REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

DTIC LECTE
MY 03 1988
DULE

AD-A194 237

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	Approved for public release distribution unlimited
4. PERFORMING ORGANIZATION REPORT NUMBER(S) 3	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 88-0461 AFOSR-TR

6a. NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
New York University		Air Force Office of Scientific Research

6c. ADDRESS (City, State, and ZIP Code)	7b. ADDRESS (City, State, and ZIP Code)
Departments of Physics and Psychology 4 Washington Place – New York, NY 10003	Building 410 Bolling Air Force Base, DC 20332-6448

8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
AFOSR	NL	AFOSR-84-0313

8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS			
	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION N
Building 410 Bolling AFB, DC 20332	61102F	2917	A4	

11. TITLE (Include Security Classification)

CYROSQUID: A SQUID-BASED MAGNETIC FIELD SENSOR

12. PERSONAL AUTHOR(S)
S.J. Williamson and Lloyd Kaufman

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final Technical Report	FROM 8/15/84 TO 11/30/87	88/3/15	17

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	
			cryogenic regrigerator, magnetic sensor, neuromagnetism

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A novel system consisting of a state-of-the-art magnetic field sensor and a low-temperature refrigerator incorporating cascaded cryocoolers has been developed that does not require liquid helium for operation. Called "CryoSQUID", this system consists of a refrigerator contained within the sensor's cryogenic dewar and an external compressor for providing gaseous helium at moderate pressure for closed-cycle operation. The refrigerator has a Gifford-McMahon cooler providing stages at 77 K and 15 K that physically supports a Joule-Thomson cooler operating at 4 K for the SQUID and detection coil. The dewar can be operated in any direction, including upside-down. Developed for studies of the magnetic field of the human brain, the full system consists of two such sensors, each held by a gantry for flexible operation. Residual magnetic noise introduced by the moving displacer of the Gifford-McMahon cooler is essentially eliminated by a computer-based adaptive filter, resulting in a white-noise noise spectral density of about 20 fT/Hz$^{1/2}$.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
Dr. Alfred R. Fregly	202-767-502	NL

DD Form 1473, JUN 86 · Previous editions are obsolete.

AFOSR·TR· 88 - 0 4 6 1

CryoSQUID: A SQUID-Based Magnetic Field Sensor

Cooled by a Closed-Cycle Refrigerator

S.J. Williamson and L. Kaufman
Neuromagnetism Laboratory
Departments of Physics and Psychology
4 Washington Place
New York University
New York, NY 10012

Introduction

A new type of neuromagnetometer has been developed to enhance the capability for measuring the magnetic field of the human brain. This system – known as "CryoSQUID" – results from the marriage of two advanced technologies: a refrigerator incorporating closed-cycle operation of a pair of cryocoolers and a sensor incorporating the superconducting quantum interference device (SQUID). The apparatus is relatively small and requires no supply of liquid helium for initial cooling or operation. Only a source of electrical power is needed. Each sensor relies on a detection coil wound in the geometry of a second-order gradiometer so as to minimize the effects of ambient magnetic noise found in typical unshielded environments. The intrinsic noise level of CryoSQUID is comparable to a magnetic field sensitivity of 20 femtotesla within a one-hertz bandwidth. Residual noise at 1.2 Hz and its harmonics, contributed by the displacer in the Gifford-McMahon cooler, is virtually eliminated in real time by an adaptive filter run on a personal computer.

CryoSQUID Development

During the past decade there has been continued interest in developing closed-cycle refrigerators to cool SQUID-based magnetometers. The motivation stems from a variety of applications, including the study of biomagnetic fields (Zimmerman and Radebaugh, 1978; Cox and Wolf, 1978; Sullivan, Zimmerman, and Ives, 1981; Tward and Sarwinski, 1985). Such a system may offer enhanced flexibility in operation and lower operating cost in areas where liquid helium is expensive. Its use may prove to be more reliable than services that deliver liquid helium. Moreover, it could be operated in a remote environment where providing liquid helium is difficult or impossible, and it could be operated without need for constant attendance. An even greater advantage is that with certain types of refrigeration and cryostat design, such a magnetic sensor can be oriented in any direction, including upside-down, so the sensor could detect a chosen component of the local field. This is particularly useful in neuromagnetic applications when measurements over the side of a subject's head are desired. This can be of great value in studies of visual cortex when a sitting subject views diplays presented in the upper half visual field. Then the dominant activity in the visual center of the brain takes place below the inion, and the corresponding fields extend over the lower back of the head and even into the neck.

88   5   02   179

With funds from this AFOSR grant, we conceived a system that would be appropriate for neuromagnetic measurements of the human brain. After discussing such a development with potential sub-contractors, we selected Biomagnetic Technologies Incorporated (BTi) in San Diego as the partner for this project. The reasons for this choice include: (1) dc-SQUIDs of that company exhibit the lowest noise of any available commercially; (2) the personnel have had extensive experience in developing a variety of cryogenic devices whose technologies were relevant; and (3) the company was willing to cost-share the development. Drs. Scott Buchanan, Douglas Paulson, and Duane Crum (Vice President for Development) were principally responsible for the technical innovations. Major decisions were made in consultation with personnel of the Neuromagnetism Laboratory.

