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BTi logo SQUID SYSTEMS

When you need the Best !

When you need a SQUID...

SQUID (Superconducting Quantum Interference Device) measurement systems were pioneered by BTi, (formerly S.H.E. Corporation) introducing the first commercial SQUID in 1970. BTi continues to play a leading role in advancing SQUID technology throughdevelopment of the toroidal point contact SQUID, the thin film toroidal HYBRID SQUID™ and most recently the DYNABIAS™ dc SQUID. BTi SQUID systems are now used routinely by scientists and engineers in laboratories around the world in a variety of research activities:

- **Physics, Chemistry, and Materials Research**
- **Geophysical Exploration and Research**
- **Biomagnetic Measurements, Clinical and Research**

When you need sensitivity...

The SQUID is the world's most sensitive magnetic flux detector. BTi dc SQUID Systems are the most sensitive you can buy. Although the measurement of extremely small magnetic fields is one of their most important applications, their scope of usefulness extends far beyond. Almost any low frequency electric or magnetic signal that can be converted into a corresponding magnetic flux signal will be detected with greater sensitivity using a SQUID than with any other instrument. With appropriately designed systems, the incredible sensitivity of the SQUID can be utilized for measurements over an extremely large range of temperatures (3 x 10^{-8} Kelvin to 800+ Kelvin) and applied magnetic fields (10^{-9} Tesla to 10+ Tesla).

* HYBRID SQUID and DYNABIAS are trademarks of BTi

When you need reliability...

BTi HYBRID SQUIDs are the most dependable SQUID Systems available — and they have the track record to prove it. Even in the field, replacement is quick and easy — and no recalibration is required. It may even be possible to upgrade an old SQUID system to a state-of -the-art BTi SQUID system.

BTi SQUID SYSTEMS

BTi offers self-contained, easy to use SQUID-based measuring instruments designed for use in a broad range of disciplines: physics, geology, geophysics, chemistry, medicine, biology, ... With a liquid helium loss rate so low that a single transfer lasts many days or weeks, these systems combine the on-off convenience of many conventional instruments with the unequaled sensitivity of the SQUID.

When you need a SQUID System...

A simple SQUID system is shown in Fig. 2. The sensor and its associated input circuitry must be operated at cryogenic temperatures. The most common means of providing this cryogenic environment is through immersion in liquid helium. Liquid helium containers, or dewars, specifically designed for SQUID use are available from BTi with capacities sufficient to operate the SQUID for weeks between refills. A transmission line connects the SQUID sensor to room temperature electronics, a pre-amplifier located at the helium dewar and a separate control unit from which the output signal is obtained.

figure 2

When you need LABORATORY SYSTEMS ...

BTi laboratory SQUID systems are extremely sensitive instruments designed to detect small electromagnetic signals. By combining SQUID electronics with various special purpose probes and auxiliary electronics, laboratory systems having a variety of capabilities are made available, having the ability to measure properties such as:

- **Magnetic Fields and Gradients**
- **Magnetic Moments and Susceptibilities**
- **Electric and Magnetic Fluctuations**
- **dc Voltage, Resistance, and Current**
- **ac resistance, self and mutual-inductance**

BTi standard systems are listed below. Each builds on the capabilities of the preceding system to provide maximum flexibility and adaptability to your specific needs.

figure 3. Model BMS - BTi's Simplest SQUID system

• **Model BMS Basic Measuring System**

The Model BMS is capable of measuring small electric currents with a noise level less than 10^{-11} A/$\sqrt{Hz}$. With a simple pickup coil, it also can be used for the detection of magnetic fields as small as 1 fT (10^{-15} Tesla).

• **Model PMS Picovolt Measuring System**

This cryogenic dc voltage amplifier with a gain of 10^8 and a rms noise of less than 10^{-13}Volts/$\sqrt{Hz}$ is used for measurements of very small voltages and resistances.

• **Model MPS Multi-Purpose System**

This system is a low impedance ac bridge system for extremely sensitive resistance and inductance measurements. Resolutions of 10^{-10} Ω and 10^{-7} μH are readily obtained. The Model MPS also has the combined capabilities of the BMS and PMS systems and allows a wide range of both ac and dc measurements to resolutions of 0.001% on single or multiple samples.

• **Model MTS Millikelvin Thermometry System**

The Model MTS combines the Model MPS with a compact easily installed Cerium Magnesium Nitrate (CMN) thermometer to form a thermometry system capable of measuring temperatures from above 6 Kelvin to less than 5 milliKelvin.

CMN thermometer assemblies are available for temperature measurement directly in liquid helium or for external attachment to an experimental package. The thermometers are easily moved so that they can be used in a variety of experimental configurations. In addition, the ability of the Model MPS to permit the measurement of multiple samples allows for multiple thermometers or a combination of thermometers and samples. Options for use with the Model MTS include the BTi Model 1000 Potentiometric Conductance Bridge/Controller permitting computer operated temperature control to 5 milliKelvin.

- **Model DBS dc SQUID System**

Expanding on the capabilities of the Model BMS, this system utilizes the Model DSQ double junction HYBRID™ dc SQUID sensor and the Model 440 DYNABIAS Bias/Feedback electronics to give the lowest noise level (<1.5 x 10^{-12} Amp/$\sqrt{Hz}$) ever achieved by a commercially available SQUID. The Model DBS is also available in multi–channel configurations.

- **Custom SQUID Systems**

BTi will produce SQUID Systems designed specifically to fit your needs. If your needs are unique, contact BTi to discuss your particular requirements. BTi's 15+ years of experience working with research scientists, and an ever-increasing quest for refinement of its product line, ensures that BTi can manufacture the ideal SQUID System to suit your needs.

When you need Geophysical Systems . . .

Magnetotellurics, magnetic detection of induced polarization, and other magnetic detection methods are important geophysical tools. Superconducting magnetometers and gradiometers offer several advantages over other detectors commonly used for such measurements.

- **Exceptionally Low Temperature Drift**
- **Constant Sensitivity from dc to 20 kHz**
- **Magnetic Field Resolution of 10 $^{-14}$ Tesla**
- **Gradient Resolution of 10 $^{-17}$ Tesla/meter**
- **Dynamic Range of 140 dB**

figure 4. BTi Geophysical systems are well suited to field use, being rugged, reliable, fast to set up, and easy to use.

The standard (Model GMSX) Geophysical system magnetometer insert includes three mutually orthogonal pickup coils allowing simultaneous data collection of all three vector field components. Other magnetometer or gradiometer configurations are available.

When you need Biomagnetic Systems . . .

Functional activity of the central nervous system and muscle action produce electric currents. These currents, generated by ion flows, can be detected magnetically with BTi SQUID Biomagnetometers.

