^N + \epsilon_4 h_y^N + \epsilon_5 h_z^N$$

The ϵ's are the Gram Schmidt coefficients. They are rather complicated functions of the angles between the SQUID axes but since the SQUID axes are known to be orthogonal to at least 10^{-2} radians then to first order in the maximum nonorthogonality β (ie neglecting terms of 10^{-4} or less)

$$H_1^N = H_x^N$$

$\epsilon_1, \epsilon_3, \epsilon_4 \sim \beta$

$\epsilon_2, \epsilon_5 \sim (1-\beta^2) \sim 1$

$$h_2^N = \beta H_x^N + h_y^N \tag{2a}$$

$$h_3^N = \beta H_x^N + \beta h_y^N + h_z^N$$

Similary for a field along E

$$H^E = h_1^E + H_2^E + h_3^E$$

$$h_1^E = h_x^E$$

$$H_2^E = \beta h_x^E + H_y^E \tag{2b}$$

$$h_3^E = \beta h_x^E + \beta H_y^E + h_z^E$$

where again H_2^E is within a part in 10^4 of H^E and h_1^E and h_3^E are two orders down in magnitude. Since we actually measure the components in the SQUID reference frame, the following product can be easily formed

$$H_1^N h_1^E + h_2^N H_2^E + h_3^N h_3^E = \text{(pseudo scalar product) PSP} \tag{3}$$

using the transformations in (2) we can rewrite (3)

$$PSP = H_x^N h_x^E + \beta^2 H_x^N h_x^E + \beta H_x^N H_y^E$$
$$+ \beta h_y^N h_x^E + h_y^N H_y^E + \beta^2 H_x^N h_x^E + \beta^2 h_y^N h_x^E$$
$$+ \beta H_x^N h_z^E + \beta^2 H_y^E H_x^N + \beta^2 h_y^E$$
$$+ \beta h_y^N h_z^E + \beta h_x^E h_z^N + \beta H_y^E h_z^N$$
$$+ h_z^N n_z^E$$

dropping all second order terms involving either an β^2 or a β times a small h. We get

$$PSP = H_x^N h_x^E + h_y^N H_y^E + h_z^N h_z^E + \beta H_x^N H_y^E$$

but $H_x^N h_x^E + h_y^N H_y^E + h_z^N h_z^E$

is just the scalar product of H^N and H^E in the orthogonal coordinate system and is equal to $|H^N||H^E|\cos(\tfrac{1}{2}\pi - n_{NE})$ where n_{NE} is the nonorthogonality of the reference coil system. Since n_{NE} is less $\sim 10^{-4}$ radians we can use the small angle approximation.

Therefore

$$PSP = |H^N||H^E| n_{NE} + \beta H_x^N H_y^E$$

but

$H_x^N H_y^E$ is the same as $|H^N||H^E|$ to a part in 10^4 so that

$$PSP = |H^N||H^E| (n_{NE} + \beta)$$

or

$$\frac{PSP}{|H^N||H^E|} = (\beta + n_{NE})$$

If one now rotates the SQUID frame so that 2 is aligned with N, 1 is aligned with -E etc. (to within 10^{-2} radians) than the sign of the β term is just opposite to what it was in the initial case.

So that in this case

$$PSP = |H^N||H^E|n_{NE} - \beta\,(H_x^N H_y^E)$$

or

$$\frac{PSP}{|H^N||H^E|} = n_{NE} - \beta$$

This result can be generalized to fields in all three directions and rotations about any axis to give Eq. (1) in the main text where the β 's have been generalized to e's.

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TABLE I

a) SQUID ORIENTATION

	Scale Factor	$X \parallel EW$			$X \parallel NS$		
		NS	EW	UD	NS	EW	UD
X SQUID	7.78mv/nanotesla	-67.1	*-9000.	-8.1	*+9000.	-2.4	-31.3
Y SQUID	8.21mv/nanotesla	*-9000.	+67.55	-6.88	-4.7	*-9000.	+2.6
Z SQUID	8.89mv/nanotesla	-9.21	-7.45	*+9000.	+28.9	-.68	*-9000.