One of our requirements for the system was that there be no mechanical linkage between the CryoSQUID dewar and an external device, such as a motor, so that flexibility can be maintained in orienting the sensor. This implied that the system would have to rely entirely on cycling helium gas between the dewar and an external source of refrigeration power. Early evaluation of a system relying entirely on a four-stage Joule-Thomson system indicated that the cooling requirements of the high-temperature stages would require massive rates of gas flow to achieve a sufficiently rapid cool-down from room temperature. As our performance target was a 24-hour cool-down, such a large system was deemed unacceptable. Following the evaluation of several possible methods of refrigeration, a combination of a Gifford-McMahon cooler to establish a temperature of about 15 K and Joule-Thomson cooler to provide a steady temperature below 5 K was chosen. Both require only a pair of thin, flexible helium gas lines.

Gifford-McMahon Cooler

The Gifford-McMahon cycle requires two pressure resevoirs and a way of alternatively connecting those resevoirs to an expander where cooling takes place. The expander is a long chamber within which a displacer is driven back and forth by the gas. The cooling cycle proceeds as follows. High pressure gas is admitted to the expander while the displacer is toward the warm end of the chamber. The expander is then connected to the low pressure side. The expansion of the gas provides cooling. The displacer then shuttles the cooled gas back to the warmer region at the top, extracting most of the cooling as the gas is transfered. The cold surfaces of the expander are used to pre-cool the high pressure, warmer incoming gas, which is then once again expanded to provide additional cooling. This regenerative type of heat transfer can be very efficient. A particularly attractive feature of the Gifford-McMahon cooler is the extensive experience that various manufacturers have had in producing commercial versions. This has resulted in the production of equipment of high reliability and acceptable price. Several commercial units were evaluated by BTi, and one was chosen on the basis of low vibration, low magnetic background, simplicity, and high reliability.

The compressor provides helium gas at a pressure of about 300 psi to the displacer, and the return gas has a pressure at about 100 psi. Pressures are kept above atmospheric pressure to reduce the possible inflow of air should the system develop a small leak. Figure 1 shows a photograph of the compressor together with a gas handling system during

system testing at BTi. The gas handling system insures safety by including a pressure-release connection to a large-volume gas tank, so should blockage occur in the feed line the gas would be dumped into this tank.

Joule-Thomson Cooler

Joule-Thomson cooling is achieved by allowing high-pressure gas to expand through a high impedance orifice into a low pressure region. The supply pressure was chosen to be the same as for the Gifford-McMahon cooler (300 psi), and the low-pressure return is slightly greater than atmospheric pressure (15 psi). Since sufficient cooling can be produced to liquify helium, a small chamber was included in the Joule-Thomson stage to store this liquid as a thermal "mass" in the system. The advantage of this arrangement is that any temperature variations that might result from changes in supply pressure would be smoothed out temporally.

The liquid helium reservoir also permits the valve motor of the Gifford-McMahon stage to be turned off for periods of time as long as 20 minutes *to completely eliminate magnetic noise contributed by the refrigerator* when ultimate field sensitivity is required. The Gifford-McMahon stage can then be started again by running the valve motor to regain temperature equilibrium throughout the system. Shorter shut-down intervals can also be carried out on a periodic basis, as when recording sensory evoked responses, and the Gifford-McMahon cooler run during the intervals when repositioning dewars for the next measurements.

Dewar

A key feature of CryoSQUID is the use of a small dewar for ease in supporting and positioning the sensor. Its total weight is less than 12.5 kg. Figure 2 shows the dewar oriented vertically, with gas tubes attached to the top. There is a common vaccuum space within the entire dewar for thermal insulation. The body of the dewar is fiberglass, and a narrower tail section extends well below the body to house the detection coil. This geometry affords generous space for the coolers and yet permits the detection coils of both CryoSQUIDs to be placed close together when the tails of the two dewars touch. The body of the dewar supports a header at its top, with removable ports for input and output connections. At the top of the header is mounted a set of black convection-cooling fins for the Gifford-McMahon cooler. The fins become quite warm (60 C) during initial cool-down when heat is removed from the system at a substantial rate, but during steady operation their temperature is comfortable to the touch. The total length of the dewar from the top of the cooling fins, where the gas tubes attach, to the bottom of the tail is 92 cm. The diameter of the tail is 5.7 cm. Figure 3 shows the interior structure with the dewar removed. The top portion of the interior of the header, is depicted in Figure 4.