The magnetic detection of bioelectric phenomena yields information that is difficult or impossible to obtain with classical electrical techniques such as ECG, EEG, and EMG. The principal promise of biomagnetism lies in its specificity and noninvasive approach. New areas opened to practical research through use of the BTi SQUID include:

- Single and multichannel Neuromagnetometers™ for measuring brain function (magnetoencephalography)

- Ferritometer™ for measuring hepatic iron stores in the Liver

- Instrumentation for measuring lung function and quantitative assessment of contamination levels (magnetopneumography)

- Biomagnetometers for measuring heart function (magnetocardiography)

- Instruments for investigating peripheral nerve and muscle activity

Fig. 5 14 channel Neuromagnetometer (BTi Model 607-25D)

BTi is the leading supplier of DELETION biomagnetic instrumentation. Multi-axial magnetometer and gradiometer configurations are available with sensitivities to 10^{-14} Tesla/$\sqrt{Hz}$. Operation without magnetic shielding is possible using first or second derivative gradiometers which reduce uniform field noise by 10^6 or more. Additional information about this exciting application of SQUID technology is available from BTi on request.

* Neuromagnetometer and Ferritometer are trademarks of BTi

COMPONENTS

When you need SQUID Electronics...

BTi electronics are the industry standard worldwide -- and they have been for over 15 years.

- **Low Noise**
- **Large Dynamic Range**
- **Wide Bandwidth**
- **Unsurpassed dc Stability**
- **Fully Remote Tuning and Operation**

BTi electronics are the most versatile, easiest to use SQUID–based electronics available. They incorporate a number of unique important features that dramatically improve performance, both in the laboratory and under the most difficult field conditions.

- **Model 330X rf SQUID electronics**

The Model 330X consists of the Model 300X low noise rf head and the Model 30 SQUID Control electronics. Renowned for their reliability and ease of operation, the 330X electronics offer a large (134 dB) dynamic range, unsurpassed dc stability and fully remote tuning and operation. The Model 30 offers three gain stages, five filter settings, and three operating modes with differing slew rates.

- **Model 440 DYNABIAS dc SQUID electronics**

The Model 440 employs a unique* bias and demodulation design to realize the lowest noise SQUID system ever offered. This DYNABIAS technique permits substantial reduction in the low–frequency noise which has limited dc SQUIDs in the past. The Model 440 consists of the Model 400 Feedback/Bias unit and the Model 40 Control electronics. Like the Model 330X electronics, the Model 440 electronics offers simple remote tuning and operation. It also offers an even larger (162 dB) dynamic range, and inputs for computer control.

The Model 40 offers four gain stages and two operating modes. An optional filter board for the Model 40 offers the choice of three low–pass filters, three high-pass filters, and a sophisticated comb filter. Like the Model 330X electronics, the Model 440 is capable of either power line or battery operation.

- **Model 48 Multi–Channel dc SQUID Controller**

The Model 48 dc SQUID controller allows simultaneous control of up to eight Model 400 Feedback/Bias units. Similar in function to the the Model 40, it allows remote operation of the Model 400 Feedback/Bias units, DELETION at a significant savings in cost.

When you need SQUID SENSORS . . .

- **Lowest Noise**
- **Highest Slew Rates**
- **Greatest Reliability**

By combining the inherent reliability of a niobium thin–film tunnel junction with the proven advantages of a bulk–niobium toroidal SQUID body, BTi has created the first high performance SQUID sensors* that are practically indestructible. The excellent coupling and self-shielding of a toroidal SQUID body is combined with tough niobium thin film junctions that are immune to repeated thermal cycling and prolonged room temperature storage. The reliability of this SQUID sensor is unsurpassed, yet it retains the low noise and exceptionally low drift characteristics that were previously available only from comparatively delicate point-contact devices. The toroidal geometry protects the weak links from exposure to stray magnetic fields and improves the coupling to external pickup coils, giving a greater usable sensitivity.

figure 6. Model HSQ

- **Model HSQ rf HYBRID SQUID Sensor**

The Model HSQ is a single junction rf SQUID sensor that offers the best performance of any commercial rf SQUID sensor with an energy sensitivity better than 10^{-28} Joule/Hz. The response of the Model HSQ is extremely linear (better than 1 ppm). Its compact construction allow easy removal and it is a direct replacement for the SHE Corporation Model TSQ SQUID sensor. It Is robust and abile to operate in fields approaching 1 kilogauss ; it is the ideal choice for operation in extreme environments.

- **Model DSQ dc HYBRID SQUID Sensor**

The Model DSQ is a double junction dc SQUID sensor offering the highest sensitivity (10-30 Joule/Hz) available. The use of DYNABIAS electronics allow this performance to be extended down to the one Hertz region, something never before available.

By virtue of its exceptional low noise and wide bandwidth, the Model DBS is well suited for many applications, including laboratory, biomagnetic, and geophysical measurements. It may be possible to substitute the Model DSQ for an existing rf SQUID sensor. Upgrading an existing BTi or SHE magnetometer system for geophysical and biomagnetic use is facilitated by retrofit kits available from BTi. BTi application engineers should be consulted for additional information concerning upgrading existing SQUID systems.

* U. S. Patent #4,403,189

When you need SQUID PROBES . . .

- **Ultra sensitive**
- **Multiple Measurement Capabilities**
- **Easy Installation**

BTi manufactures four basic SQUID probes for general laboratory use. These probes are designed to be used while immersed in a liquid helium bath. A room temperature O-ring seal allows pumped dewar operation.

A superconducting niobium cylinder surrounds the SQUID sensor and provides magnetic shielding of the sensor input terminals. Input leads, usually a shielded, twisted pair of superconducting wire, are attached to the sensor input terminals. This makes attachment of your experiment a simple process.

In all BTi probes, construction materials are non-magnetic and carefully selected to minimize conduction of heat into the helium bath. All probes (except for the SPD) are doubly shielded against rf interference and other electrical transients that may affect the SQUID operation. Probes are available separately for upgrading older SQUID systems or for expanding the capabilities of a more recently purchased system.

figure 7 Models SP, SPD, MFP, DP, and SEC

- **Models SP** DELETION, **SPD**, and DP **Magnetometer Probes**

The Models SP rf SQUID probe and DP dc SQUID probe are supplied with the Models BMS and DBS respectively. They offer easy access to the SQUID sensor, and are most commonly used as a magnetometer or galvanometer (i.e., a null detector).

The Models SP and DP are rigid probes designed for direct immersion. For installations requiring a flexible probe, a 1/16" diameter version of the SP, the Model SPD, is available.

- **Model MFP Multi-Function Probe**

The Model MFP probe is the most versatile of all BTi SQUID probes. It combines full picovoltmeter, magnetometer, and ac bridge capabilities in a compact, easy-to-use design. The probe itself is similar in design to the Model SP with a few important additions. These include additional room temperature circuitry located in a vacuum sealed housing. Also, the Model MFP accommodates a small cryogenic terminal board with the resistance and mutual inductance standards required for voltage and impedance measurements. Rewiring of the probe to change its

function is easily accomplished by moving a few jumper wires located on the terminal board. Its great versatility makes this the recommended probe when a variety of applications is required.

- **Model SEC Remote Terminal Board**

In many experimental arrangements, the signal measured by the SQUID is derived from a source within an evacuated chamber (e.g., a vacuum can) that is immersed in liquid helium. The SEC Remote Terminal Board (Fig. 5) enables these signals to be transferred to the SQUID probe which is located outside in the liquid helium.