* 9000. nanotesla assumed from 10^{-2} rad alignment

b)

SQUID ORIENTATION	ERROR QUANTITIES (10^{-3} rad)		
	$n_{NE} \pm e_{xy}$	$n_{NU} \pm e_{xz}$	$n_{EU} \pm e_{yz}$
$X \parallel EW$	.25	.26	.22
$X \parallel NS$	.06	.26	.15

$\Downarrow$

$n_{NE} = 0.15$ mrad

$e_{xy} = .09$ mrad

TABLE II

SQUID in 10^{-14} Tesla Sensitivity Mode

	Frequency (Hz)					
	5	19	29	34	76	500
X Noise 10^{-14} T/ Hz	1.74	2.2	7.87	3.0	1.7	1.24
Y Noise 10^{-14} T/ Hz	2.8	3.9	--	2.3	1.9	1.3
Z Noise 10^{-14} T/ Hz	2.4	3.4	--	3.4	1.9	1.3

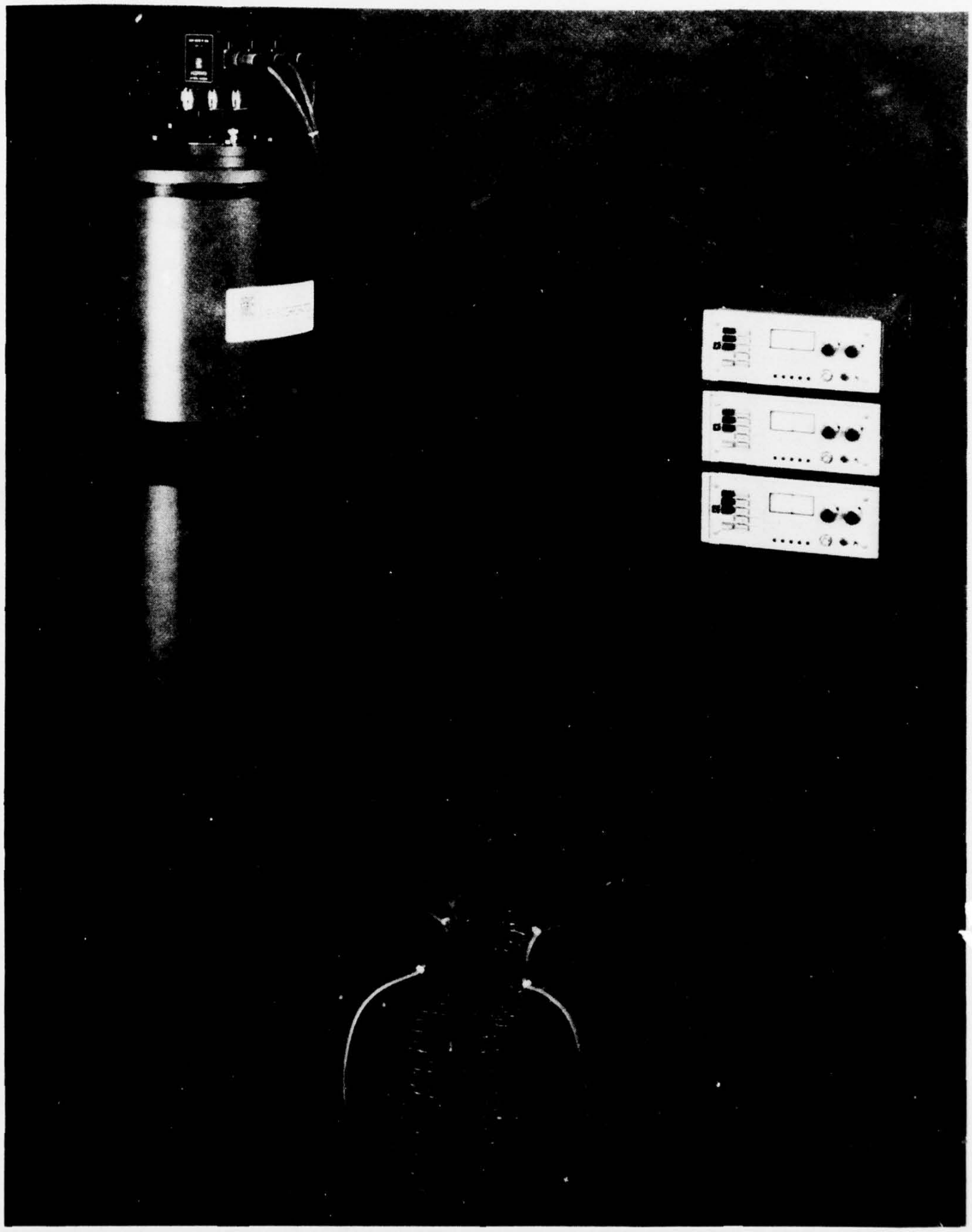

Fig. 1 — This figure is a photograph of the Triaxial SQUID Magnetometer that was tested. At the left is the cylindrical liquid helium dewar in which the magnetometer is mounted. The boxes on the right are the electronics.