The cool-down time from room temperature is 22 hours when both CryoSQUID units are cooled simultaneously. Once at the operating temperature, the heat leak into the interior is only about 20 mW. The temperature of the SQUID is sufficiently stable that there is no evidence of temperature fluctuations affecting its noise level.
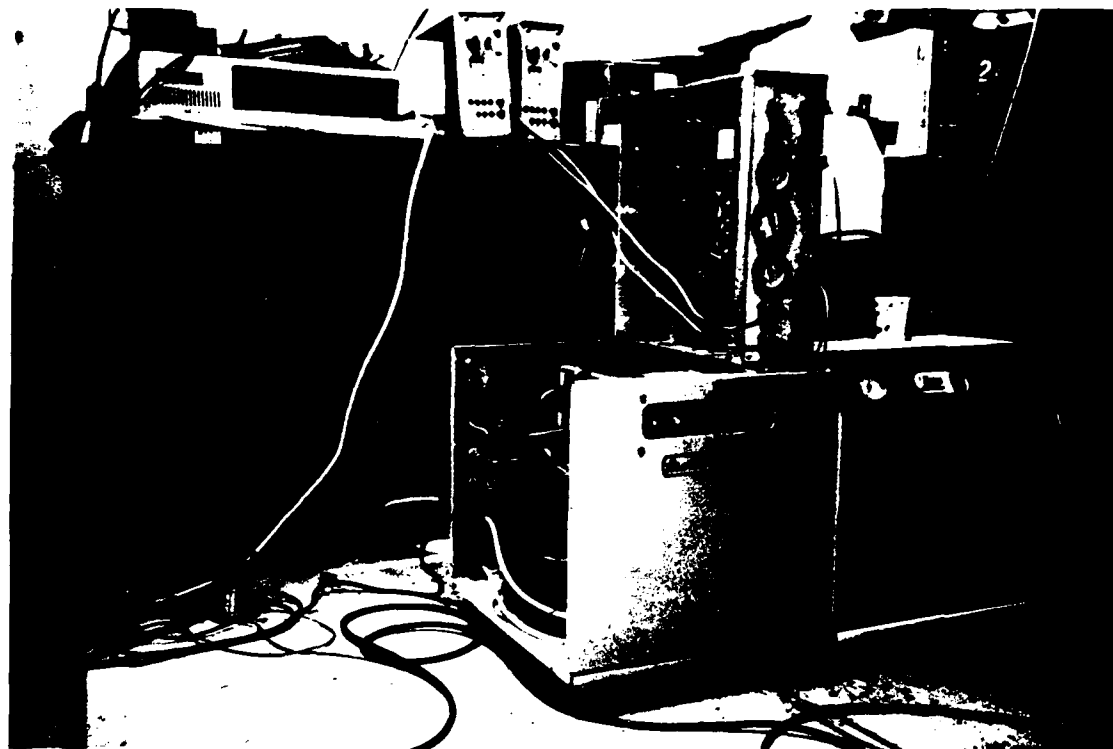
Figure 1. Compressors for Gifford-McMahon and Joule-Thomson coolers (bottom units) and automated gas-handling system (mounted above them).
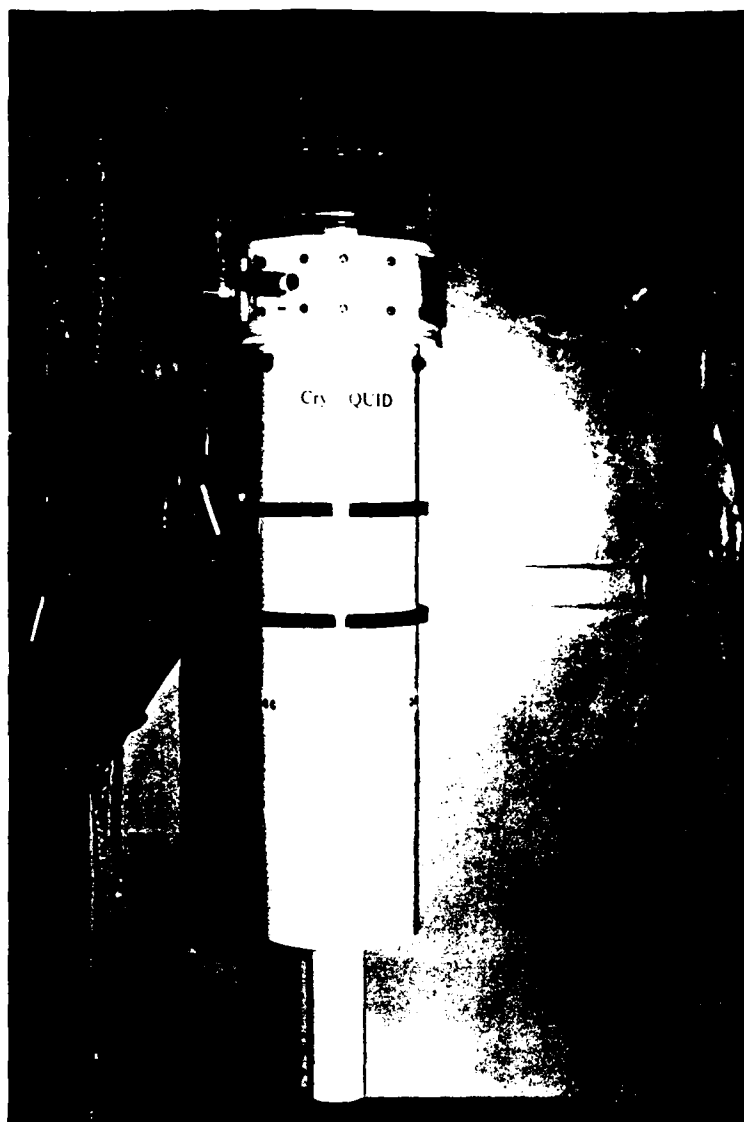