SPECIAL MATERIALS

Each BTi SQUID probe is supplied with a package containing often-used items. These include PbSn superconducting tubing, lead foil, NbTi superconducting wire, and assorted spare #0-80 UNC machine screws and flat washers. In addition, BTi maintains a supply of materials which are useful in cryogenic work. These are available in small quantities. In addition to the above items, BTi offers fiberglass sleeving, copper-nickel tubing, low thermal conductivity coaxial cable and soap-glycerine sealing compound. A complete listing of currently available items may be found in the miscellaneous item price list.

BTi has the SQUID System to suit your needs ...
call us for more information today.

The superconducting quantum interference device (commonly known by the acronym SQUID) was invented in the early 1960's but remained a laboratory curiosity for years thereafter. The development of practical measurement systems based on this remarkable device was pioneered by BTi which introduced the first commercial SQUID in 1970. These systems are now used routinely by scientists and engineers in laboratories around the world. BTi has continued to play a leading role in advancing SQUID technology by introducing the toroidal point contact SQUID, the HYBRID™ thin film toroidal SQUID and most recently the DYNABIAS™ dc SQUID*. Representative systems designed by BTi include:

• Ultrasensitive superconducting magnetometers and gradiometers used for geophysical exploration and research, magnetic anomaly detection and studies of biomagnetic fields;

• Variable temperature, magnetometers and susceptometers;

• Instruments for measuring electric and magnetic properties of materials at very low temperatures;

and

• A high gain, low impedance dc amplifier with a 10^{-4} K noise temperature.

The SQUID is the world's most sensitive magnetic flux detector. It is often referred to as a cryogenic or superconducting magnetometer, and indeed the measurement of extremely small magnetic fields is one of its most important applications. However, the scope of the SQUID's usefulness extends far beyond simple field measurements. Almost any low frequency electric or magnetic signal that can be converted into a corresponding magnetic flux signal will be detected at a greater level of sensitivity with a SQUID than with any other instrument. Applications of SQUID systems have ranged from the investigation of magnetic and electronic properties of materials to the search for geothermal energy sources, from studies of paleomagnetism to biomagnetic research and from the measurement of millikelvin temperatures to the detection and characterization of subsurface magnetic structures on land and at sea.

A simple SQUID system for making external magnetic field measurements is shown in Fig. 1. The sensor and its associated input circuitry must be operated at cryogenic temperatures. As illustrated, the most common means of providing this cryogenic environment is to immerse the SQUID and input circuitry in liquid helium which boils at 4.2 K under normal atmospheric pressure.

Liquid helium containers, or dewars, specifically designed for SQUID use are available from BTi with capacities sufficient to operate the SQUID for weeks or even months between refills. A transmission line connects the SQUID sensor to room temperature electronics, a pre-amplifier located at the helium dewar and a separate control unit from which the output signal is obtained. BTi welcomes inquiries about these instruments and invited interested parties to its plant to become acquainted with their use. In some cases, leasing arrangements can be made. Brochures giving complete descriptions of these instruments are available.
figure 1 schematic of SQUID system with dewa

COMPLETE SQUID SYSTEMS

BTi offers self-contained, easy to use SQUID-based measuring instruments designed for use in a broad range of disciplines; medicine, biology, physics, geology, geophysics and chemistry. With a helium loss rate so low that a single transfer lasts many days, these systems combine the on-off convenience of many conventional instruments with the unequaled sensitivity of the SQUID.

In designing and building these systems, BTi has taken full advantage of its staff's extensive low temperature research experience. Featured are fully automated electronic instrumentation and sophisticated cryogenic design.

Biomagnetic Systems

The magnetic field of the body may be generated by naturally occurring electric currents as well as by magnetic materials in the body. The detection of these fields is a challenging task as their values may be 10^{10} times smaller than the value of the earth's steady field. Further, these fields must be measured in the presence of magnetic noise, which may be seven orders of magnitude larger than the body's field. Only since the development of the SQUID magnetometer and gradiometer has measurement of the full range of magnetic fields associated with the brain, heart, lung, and liver been possible.

New areas opened to practical research by the SQUID include:

- Magnetoencephalography, including the spatial location of neurological activity
- Magnetocardiography, both normal and fetal
- Magnetic studies of lung impurities
- Magnetic determination of liver-iron levels

Several non-magnetic helium dewars are available, some operating for many days between helium transfers. In many, the SQUID sensing coils, at low temperatures, are only 10 mm or less from the subject, at room temperature.

The magnetometer probe includes the SQUID sensor and pickup coils. A wide variety of coil configurations, including multi-axial magnetometers and gradiometers may be obtained. Configurations are available with sensitivities to 10^{-14} T/$\sqrt{\text{Hz}}$ and different coil orientations. Operation without magnetic shielding is possible using first or second derivative gradiometers which reduce uniform field noise by 10^{6} or more.

The electronics include exclusive BTi circuitry that simplifies operation and significantly improves performance when working in noisy magnetic environments. For detailed information on S.H.E. Biomedical Systems, request Brochure BID101.

Geophysical Systems

Magnetotellurics, magnetic detection of induced polarization, and other magnetic methods are important geophysical tools. Superconducting magnetometers and gradiometers offer several advantages over other detectors commonly used for such measurements. These include exceptionally low temperature drift, constant sensitivity from dc to 20 kHz, magnetic field resolution up to 10^{-5} g magnetic gradient resolution up to 10^{-5} γ/ft, and a dynamic range of 140 dB. These systems are well suited to field use, being lightweight, reliable, fast to set up, and easy to use.

In the magnetometer, a single coil connected to the SQUID senses the change in magnetic field and generated an output voltage proportional to this change. For gradiometers, two coils spaced a few centimeters apart and wound in series opposition are coupled to the SQUID. The system generated a voltage proportional to the difference in the field at the coils, a voltage proportional to the gradient. The standard (Model GMSX) Geophysical system magnetometer insert includes three mutually orthogonal pickup coils allowing simultaneous data collection of all three vector field

components. Other magnetometer or gradiometer configurations are available. Request the GMSX brochure or contact S.H.E. for further details.

Absolute Field Magnetometers

The Model FCM absolute field magnetometer allows the unsurpassed sensitivity to be used to determine total magnetic fields. When a loop of superconducting wire is used to detect magnetic field changes (for example in the Model GMSX Geophysical System or by using a Model BMS System), the output is proportional to changes in the magnetic field relative to some arbitrary level. If absolute field information is needed the sensing coil must be rotated 180°. The change in flux penetrating the pickup coils is then twice the magnetic field. The Model FCM Absolute Field Magnetometer allows the user to rotate a superconducting pickup coil 180° in all three axes.

The Model FCM allows absolute field measurements to less than 5×10^{-12} T/$\sqrt{\text{Hz}}$. The standard Model 330X SQUID electronics allow a 134 dB dynamic range.

LABORATORY SYSTEMS

BTi laboratory SQUID systems are extremely sensitive instruments designed to detect small electromagnetic signals. By combining SQUID electronics with various special purpose probes and auxiliary electronics, laboratory systems having a variety of capabilities are made available. Detailed specifications are given in separate data sheets.

Among these systems are:

• Model BMS Basic Measuring System
Comprising the Model SP (or SPD) probe and the 330X SQUID electronics, this system is used for the detection of small electric currents and has a noise level less than 10^{-11} A/$\sqrt{\text{Hz}}$. With a simple pickup coil, it is also useful for the detection of magnetic fields.