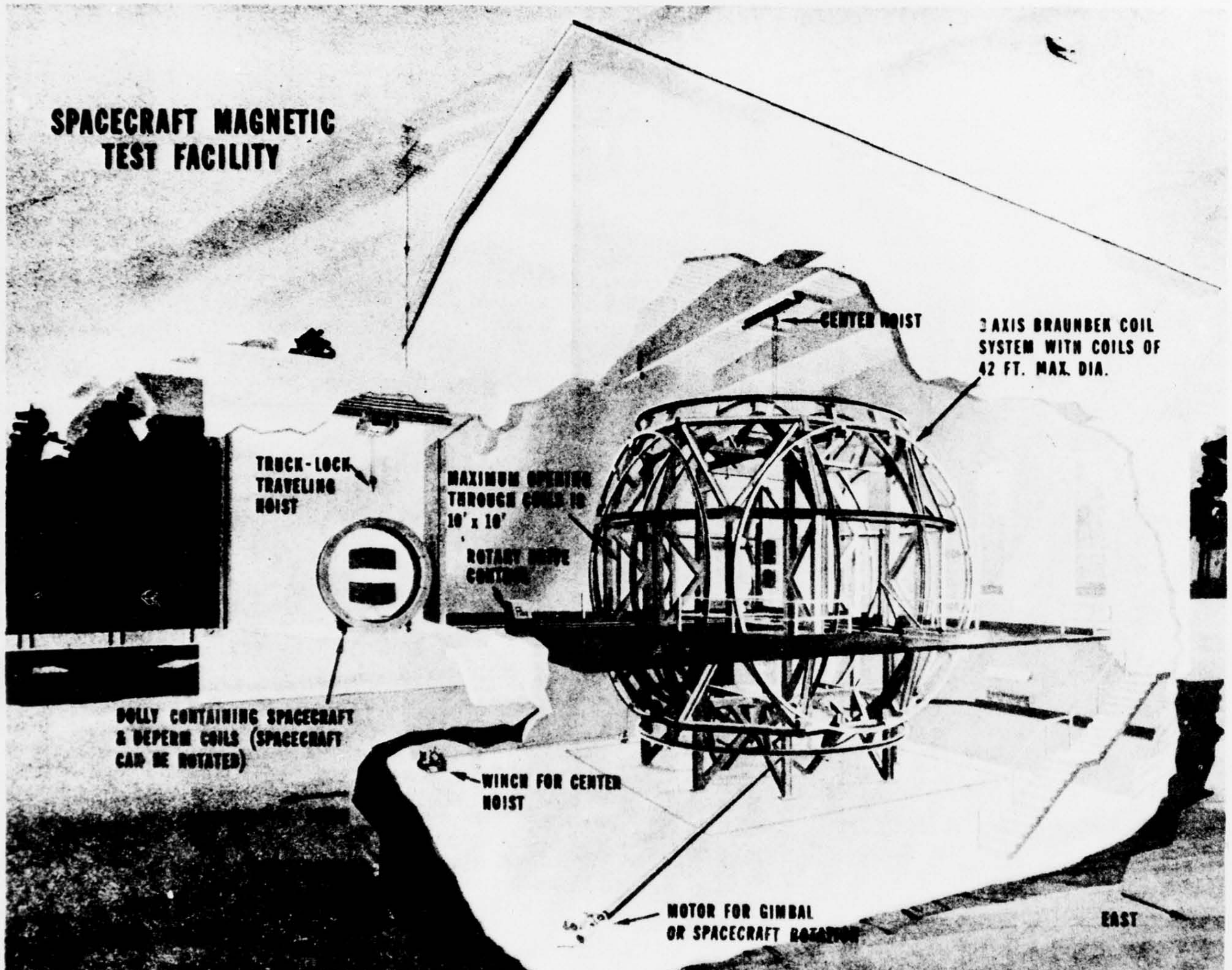

Fig. 2 — A schematic illustration of the Goddard Facility

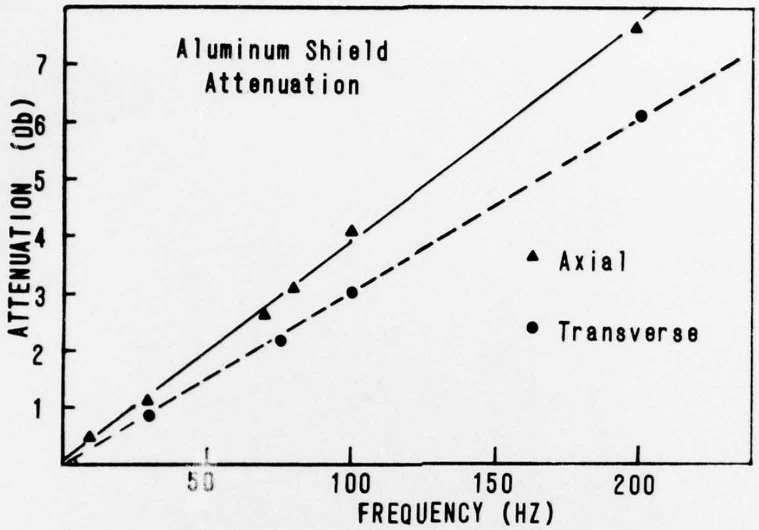

Fig. 3 — Attenuation versus frequency for the cylindrical aluminum shield. Triangles are the data for the field along the axis of the shield for perpendicular fields.