Figure 2. Dewar held in the vertical position, with gas supply and return tubes extending from the top and SQUID electronics unit placed just to its left. Its total length is 92 cm.
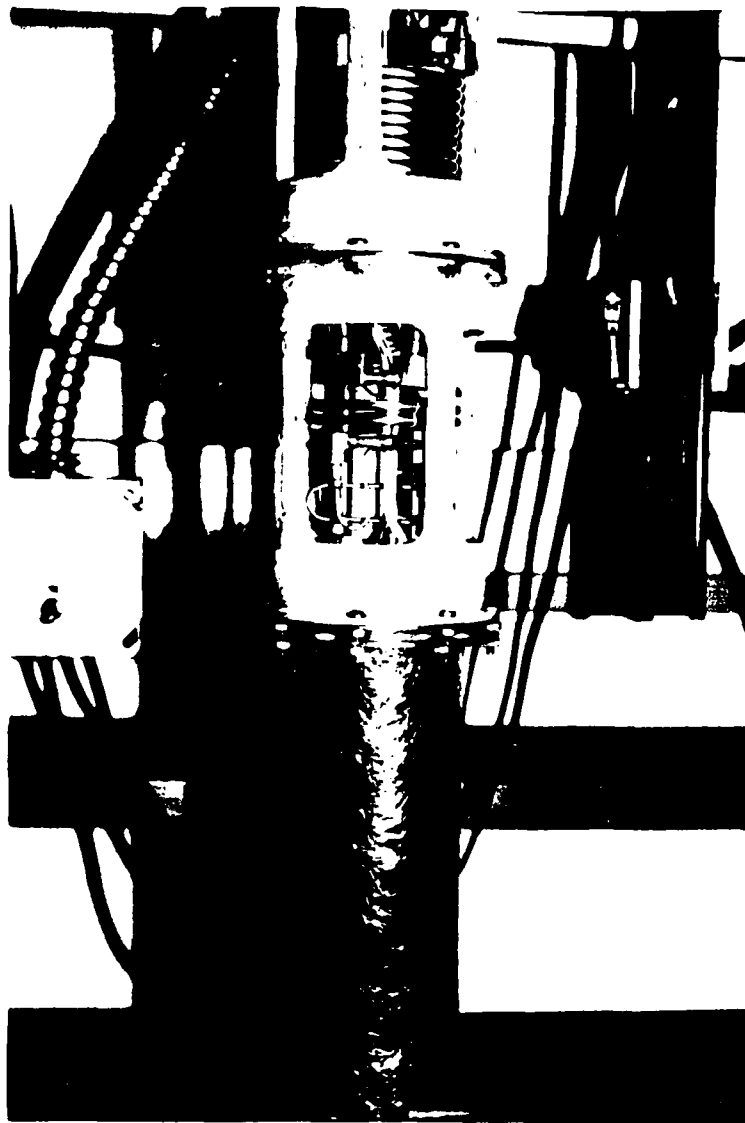
Figure 3.   Interior structure of the dewar assembly with the body of the dewar removed. Superinsulation at the bottom covers the region of the Joule-Thomson cooler, SQUID, and detection coil. Exposed through the cutaway in the white supporting structure are heat exchangers that cool the incoming helium for the Joule-Thomson cooler.