• Model PMS Picovolt Measuring System
This is a cryogenic dc voltage amplifier with a gain of 10^8 and an rms noise of less than 10^{-13}V/$\sqrt{\text{Hz}}$. Comprising the Model MFP probe, Model 330X SQUID controller and Model CCS constant current source, this system is used for measurements of very small voltages and resistances.

• Model MPS Multi-Purpose System
Comprising the Model MFP probe, Model 330X SQUID controller, Model RBU impedance bridge and Model BPD biphase null detector and Model CCS constant current source, this system is a low impedance ac bridge system for extremely sensitive resistance and inductance measurement. Resolution of 10^{-10} Ω and 10^{-7} μH is readily obtained. The Model MPS also has the combined capabilities of the BMS and PMS systems to allow a wide range of both AC and DC measurements.

• Model DBS dc SQUID System
Similar to the Model BMS, this system utilizes the Model DSQ double junction HYBRID dc SQUID sensor and the Model 440 DYNABIAS Bias/Feedback electronics to give the lowest noise level (1.5×10^{-12} A/$\sqrt{\text{Hz}}$) ever achieved by a commercially available SQUID system.

• Custom SQUID Systems
BTi has supplied a wide variety of unique SQUID-based instrumentation.

Examples include:

- Current comparator systems to provide ultra-stable current sources.
- Multi-element magnetometer/gradiometers for both geophysical and biomedical applications.
- Cryogenic Noise Thermometers to provide a primary standard for temperature determination.
- Systems designed for detection of Magnetic Monopoles.

Should you have a need for an instrument similar to these or one that is unique to your experimental conditions, you are invited to contact BTi to discuss your particular requirements.

MODEL BMS BASIC SQUID SYSTEM
photo of BMS system

FEATURES

- Large Dynamic Range
- Simple, Reliable Operation
- Unsurpassed dc Stability
- Fully Remote Tuning and Operation

The Model BMS is the most versatile, easiest to use SQUID-based measurement system available. It incorporates a number of unique, important features that dramatically improve performance, both in the laboratory and under the most difficult field conditions. Other BTi SQUID systems use the BMS as their core element, along with special input circuits and additional electronics, to measure a wide variety of parameters including resistance, inductance, voltage, magnetic field, and magnetic susceptibility. The specifications given here describe fully the Model BMS Basic Measuring System and also provide the basis for the specifications of other BTi SQUID systems.

The major components of the Model BMS are Shown in Fig. 1.

- Model SP or SPD probe with HYBRID SQUID™ sensor.
- Model 300X rf head.
- Model 30 Control Unit.

BASIC OPERATING PRINCIPLES

The Model BMS is an ultra-low noise, current sensitive amplifier whose output voltage changes in proportion to the change in current at its input. The input signal is joined to the SQUID sensor, located in liquid helium at the bottom of the SQUID probe, by a pair of superconducting screw terminals. Current through these terminals couples magnetic flux into the SQUID sensor via an integral 2 μH input coil. The sensor also contains an rf coil which is used to inject a 19 MHz bias signal from the Model 300X rf head. The amplitude of the rf bias in the sensor is modulated by the input signal, detected by the rf head, and transmitted via an interconnecting cable to the Model 30 control unit. There it is used to generate a negative feedback signal which cancels the flux change in the sensor caused by the input signal. The amplitude of this feedback signal is therefore proportional to the input current and is used to generate the system output voltage.

In addition to generating the required feedback and output signals, the Model 30 control unit provides other useful functions. These include amplification and filtration of the output signal, remote control of the rf head, and generation of diagnostic test signals.

REMOTE SETUP AND OPERATION

To facilitate the operation of the SQUID system at locations remote from the rf head, all setup controls are located at the control unit, shown in Fig. 3. The SET 1 and SET 2 functions activate special internal test circuits and convert the panel meter into a sensitive tuning indicator. This allows setup adjustments to be made quickly and precisely without auxiliary test equipment. Once set, usually no further adjustments are required, even after warming the probe to room temperature. Control units, rf heads and SQUID probes are easily interchanged and the internal setup functions rapidly re-establish the optimum operating conditions.

Another important benefit of this tuning circuitry is that optimum settings can be established even in the presence of relatively large input signals. For example, magnetometers can be adjusted for optimum performance while exposed to 50 or 60 Hz fields that are six orders of magnitude larger than the magnetometer noise level. This capability, available only from BTi, is often essential for sensitive SQUID magnetometry, and it removes a serious limitation for many other applications.

Standard length for the cable connecting the Model 30 to the Model 300X rf head is 6 m. Longer cables, up to 100m, will not degrade the performance and are available as options.

MULTIPLE SLEW RATES

A significant feature of the control unit is the availability of three operating modes, SLOW, MED, and FAST, each characterized by a different slew rate. The technique used to obtain large linear dynamic range must be examined to understand the critical importance of selectable slew rates. The rf-biased SQUID has an intrinsically periodic response to magnetic flux quantum, Øo (Øo = 2.07 X 10^{-15} Wb).

To obtain an output that is a linear, rather than a periodic function of the input flux signal, a negative feedback is applied to the SQUID sensor such that the flux change due to the input signal is cancelled by the feedback. This is called a flux-locked loop. If the input signal changes at a greater rate than the feedback loop can follow, the output will exhibit occasional discontinuities, or "flux jumps," that result in distortion and may produce a permanent dc output shift.
figure 2 model 300X rf head

When referred to the SQUID input, the slew rate is given as the maximum rate of current change (A/sec) that can be followed without flux-jumping. With the Model 30 control unit, one can track fullscale (100µA p-p) sinusoidal signals at frequencies above 100 Hz. This corresponds to a slew rate in excess of 30 m A/sec. The maximum sinewave input amplitude as a function of frequency for the three operation modes (SLOW, MEDIUM, FAST) is shown in Fig. 7.

Although the user may not intend to measure signals requiring such a large slew rate, situations arise where ambient noise (line-frequency interference, for example) rather than the desired signal determines the slew rate requirement. To recover small signals from a noisy background, it is first necessary that the SQUID system be able to accurately track all signals present at the input, including the noise. Thus, a large reserve slew rate capability is often the deciding factor in performing a given measurement successfully.

It should be noted that a fast slew rate increases the sensitivity of rf interference. Arising from lightning strokes, electric motor arcing, or other phenomena, such interference is almost always present. The existence of several operating modes in the Model 30 allows adjustment of slew rate capability to optimize performance. In the SLOW mode, the system is most able to remain locked

in the presence of large rf transients; ability to track rapidly-varying magnetic signals is greatest in the FAST mode.

RESPONSE TO 200 kHz

The locked-loop frequency response of the Model BMS is essentially flat from dc to 20 kHz in the FAST mode. A separate high frequency output with response extending beyond 200 kHz is provided for signal amplitudes less than 50 µA p-p.
figure 3 mod 30 front panel
SELECTABLE OUTPUT FILTERS

To assist in removing unwanted noise from the output, the control unit also has five low-pass filters with 12 dB/oct rolloff commencing at 100,10, 1, and 0.1 Hz respectively, and a power line frequency notch filter. The filter capacitors always track the output voltage to minimize transients when a new filter is switched into use.