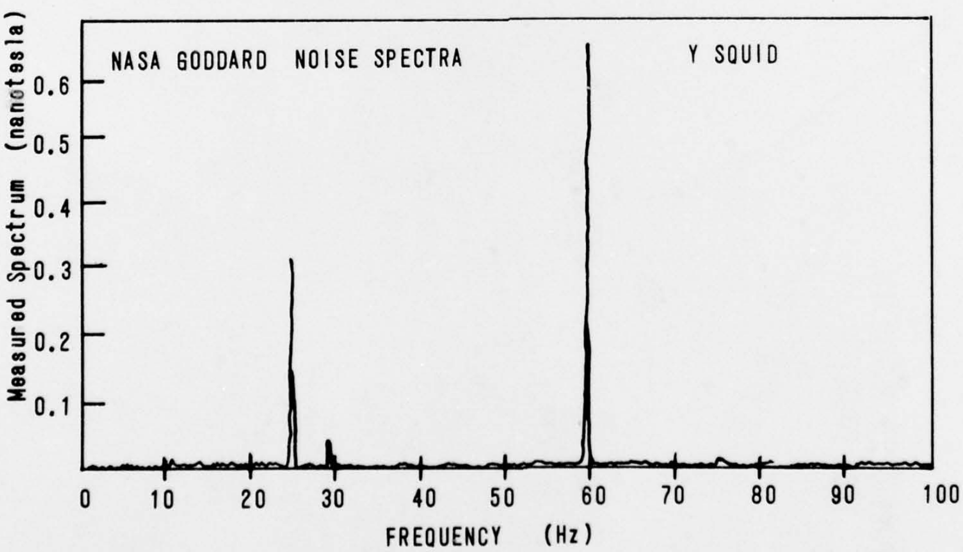

Fig. 4 — A typical noise spectrum along one axis of the Goddard facility. Tape recorded data was analyzed using a spectrum analyzer whose output in magnetic field units was plotted versus frequency.