Figure 4. Upper portion of the dewar assembly showing gas input and output ports for the Joule-Thomson cooler on the outside of the header. Inside the header and lower down are mounted heat exchangers for cooling the incoming gas and heat switches for increasing efficiency of the initial cool-down.

SQUID System

A commercial BTi dc-SQUID system is used as the magnetic sensor. It consists of a niobium-based SQUID, Model 40 SQUID Electronic Control, Model 400 unit providing bias currents and preamplifier, and a superconducting flux transformer. This transformer is a closed superconducting circuit consisting of an input coil mounted in close proximity to the SQUID and a detection coil wound on a former suspended at the bottom of the dewar's tail to respond to the field of interest. To minimize the pickup of unwanted ambient field noise, the detection coil has the geometry of an axial second-order gradiometer, with center coil having twice as many turns and wound in the opposite sense as each end coil. The baselength is 5 cm between each end coil and center coil, and the coil diameter is 2 cm. The area-turns balance is quoted as 2×10^{-4} or better overall, and 4×10^{-5} along the axial direction.

The input sensitivity of the SQUID system is quoted as 1.2×10^{-7} ampere in the input coil creating one flux quantum in the SQUID (i.e., 1.2×10^{-7} A/ϕ_o). The voltage gain factor is quoted as 5.2 mV output from the SQUID Electronic Control per flux quantum in the SQUID (i.e., 5.2 mV/ϕ_o). The measured SQUID system noise is 20 fT/Hz$^{1/2}$ at 400 Hz, and this was found to be white noise at the same level down to frequencies below 1 Hz. Both SQUID systems have virtually identical performance.

Installation

The CryoSQUIDs are installed in the Neuromagnetism Laboratory of NYU in the same magnetically shielded room (MSR) as houses a five-sensor neuromagnetometer system (called "Freddy"). This enables us to use the three dewars together for simultaneous measurements of brain activity in three widely separated areas of the head. In studies of a sensory-motor task this would be, for example, an auditory or visual sensory area, a motor area, and a somatosensory area. The arrangement enables us to follow neural activity from primary sensory areas to motor area, and monitor the somato-motor feedback loop as a subject responds with a manual task to instructions. Or in another example, it will permit monitoring of sensory, parietal, and frontal areas which are important in tasks involving judgement and discimination.

To permit independent movement of the dewars, Freddy has been mounted in a new overhead gantry system supported by the ceiling of the MSR. Each CryoSQUID dewar is supported by a different type of non-magnetic gantry that reaches out from opposite sides of the MSR and provides three-point support (see Figure 5). When the dewar is positioned, the operator presses a switch, and a vaccuum system secures the leg to the floor and applies a friction break to each joint in the arms. The MSR reduces ambient magnetic noise to below the white noise of the sensors, for frequencies as low at 0.8 Hz. It also provides another advantage in that the residual field inside is weaker by a factor of 10^3 than the earth's field. Therefore magnetic noise introduced by the susceptiblity of the Gifford-McMahon displacer is reduced by a similar factor.

Each CryoSQUID gantry has a vertical supporting "leg" where the arms join. Once the gantry is positioned so that the dewar is properly oriented with respect to the
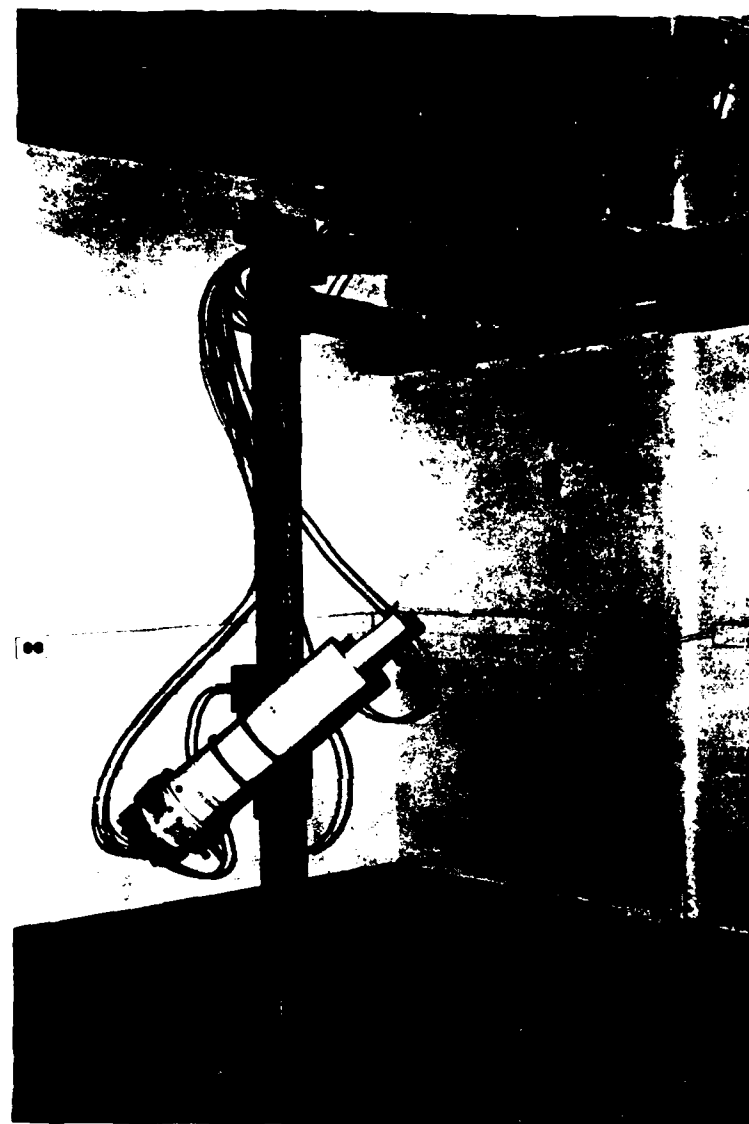
Figure 5. CryoSQUID supported by its gantry is oriented in an upward facing direction. The gantry provides three-point securement: an articulated arm (upper one), a fixed-length arm (lower one) whose attachment at the wall slides along a rail, and a leg that slides across the floor. The dewar is held to the leg by a counter-weighted carriage that moves up and down, and the the dewar can be rotated about a horizontal axis and vertical axis. Once positioned, all flexible joints and the bottom of the leg are secured by vacuum clamps.