UNIQUE NOISE REJECTION CIRCUIT*
To enhance the system stability in all modes, a novel noise rejection circuit has been devised which selectively discriminates against transients that could not have been caused by proper magnetic input signals. As the result, the system remains locked, even in the FAST mode, under conditions that were previously impossible to handle. In the LOW mode, it has the greatest stability in the presence of electrical transients of any SQUID system we know.

VERSATILE RESET CIRCUITRY

Automatic circuitry takes advantage of the sensor's quantum periodicity to eliminate output saturation and increase the dynamic range of the system. Whenever the output voltage exceeds a value set using the DISCRIMINATOR control, it is reset automatically to the value near zero. It can also be reset manually by depressing a front panel pushbutton or by applying a TTL signal to the SYSTEM INTERFACE connector.

Since the rf biased SQUID response is periodic in flux at the sensor, operation in a flux-locked mode is possible for lock points located in every cycle of the periodic response. Lock points differ in flux by exactly integral multiples of the flux period, Øo, and the system output voltage for operation at these different lock points differs by precisely known amounts. The reset circuitry changes the lock point to that cycle of the periodic response which most nearly corresponds to zero volts output. If desired, the output may then be set precisely to zero by means of the 10-turn OFFSET control which can shift the flux in the sensor by 0-2 Øo.

Since the change in output voltage corresponding to one flux quantum can be precisely measured, it is a simple matter to know the number of quanta traversed by the reset operation. This feature allows an enormous increase of the system dynamic range by counting the resets. TTL compatible signals containing the reset information are provided at the SYSTEM INTERFACE connector for this purpose.

EXCELLENT DC STABILITY

An intensive effort was made to identify and eliminate every principal source of drift. The successful result of this effort is illustrated in Fig. 4. The measurement was taken in our plant over a 16-hour period without any special electromagnetic shielding or temperature regulation. the sensor was cooled and operated in the earth's field by direct immersion in a vented liquid helium

dewar. Our normal activities, including electric arc welding in an adjacent room, continued as usual. Note the complete absence of flux jumps and the extremely small zero drift. These tests have been extended to as long as three days during which the total drift does not exceed 6 x 10^{-11} A (6 x 10^{-4} Øo).
figure 4 drift in Øo
In order to achieve these results, a new feedback scheme* was developed that reduces by three orders of magnitude the dc drifts due to changing thermal emfs or ground loop potentials generated between the rf head and control unit. These emfs may vary with helium level in the dewar, position of the sun (for outdoor measurements), or changes in ambient temperature, pressure, or humidity. An added benefit of this circuitry is that interchannel crosstalk between several SQUID systems sharing a common ground, such as a multi-access magnetometer system, is effectively eliminated.

Great care has also been taken with the temperature compensation of the electronic units. The incredibly low temperature coefficient of the Model 300X rf head (0.04 ppm of full scale/°C) is of particular importance since it is frequently operated outdoors and exposed to large temperature variations.

RUGGED, LOW-NOISE SENSOR

The HYBRID SQUID sensor*, shown in Fig. 5, features an entirely new type of weak link incorporated into an optimal toroidal SQUID geometry. The reliability of this SQUID sensor is unsurpassed, yet it retains the low noise, exceptionally low drift, and freedom from small, subquantum flux jumps that was previously available only from comparatively delicate point-contact devices. The toroidal geometry protects the weak link from exposure to stray magnetic fields and improves the coupling to external pickup coils, giving a greater usable sensitivity.

The junction itself is a thin-film tunnel junction constructed from refractory materials. This ensures repeatability on thermal cycling and greatly extends the lifetime of the SQUID junction itself.
figure 5 TSQ
The response of the HYBRID SQUID sensor is extremely linear (better than 1 ppm) over an enormous dynamic range, not only at dc but also when operating near the very high slew-rate limits of our electronics. Furthermore, the HYBRID SQUID is about an order of magnitude less sensitive to temperature variations than other commercially available SQUIDs.

The SQUID itself is hermetically sealed in a protective casing to prevent damage from condensation, ice or excessively fast temperature changes. Screw terminals are provided at each end of the package to facilitate making connections to the rf and signal coils which are permanently installed inside the SQUID.

The basic response of a SQUID is to magnetic flux and it is often convenient to specify noise and performance of the device in terms of the flux quantum. The intrinsic noise of the SQUID if very small and usually masked by electronic noise. The total system noise for the Model BMS is essentially white above 0.1 Hz and less than 10^{-4} Øo rms per root Hz (10^{-11} A/$\sqrt{Hz}$). This result is obtained without unusual precautions such as careful regulation of the helium bath temperature or pressure, cancellation of the earth's field prior to cooldown, or use of an electromagnetically screened room.

When comparing different SQUID systems it is most important to note that low flux noise in the sensor itself is of little value if an efficient means is not provided to couple to an external signal. The most useful quantity for comparison is the signal-to-noise ratio that can be obtained at the input terminals: this involves three input coil inductance and its coupling to the SQUID (mutual

inductance) as well as the flux noise in the SQUID. An appropriately combined measure of all these quantities is the energy sensitivity δEi at the sensor input:

$$\delta Ei = LiI_N^2/2 = Li/2 \cdot (Ø_N/M)^2$$

where $Ø_N$ is the rms equivalent flux noise in the SQUID, M is the mutual inductance between the input coil and the SQUID, $I_N = Ø_N/M$ is the equivalent input noise current corresponding to $Ø_N$, and Li is the *in-situ* self inductance of the input coil.

For the Model BMS the guaranteed maximum values of these quantities are:

Li = 2 µH M = 20 nH (corresponds to 0.1 µA/Øo)

$Ø_N = 10^{-19}$ Wb(max.) in a 1 Hz bandwidth

$I_N = Ø_N/M = 10^{11}$ A (max.) in a 1 Hz bandwidth

Therefore, the guaranteed maximum equivalent input nose energy for the Model BMS is 10^{-28} J/Hz, with typical measured values being two times less.

Figure 6 presents the typical "shorted input" noise spectrum of the Model BMS. Note that the onset of the 1/f region of the noise spectrum is a very low frequency.

SPECIFICATIONS

SENSOR: Single weak link rf biased encapsulated toroidal SQUID. The standard sensor is designed for optimum operation at 4 K.

INPUT: Two niobium titanium screw terminals for making a superconducting connection to the niobium input coil. Current sensitivity is 0.1 µA/Øo in SQUID, corresponding to a mutual inductance of 20 nH. Input coil inductance is 2 mH.

OUTPUT: Front panel floating BNC jack ±10 V full scale, output impedance 200Ω. Rear panel output available at System Interface Connector. Panel meter monitors output voltage.

RANGE: Three sensitivity ranges are selected by pushbuttons. The table gives typical input current and equivalent flux change for full-scale deflection (FSD). Relative accuracy of the scale factor is within 2% of the nominal value.

NOISE: Less than 10^{-11} A (rms)/√Hz, referred to input, in the frequency range 0.5 Hz to 5 kHz.

FREQUENCY RESPONSE: Nominally flat (with filters switched out) from dc to the high frequency rolloff commencing at frequency fc (-3 dB point) given in table.

Mode	fc
FAST	20 kHz
MED	5 kHz
SLOW	1 kHz

There is a change in scale factor less than 1 dB occurring around 800 Hz in MED and FAST modes and a peaking of up to 2dB at about 10kHz, depending on cable length, in the FAST MODE only.

