EVALUATION OF A TRIAXIAL SQUID MAGNETOMETER DESIGNED FOR USE AS--ETC(U)

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

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

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.
CONTENTS

I. INTRODUCTION ........................................... 1

II. BACKGROUND ........................................... 2

III. RESULTS .................................................. 5
     A. Goddard Tests ......................................... 5
     B. Shielded Room Tests ................................... 9

IV. CONCLUSION ............................................. 11

V. ACKNOWLEDGMENTS ....................................... 12

APPENDIX ................................................... 13

REFERENCES ............................................... 17
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 x 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 x 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. *

*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.

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 and 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, 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 deficiencies 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 $10^4$ 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 ($10^{-2}$ 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 sequentially
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 $\eta_N$, $\eta_E$, $\eta_U$, $\eta_U$, $\eta_E$, $\eta_N$.
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)

(a) $H_1 N_h + h_2 E + h_3 E$

$$\frac{N + e}{81 \times 10^6} = n_{NE} + e_{x,y} \quad \text{(radians)}$$

(b) $H_1 N_U + h_2 E + h_3 E$

$$\frac{N + e}{81 \times 10^6} = n_{NU} + e_{x,z} \quad \text{(1)}$$

(c) $h_1 h_2 + h_3 E$

$$\frac{N + e}{81 \times 10^6} = n_{EU} + e_{y,z}$$

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 $-10^{-4}$ 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 $1.5 \times 10^{-4}$ radians for $x-y$, $1.6 \times 10^{-4}$
radians for $x-z$ and $1.2 \times 10^{-4}$ 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

\[
\begin{align*}
H_E^{\text{N}E} + h_1h_2 + h_3h_4 - r & = \frac{n_{\text{NE}}}{} \\
& = e_{x,y} (\text{radians})
\end{align*}
\]

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 \( n_{\text{NE}} = 1.5 \times 10^{-4} \text{ radians} \) and \( e_{x,y} = 0.9 \times 10^{-4} \text{ radians} \).

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 \( 10^{-4} \text{ radians} \).

In addition to the tests just described several auxiliary 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 $2 \times 10^{-14} T/Hz^{1/2}$ 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 practically 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 $2 \times 10^{-14}$ 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 $2 \times 10^{-14}$ 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 $1 \times 10^{-13}$ 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 $2 \times 10^{-4}$ radians and that the noise is less than $1.6 \times 10^{-14}$ T/Hz$^{1/2}$. These limits of verification are a reflection of the precision 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 $10^{-2}$ 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 $10^{-4}$ 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:
The \( \epsilon \)'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 \( \nu^{-2} \) radians then to first order in the maximum nonorthogonality \( \beta \) (ie neglecting terms of \( \nu^{-4} \) or less)

\[
\begin{align*}
\epsilon_1 & = \beta \\
\epsilon_2 & = (1-\beta)^{-1} \\
\epsilon_3 & = \epsilon_4 \\
\epsilon_5 & = (1-\beta)^{-1} \\
\epsilon_6 & = \beta
\end{align*}
\]

(2a)

Similarly for a field along \( E \)

\[
\begin{align*}
\epsilon_1' & = \beta \\
\epsilon_2' & = (1-\beta)^{-1} \\
\epsilon_3' & = \epsilon_4' \\
\epsilon_5' & = (1-\beta)^{-1} \\
\epsilon_6' & = \beta
\end{align*}
\]

(2b)

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

\[
H_1^N h_1^E + h_2^N h_2^E + h_3^N h_3^E = \text{(pseudo scalar product) PSP} \quad (3)
\]

using the transformations in (2) we can rewrite (3)
dropping all second order terms involving either an $\beta^2$ or a $\beta$ times a small $h$. We get

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

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 $|h^N| |h^E| \cos (\frac{1}{N} - n_{NE})$

where $n_{NE}$ is the nonorthogonality of the reference coil system. Since $n_{NE}$ is less than $10^{-4}$ 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 \( \beta \) term is just opposite to what it was in the initial case.

So that in this case

\[
PSP = |H^N| |H^E| n_{NE} - \beta \left( H^N_x H^E_y \right)
\]

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 \( \beta \)'s have been generalized to \( e \)'s.
REFERENCES


### TABLE I

| SQUID ORIENTATION | Scale Factor | X || EW     | X || NS     |
|-------------------|--------------|------------|------------|
| 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) ERROR QUANTITIES ($10^{-3}$rad)

<table>
<thead>
<tr>
<th>SQUID ORIENTATION</th>
<th>$n_{NZ}$ $\pm e_{xy}$</th>
<th>$n_{MU}$ $\pm e_{xz}$</th>
<th>$n_{EU}$ $\pm e_{yz}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td></td>
<td>EW</td>
<td>.25</td>
</tr>
<tr>
<td>X</td>
<td></td>
<td>NS</td>
<td>.06</td>
</tr>
</tbody>
</table>

\[ \psi \]

\[ n_{NE} = 0.15 \text{ mrad} \]

\[ e_{xy} = 0.09 \text{ mrad} \]
<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>5</th>
<th>19</th>
<th>29</th>
<th>34</th>
<th>76</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X Noise</strong></td>
<td>1.74</td>
<td>2.2</td>
<td>7.87</td>
<td>3.0</td>
<td>1.7</td>
<td>1.24</td>
</tr>
<tr>
<td>$10^{-14}\ T/\ Hz$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Y Noise</strong></td>
<td>2.8</td>
<td>3.9</td>
<td>--</td>
<td>2.3</td>
<td>1.9</td>
<td>1.3</td>
</tr>
<tr>
<td>$10^{-14}\ T/\ Hz$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Z Noise</strong></td>
<td>2.4</td>
<td>3.4</td>
<td>--</td>
<td>3.4</td>
<td>1.9</td>
<td>1.3</td>
</tr>
<tr>
<td>$10^{-14}\ T/\ Hz$</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
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. 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.