Neuromagnetism Laboratory   **New York University**

subject's head, a vacuum hold-down secures the leg to the floor. To prepare a proper surface for the vacuum hold-down, the original carpet provided with the MSR was removed, a layer of masonite was secured to the underlying wood floor, and layer of linoleum was glued to the masonite. The firm linoleum surface makes it easy to move the CryoSQUID gantries and insures tight holding when the vacuum is established.

The CryoSQUID compressors are installed in an adjacent laboratory room to minimize acoustic noise within the MSR. Small holes through the sides of the MSR admit the gas lines with no detectible compromise in magnetic shielding. The personal computer for adaptive filtering is placed just above the operator's console at the entry to the MSR. When conducting studies, the operator can control the entire procedure of data acquisition from a single console placed within the MSR, if desired.

Probe Position Indicator

The position of each dewar relative to the subject's head will be determined by a system developed by BTi called the *Probe Position Indicator*. It is a modified version of the McDonald-Douglas Polhemus system developed for the Air Force. Ordinarily a PPI transmitter is mounted on the SQUID system's dewar, and three PPI sensors are held against the subject's head by a Velcro^{TM} band. The PPI program as modified by BTi determines the position and orientation of the dewar relative to the set of sensors by sending in turn a high-frequency sinusoidal current through three mutually orthogonal coils of the transmitter, and the induced voltage in each of three mutually orthogonal coils in each sensor are measured. From the 18 amplitudes of induced voltage, the 6 parameters determining the position and orientation of the dewar are computed by a dedicated integrated circuit.

Because PPI can accommodate only two transmitters and three sensors, One magnetic transmitter is mounted on the dewar containing Freddy, and a second transmitter is mounted on one of the CryoSQUID dewars. Two sensors are held against the subject's head by a Velcro band, and a third sensor will be mounted on the second CryoSQUID dewar. In this way the position of Freddy's dewar and one CryoSQUID dewar can be determined by a slightly modified BTi software routine. Additional software is being developed in the Neuromagnetism Laboratory to determine the position of the other CryoSQUID dewar on which the third sensor is mounted. This method is expected to achieve an accuracy of better than 2 mm in determining the position of all three dewars relative to the subject's head. Such accuracies have been verified for a single dewar. The use of PPI for CryoSQUID will greatly enhance the speed with which SQUID sensor positioning can be made and recorded.

Adaptive Filter

Movement of the Gifford-McMahon displacer introduces undesirable noise at 1.2 Hz and its harmonics. Figure 6A gives an example of a recording made at BTi, showing the resulting noise peaks in a noise spectrum (Buchanan et al. 1988). These data were obtained with the system in a mu-metal^{TM} can to shield the system from ambient field noise, as the MSR does. Because of the stable temporal character of the vibrational
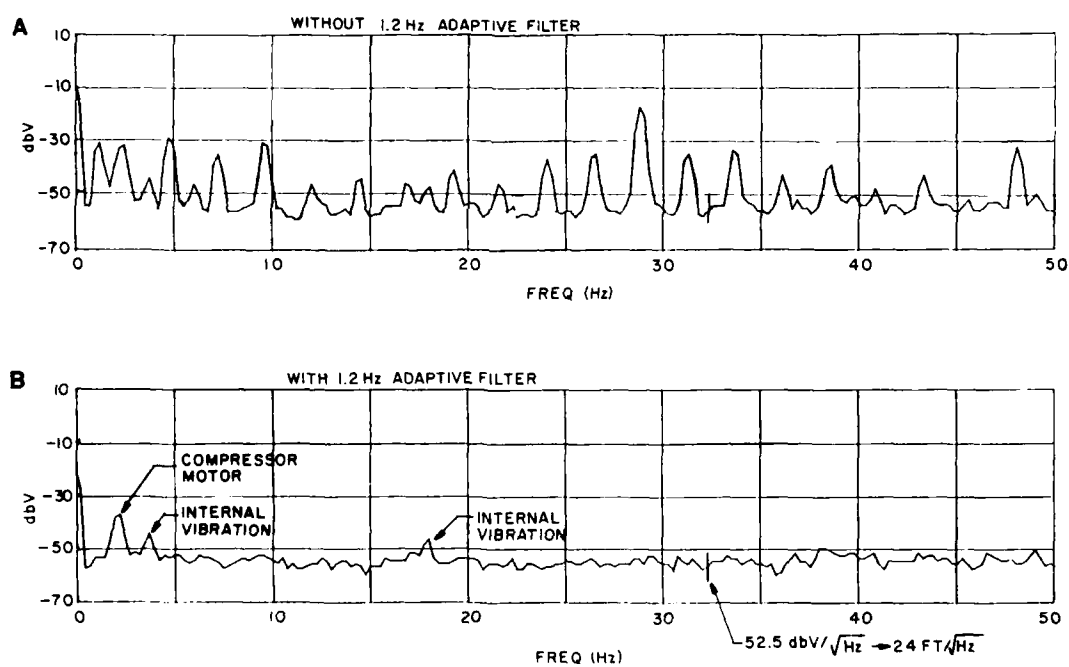
Figure 6. Noise spectra of a CryoSQUID when the dewar is positioned vertically in a magnetic shield: A) When the system is operating without adaptive filter, B) When operating with the adaptive filter.