(Frequency response can be compensated to be flat ±0.2 dB from dc to 5kHz on special order.) Response to over 200kHz is available from HIGH FREQUENCY OUTPUT (see below).

HIGH FREQUENCY OUTPUT: Special high frequency output (rear panel BNC) for signal amplitudes less than Øo/2 p-p. Response extends from upper rolloff frequency of normal output to 200 kHz (-3 dB). Usable in presence of large amplitude, low frequency signals falling within the envelope given of Fig. 2. Output voltage is 4 V/Øo, source impedance 47Ω. This output contains some additional noise at the 50 kHz subcarrier frequency and harmonics. Noise at 50 kHz is less than 70 mV rms.

MAXIMUM INPUT AMPLITUDE: Maximum amplitude for reversible locked-loop operation is limited by the maximum slew rate of the feedback amplifiers, as shown in Fig. 7. Performance on down-sloping portions of graph will be degraded by any additional (external) noise.

FLUX FEEDBACK: Applied internally (to rf coil in SQUID) when INT FB button is depressed. For external feedback, a suitable voltage is available at rear panel BNC jack with 100Ω output impedance, ±5 mA maximum current and ±10 V range. External feedback is required for use with SHE Picovolt Measurement System and other applications requiring feedback directly to the input circuit attached to the SQUID terminals.

MAXIMUM SLEW RATE: Guaranteed to exceed 31 mA/sec (referred to input) in the FAST mode.

OUTPUT FILTERS: Four low-pass and one line-frequency notch filter may be selected by pushbuttons. Low-pass filters rolloff at 12 dB/octave with -6 dB points at 100 Hz, 10 Hz, 1 Hz and 0.1 Hz. Filters track output voltage at all times to minimize long transients when switched into use. The notch filter may be used independently or in combination with one of the low-pass filters. The additional temperature coefficient is typically 10^{-7} FSD/°C for each filter in use (worst case coefficient is 5 times the typical value).

DETECTOR AND SYNC OUTPUTS: Provided for monitoring and troubleshooting purposes.

TEST INPUT: Provides convenient means to check system performance by injecting a signal into the SQUID rf coil via a 20kΩ resistor. A low-pass filter rolls off the response above 800 Hz.

SYSTEM INTERFACE CONNECTOR: Provides for TTL Input for automatic reset and ±24 V dc input (with electrical ground) for battery operation. Outputs include autoreset, reset sign, floating signal output, external feedback, rf detector, modulation, sync and high frequency output.

INITIAL OPERATING ADJUSTMENTS AND CONTROLS: All adjustments are performed at control unit using only the panel meter and self-contained test circuitry activated in the SET 1 and SET 2 modes. Precise set up adjustment is possible in presence of input noise or signals having slew rates as great as 10 Øo/sec.

RESET CONTROLS: Reset may be initiated by front panel pushbutton, by TTL compatible input at system interface connector, or automatically when the output exceeds a predetermined level that may be set anywhere from one volt to full scale output. Minimum time required for remote reset varies between 100 µsec and 300 msec depending on the voltage change between reset points and on the operating mode (SLOW, MED or FAST). Automatic reset time may optionally be specified as short as 100 µsec, but the factory should be consulted first regarding possible operational

limitations. TTL compatible outputs needed to operate an up/down counter are provided by the auto reset circuitry and are available at the System Interface connector.

OFFSET CONTROL: Used in conjunction with reset controls to set output voltage to any value within ±10 V operating range of instrument. Typically used to accurately zero output for use with a high sensitivity recorder. Range of control is 0 - 2 x 10^{-7} A set by 10-turn, calibrated dial with 10 $^{-12}$ A resolution. The additional temperature coefficient is proportional to the offset control setting and equal to 2 x 10^{-12} A/°C (referred to input) at maximum control setting.

TEMPERATURE STABILITY: Because the control unit and rf head may be subjected to different ambient temperatures, the effect of changing ambient temperature is stated separately. Specification on the control unit is given for the offset control turned to zero and all filters switched out (see specifications on OFFSET CONTROL and OUTPUT FILTERS for their respective effect on temperature stability). Specifications are valid for temperature range 0 - 40 °C.

ZERO DRIFT: In a typical laboratory environment with the SQUID shielded from external fields (no connection to input terminals) and operated in a helium bath freely vented to the atmosphere, drift referred to input is typically within ± 2 x 10^{-11} A/hour and within ± 3 x 10^{-11} A over a 24-hour period on the most sensitive range (x 100).

EFFECT OF GROUND LOOP VOLTAGE AND THERMAL EMFS: The effect of spurious dc voltages introduced in the feedback path between the control unit, rf head and SQUID by connecting units to different parts of electrical ground system, or by thermal emfs in the cryogenic transmission line, is attenuated by at least 60 dB. Offset produced is less than 10^{-12} A (referred to input) per mV of spurious emf.

Fig. 7. Maximum sinewave input amplitude as a function of frequency. Ideal performance is shown by solid lines for each sensitivity (x1, x10, x100) and for the three operating modes (SLOW, MED, FAST). Read graph by following horizontal line corresponding to proper sensitivity until it meets the down sloping line corresponding to mode selected. Operation is possible in the amplitude-frequency region below and to left of the boundary lines for each sensitivity-mode combination. The ideal performance can be approached only under very quiet conditions. Guaranteed performance specification points are indicated by a shaded "corner" and will be achieved with a shorted, well-shielded sensor input. Example: In the MED mode for x10 sensitivity, full scale (100 Ø or 10 µA p-p) sinewave signals can be tracked at frequencies up to 100 Hz.

RF BIAS FREQUENCY: 19 MHz ± 0.1, crystal controlled.

RF HEAD VOLTAGE NOISE: <1 nV/$\sqrt{Hz}$ referred to input (Model 300X)

RF TUNING CAPACITANCE: 35-85 pF, adjusted from control unit.
CABLE LENGTH: 6 meter (20 ft.) standard, 100 meter (328 ft.) optional. Internal switch selects compensation required for long/short cable to give rated slew rate performance. Cables much longer than 100 m may be used with some loss of slew rate and high frequency response.

POWER REQUIREMENTS: 115 Vac (75 mA) or 230 Vac (37 mA), 48-400 Hz; or ±24 V dc (150 mA).

DIMENSIONS: Model 30 Control Unit, 87 mm x 215 mm x 336 mm; Model 30X RF Head, 37 mm x 76 mm x 95 mm, Model SP Probe (below N connector), 922 mm, length x 16 mm, maximum diameter.

WEIGHT: Model 30 Control Unit, 3.6 kg; Model 300X RF head, 0.5 kg; Model SP Probe, 2.2 kg.

Fig. 8. Model 30 Rear Panel

PICOVOLT MEASURING SYSTEM

A unique instrument of unsurpassed sensitivity whose applications include:

- Thermopower measurements at low temperatures
- DC measurements of very small resistances
- Sensitive detection of superconducting-to-normal transitions
- Thermocouple thermometry at low temperatures
- Infrared detection with low impedance bolometers

The SHE Picovolt Measuring System is a cryogenic dc voltage measuring amplifier with a gain of 10^8 and an rms noise of less than 10^{-13} volts per root hertz of measurement bandwidth. The Picovolt Measuring System consists of a low temperature SQUID probe, a SQUID electronics system, and a low noise current supply.