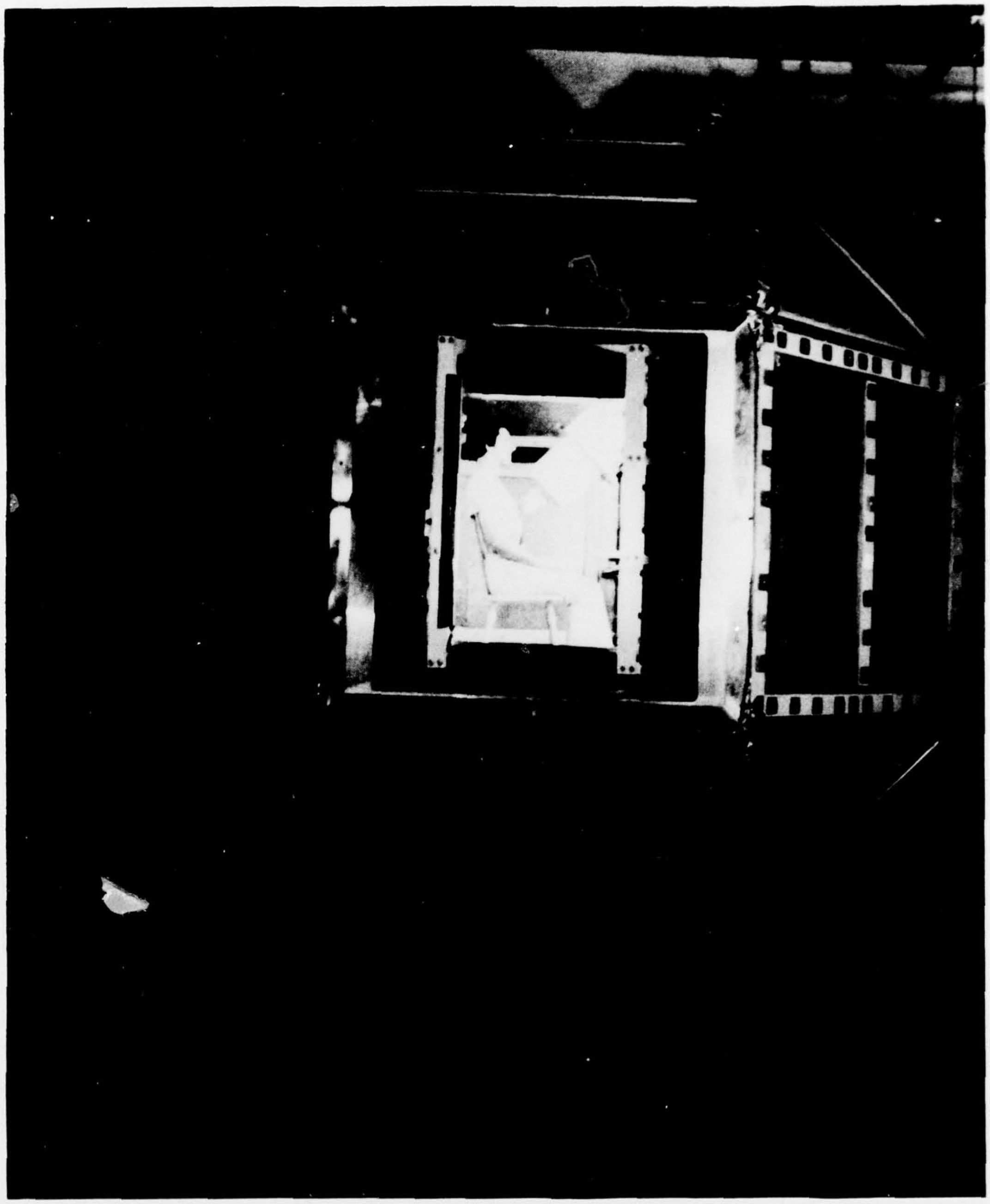

Fig. 5 — A photograph of the MIT shielded room facility

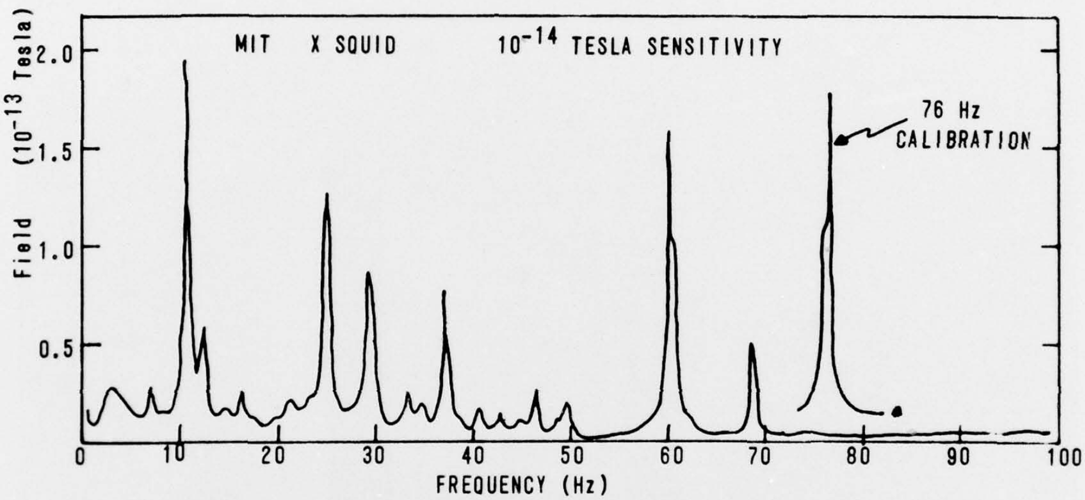

Fig. 6 — A typical noise spectrum obtained with the SQUID along one direction in the MIT shielded room. Data were tape recorded at MIT and spectrum analyzed at NRL. Magnetic field is plotted versus frequency.