noise, for a given dewar orientation, most of it can be eliminated by the use of a computer-based adaptive filter as shown in Figure 6B. Here the noise characteristics were monitored for about 30 seconds and averaged by computer with a reference synchronized to the Gifford-McMahon basic period. Thereafter this template can be subtracted from the sensor output in real time to produce the relatively flat spectrum shown in Figure 6B.

Additional noise spectra are shown in Figure 7, with the dewar operating at a $90°$ tilt (i.e., horizontally). In this case, however, the dewar was not shielded magnetically. Figure 7A shows the compressor and valve motor running with no filtration. The vibrational peaks range from 10 db to 35 db above the background. Because the compressor was near the magnetically unshielded sensor, its noise is also registered at 2.5 Hz. In addition to these instrumental peaks there are numerous environmental peaks as demonstrated in Figures 7B and 7C. All these peaks as well as the compressor peak disappear when the system is operated in the MSR.

A complete noise evaluation of the system is presently underway at the Neuromagnetism Laboratory. One of the prospects to be explored is the degree to which the three reference sensors in Freddy, which provide signals proportional to the three components of the residual field inside the MSR, can be used to reduce the very low frequency environmental noise within the MSR that appears below about 0.8 Hz in both the Freddy and CryoSQUID sensors. Such electronic noise cancellation techniques have been shown to improve the noise level in Freddy so that noise spectra remain flat down to about 0.1 Hz (Williamson et al. 1988).

Data Acquisition System

A Hewlett Packard 6942 data acquisition unit has been connected to the Neuromagnetism Laboratory's Hewlett Packard 9000 Model 550 computer. A pair of BTi amplifier/filter boards – identical to those used for Freddy's signal channels – have been installed to process the CryoSQUID signals. In this way the bandpass filters are exactly matched so that signals from Freddy can be directly compared with those from the CryoSQUIDs. Software has been developed and installed so that the computer can accept data from both Freddy and the CryoSQUIDs simultaneously. Also, software has been developed by Bti to allow the CryoSQUIDs to be turned off automatically during data acquisition to eliminate the 1.2 Hz noise (both magnetic and acoustic). Terminals have been installed to display the data for guidance of the operator when conducting an experiment and subsequently to display the processed data off-line. In addition to the original cost-sharing contribution from NYU, the university has recently provided an AT&T 3B2 Model 400 computer, with a graphics terminal and non-graphics terminal, and two AT&T 7300 microcomputers for program development and data analysis. These communicate with the HP9000 by a serial line and with the rest of the world by ethernet connections.
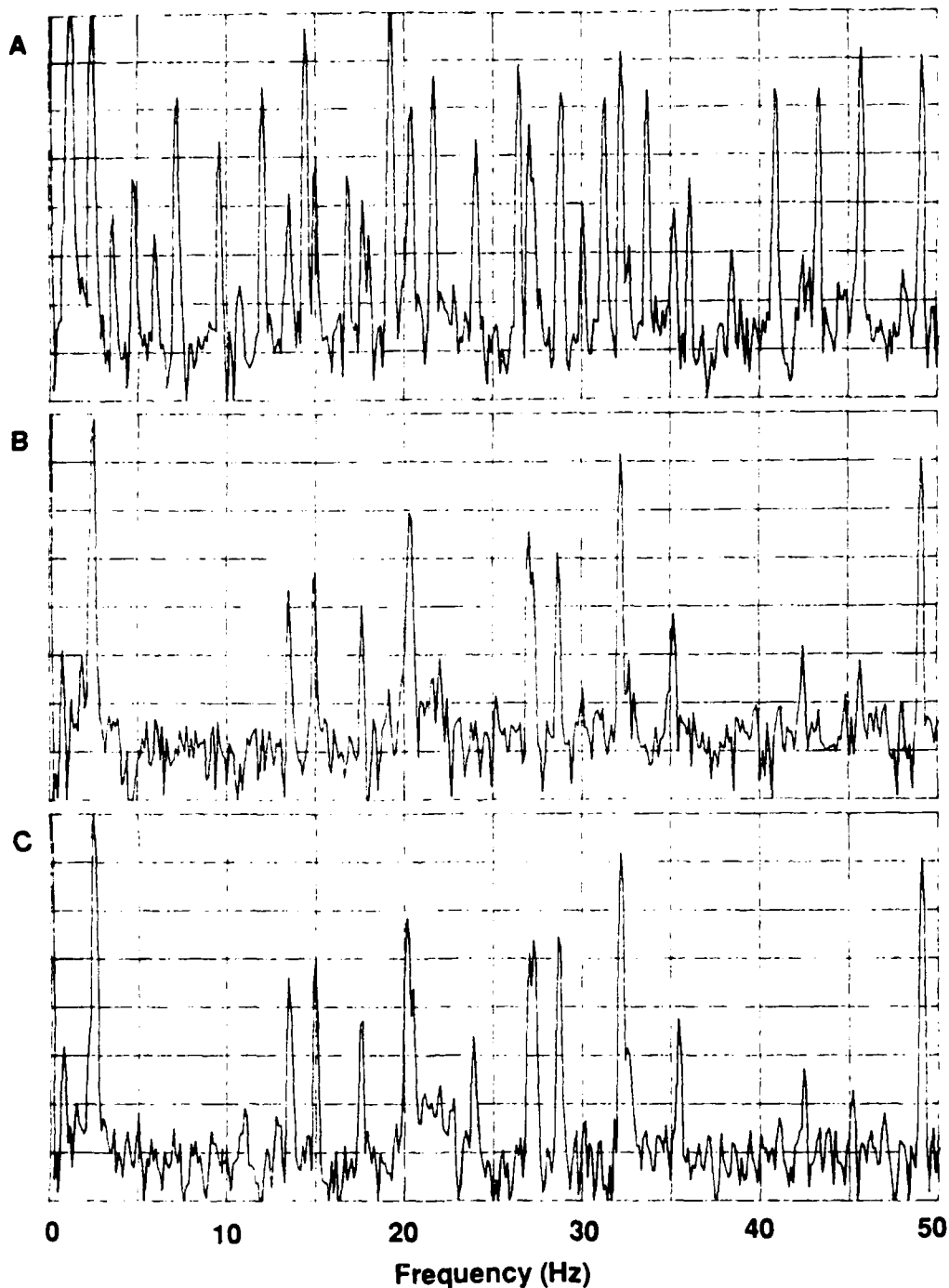
Figure 7. Noise spectra when CryoSQUID is operating horizontally in an unshielded environment in the BTi development laboratory. The vertical scale is logarithmic, with each division corresponding to 4 db. A) Compressor and valve motor operating, with no adaptive filtering of the SQUID output. B) Output signal after being passed through the adaptive filter. C) As for B but with valve motor turned off to elminate all effects of the displacer movement. Aside from the compressor noise at 2.5 Hz, all the peaks correspond to environment noise.