OPERATING PRINCIPLES

The SQUID employs the phenomena resulting from flux quantization and the Josephson effect in a superconducting circuit containing a weak link to provide an exceptionally sensitive indication of the current flowing in an adjacent superconducting coil which forms part of the input circuit. Voltage feedback is applied to the input circuit by means of a low value series resistor r std (see Fig. 2). A high degree of negative feedback raises the input impedance of the voltmeter, with the result that voltage measurements can be made at a temperature of 4.2 K with low noise factors and without loading the source.

Fig. 1. The SHE Picovolt Measuring System. The Model MFP Probe is shown in use with the System 330X SQUID electronics and Model CCS Constant Current Source.

SENSITIVITY

The sensitivity of the picovoltmeter is limited by three sources of random electrical noise. The relative importance of these contributions to the system noise over a range of input impedances is shown in Fig. 2. The resistive portion of the voltmeter input circuit displays a thermal Johnson noise component of about 10^{-13} volts rms per root-hertz of measurement bandwidth. With small source resistances, this will be the dominant noise.

Figure 2

When a voltage source having resistance Rs and temperature Ts is connected to the input terminals, and the product RsTs is larger than about 10^{-4} ΩK, Johnson noise in the source is also significant. The thermal noise characteristics for source temperatures of 4.2 K, 0.4 K, and 0.04 K are shown in Fig. 2. The SQUID system also gives rise to a random noise contribution, which has an effect equivalent to a current source developing a noise voltage across the source resistance. This becomes significant at high source resistances, and a typical variation is shown in Fig. 2. It can be seen that the specified noise level of 10^{-12} volts rms will not be degraded for source resistances smaller than 10^{-2} Ω whose RsTs product is less than 2×10^{-2} ΩK. The sensitivity of the voltmeter

may be degraded, however, if the voltage source and input leads are not adequately shielded and decoupled from rf signals.

APPLICATIONS

The superconducting picovoltmeter makes possible detection and measurement of extremely small dc voltages from sources at low temperatures that would be overwhelmed by thermally induced emfs in the leads to a room-temperature measuring instrument. The terminals and almost all of the input circuitry of the cryogenic picovoltmeter are constructed of superconducting material to eliminate noise and thermal voltages. Since connection to the input may be made by means of a moderately long (up to 1 m or more) twisted pair of low thermal conductivity superconducting leads, the voltage source to be measured can be located at a distance from the probe and at a much lower temperature.

The SQUID picovoltmeter will be particularly useful for measurements of thermopower at very low temperatures (and, conversely, measurements of very low temperatures by means of thermocouples(, measurements of voltages associated with the onset of superconducting-to-normal transitions, the detection of infrared radiation by means of a suitable low impedance bolometer, and dc measurements of very small resistances. In order to facilitate true four-terminal measurements of low resistances, a pair of shielded and rf-decoupled leads capable of carrying 0.5 A are installed in the probe. Connection to the current source is made by a shielded connector on the probe housing, and brass screw terminals are provided at the probe tip for connection to the sample.

Fig. 2. Typical rms voltage at the output of the Picovolt Measuring System, referred to the input, is plotted as a function of the source resistance Rs for various source temperatures Ts. The inset shows how negative feedback from the SQUID electronics output is applied to the cryogenic input circuit through the voltage divided formed by Rf and rstd. The ratio Rf/rstd determine the voltage gain of the instrument.

SPECIFICATIONS

The specifications given below are for a complete system comprising the Picovolt Probe (Model MFP), Model CCS Current Supply (described on a separate data sheet), and Model 330X SQUID electronics.

SYSTEM VOLTAGE GAIN: $1.00 \times 10^8 \pm 2\%$, temperature coefficient 100 ppm/°C with respect to changes in room temperature.

NOISE: Voltmeter rms noise per root-Hz of bandwidth referred to input is given in terms of source resistance Rs by $\sqrt{\langle V^{-2} \rangle} < (10^{-26} + 10^{-22} Rs^2 \Omega^{-2} + 4KTsRs)\ 1/2$.

INPUT IMPEDANCE: $R = 10\Omega$ at dc, capacitive at non-zero frequency with $Z = 1/j\omega\ 10$.

INSTRUMENT BANDWIDTH: Zero to 3 Hz low-drift output at probe for dc measurements. Zero to 100 Hz ac output is available at SQUID Control Unit Output BNC; Control Unit filters may be used to obtain 0 to 10, 0 to 1, or 0 to 0.1 Hz bandwidths.

INSTRUMENT RISE TIME: 10% - 90% rise time, $\tau r = 0.11$ sec at probe output.

MAXIMUM PERMITTED SLEWING RATE OF INPUT SIGNAL: 50 nV/second for reversible operations.

MAXIMUM INPUT SIGNAL: 100 nV (for reversible operation).

Fig 3. Actual recorder traces of the Picovoltmeter output. The top trace shows a series of 2 x10^{-12} V amplitude pulses obtained by switching a 4.5 x 10^{-7} A current through a 4.4 x10^{-6} resistor connected to the Picovoltmeter input. The response time shown is indicative of the recorder rather than the Picovoltmeter response, the latter being determined by a fixed 50 msec output filter time constant. The bottom trace shows typical output noise (referred to input) with a superconducting short across the Picovoltmeter input terminals. The rms noise amplitude on the trace is approximately 6 x10^{-14} V, or 3 x10^{-13} V "peak-to-peak".

INPUT CONNECTION: Niobium terminals with brass screw provided for voltage connections. "Low" side of input grounded via ~ 1Ω.

OUTPUT CONNECTION: Grounded BNC connector, impedance 10KΩ in parallel with 5 µF.

CURRENT LEADS: rf-decoupled floating pair, maximum, current 0.5A. Brass Screw terminals at low temperature, multi-pin connector at room temperature.

WORKING TEMPERATURE: Cryogenic probe tip must be maintained at 4.2K.

SUBSIDIARY EQUIPMENT: In addition to the Model PVP Picovolt Probe, a suitable read-out device having a fsd of 10 V and input noise smaller than 10 µV is required for optimum sensitivity.

COMPONENTS

Model CCS Constant Current Supply
A low-noise, wide range current source, the Model CCS is used for making four-terminal resistance measurements with the MFP. It, or an equivalent supply, is required for such measurements. See Model CCS Constant Current Source data sheet.

Model 330X SQUID Electronics
The Model 30 control unit and the Model 300X rf head provide for totally self-contained SQUID sensor operation.

SQUID Probe
The Model MFP probe contains the calibrated resistors, SQUID sensor, and excitation leads. The MFP probe is normally supplied with the system and contains two twisted pairs of excitation leads, enough to make sequential resistance measurements on as many as three samples in a single cooldown. It also has the additional capability of making ac impedance measurements (see MPS Multipurpose Measuring System data sheet); it requires modification if more than one unknown impedance is to be measured. It can also be used to make all measurements that are possible using the Model SP probe. The physical dimensions of all probes can be found in the SQUID probe section of this catalog.