Summary

A SQUID-based magnetic sensing system that relies entirely on a closed-cycle refrigerator has been developed and successfully tested. The white noise level is identical with similar systems operating in a liquid helium environment. Noise contributed by the refrigerator is so stable that it can be adaptively filtered from the real-time record. A gantry has been devised so that CryoSQUID can operate as an independent unit, with support from a wall and floor. Two CryoSQUIDs have been installed in the MSR of the Neuromagnetism Laboratory of New York University and are being used in conjuction with a five-sensor neuromagnetometer, so that activity in three separate areas of the brain can be monitored simultaneously.

References

D.S. Buchanan, D. Paulson, and S.J. Williamson (1988). "Instrumentation for clinical applications of neuromagnetism," in: *Advances in Cryogenic Engineering*, Volume 34, R.W. Fast, Ed. (Plenum Press, New York), in press.

J.E. Cox and S.A. Wolf (1978). "Magnetic and vibrational characteristics of a closed cycle refrigerator," in: *Applications of Closed-Cycle Cryocoolers to Small Supercon-ducting Devices*, NBS Special Publication 508, National Bureau of Standards, pp. 123-129.

D.B. Sullivan, J.E. Zimmerman, and J.T. Ives (1981). "Operation of a practical SQUID gradiometer in a low-power Stirling cryocooler," in: *Refrigeration for Cryogenic Sensors and Electronic Systems*, NBS Special Publication 607, National Bureau of Standards, pp. 186-194.

E. Tward and R. Sarwinski (1985). "A closed cycle cascade Joule Thomson refrigerator for cooling Josephson junction devices," in: *NBS Special Publication 698*, National Bureau of Standards, pp. 220-225.

S.J. Williamson, S.E. Robinson, and L. Kaufman (1988). "Methods and instrumentation for biomagnetism," in: *Biomagnetism '87: Proceedings of the 6th International Conference on Biomagnetism*, K. Atsumi, T. Katila, S.J. Williamson, and S. Ueno, Eds. (Tokyo Denki University Press, in press).

J.E. Zimmerman and R. Radebaugh (1978). "Operation of a SQUID in a very low-power cryocooler," in: *Applications of Closed-Cycle Cryocoolers to Small Superconducting Devices*, NBS Special Publication 508, National Bureau of Standards, pp. 59-65.

END

DATED

FILM

8—88
DTIC