The most versatile of all SHE SQUID probes, the Model MFP, can be used for all the different measurements described in the laboratory SQUID section of the "Introduction to SHE SQUID Systems" data sheet.

ACCESSORIES

Model SEC Remote Terminal Board

The Model SEC terminal board is designed to accommodate experimental arrangements in which the input signal to the probe is derived from a source within a vacuum can. Superconducting screw-type junctions are made at the board and superconducting leads from the board pass through a helium-leaktight seal. These leads then can be connected to the signal terminals of the probe. See "Laboratory SQUID Probes" data sheet.

Fig. 4. The Model MFP Picovoltmeter Probe top housing (left) and cryogenic tip with the noibium shield in its raised position (right). The terminals at the bottom may be connected for voltage measurements, 4-terminal resistance measurements, or directly to the SQUID sensor for magnetometry.

MPS MULTIPURPOSE MEASURING SYSTEM

FEATURES

- Measures 10^{-10} Ω in a 10^{-5} Ω resistor at 2 x 10^{-12} watt dissipation
- Measures 10^{-12} H in a 10^{-7} H inductor with 10^{-3} Ampere primary current
- Measures temperature below 1K with only 10 mg CMN
- 0.001% resolution maintained by continuously variable full-scale setting
- Four switch-selected operating frequencies between 16 and 160 Hz
- Measure multiple samples in a single cool-down

The SHE MPS Multipurpose Measuring System is a cryogenic low impedance AC bridge in which a SQUID is employed as the null detector. The exceptional sensitivity of the SQUID enables high resolution measurements to be made while dissipating an almost negligible power in the unknown. Four-terminal measurements can be made below about 10K on resistive elements displaying significant inductance and on inductors or mutual inductors with a considerable loss component.

Use of the SQUID results in a measuring system whose resolution at a given level of power dissipation is generally limited by "Johnson noise" in the unknown. The sensitivity of the system for measurements at 4.2K actually exceeds its maximum resolution of 0.001% as long as the resistive component of the unknown is between 10^{-4} Ω and 2 x 10^{-2} Ω. This range of highest sensitivity extends downward as the temperature of the unknown is reduced. These figures are obtained with a resistive dissipation not exceeding 40 picowatt at any point within the range. The above sensitivity is maintained for mutual inductance in the range 2 x 10^{-8} H to 10^{-4} H.

Fig. 1. The Model RBU Bridge (bottom) and Biphase Detector which, along with a SQUID system employed as a null detector, comprise the MPS Multipurpose Measuring System.

APPLICATIONS

The MPS Multipurpose Measuring System makes high resolution resistivity measurements on samples with very low absolute resistances. For example, at 160 Hz and 4.2 K a resolution of 10^{-10} Ω can be obtained for a 10^{-5} Ω resistor with power dissipation of only 2 x 10^{-12} W. Consequently, resistivity measurements of materials such as metals, can be made on large bulk samples. Exceptionally low power dissipation enables accurate measurements to be carried out without heating problems, even at the lowest attainable temperatures.

The MPS Multipurpose System's ability to detect mutual inductance changes as small as 10^{-12} H makes possible magnetic measurements on extremely small quantities of paramagnetic or superconducting material. An excellent paramagnetic susceptibility thermometer can be made using only 10 mg of Cerium Magnesium Nitrate (CMN), with a total coil volume of approximately 0.01 cm^3. The low optimum inductance (~1μH) results in a considerable simplification in coil construction. The small overall size of coils and sample reduces the effects of eddy currents in surrounding materials. Measuring fields associated with the MPS Multipurpose System are very small, typically of order 10^{-2} gauss.

Since the MPS system includes the MFP probe and the Model CCS Constant Current Supply, the MPS is also capable of making the same measurements as the Model PMS Picovolt measuring system.

WORKING PRINCIPLES

A simplified schematic diagram of the measuring system is shown in Fig. 2. The unknown impedance Z is excited by a current proportional to the oscillator voltage V and defined by Resistor R_1 or capacitor C_1. When the range switch is in the DIVIDE position, the voltage applied to R_1 or C_1 is reduced to a voltage λV by means of a precision variable ratio range transformer T. The difference between the voltage developed across the unknown and that developed in the secondary of the nulling mutual inductor m is applied to the SQUID null detector. The primary current in **m** is proportional to V and defined by the settings of the in-phase and quadrature ratio transformers A and B and by the series elements R_2 and C2. When the range switch is in the MULTIPLY position, the oscillator voltage applied to A and B is reduced to λV by the range transformer T while the full voltage V is applied to either R_1 or C_1.

In practice, the SQUID null detector, the unknown impedance Z, and the nulling mutual inductor m are mounted in the cryogenic environment. The nulling circuit is made superconducting, with the exception of any resistance in Z, to avoid additional Johnson noise. The amplified off-balance signal which appears at the output of the SQUID control unit can be displayed by means of a selective amplifier or lock-in detector tuned to the oscillator frequency.

For the Model RBU Bridge the reactances of R_1, C_1, and C_2 are much larger than the unknown impedance Z. Therefore, at an excitation frequency Z. Therefore, at an excitation frequency w, the balance conditions are as follows:

1) "R" Mode Operation
If the unknown impedance can be expressed as $Z = R + j\omega L$, then

$$R = F\alpha \frac{\mathbf{m}}{R_1 C_1} \qquad L = f\beta\mathbf{m}$$

where f is the scale factor given by $f = 1/\lambda$ in the RANGE DIVIDE mode, and $f = \lambda$ in the RANGE MULTIPLY mode.

2) "L, M" Mode Operation

If the unknown impedance can be expressed as a lossy mutual inductance $Z = j\omega(M' + j\omega M'')$, then

$M' = f\alpha m$ $\quad M'' = f\alpha\mathbf{m}R_1C_1$ where the scale factor f is defined in (1.).

If the unknown impedance can be expressed as $Z = R + j\omega L$, then

$$L = \alpha f m \qquad R = -\omega^2 f \beta m R_1 C_1$$

where the scale factor f is defined in (1.)

.

Fig. 2. Simplified circuit diagram for the MPS measuring system showing the principal components.

The provision of the range transformer T permits continuous and precisely calibrated adjustment of the scale factor of the bridge. Consequently, balance may always be obtained near the maximum setting of the dominant null control with the result that the maximum resolution of 0.001% can be obtained over a wide range of values of Z.

The internal oscillator frequency is variable over an order of magnitude to enable frequency dependences to be evaluated. Higher sensitivity is generally obtained by increasing the oscillator frequency. External oscillators and other frequencies may be used - consult the factory for details.

MULTIPLE SAMPLE MEASUREMENT

Multiple unknown impedances may be measured on a single cooldown without the need for cryogenic switches and usually without loss of sensitivity. The potential leads of the unknown impedances are wired in series and connected into the cryogenic bridge circuit in the same way as the single impedance shown in Fig. 2. Individual pairs of excitation (current) leads are run from each impedance to the room temperature bridge. The bridge excitation is then simply switched to the desired unknown to measure its impedance. Full resolution (0.001%) is possible for total series resistance between about $10^{-4}\ \Omega$ and $10^{-2}\ \Omega$ or total inductance between 10^{-8} H and 10^{-4} H.

This capability is extremely useful for experiments, such as those done in dilution refrigerators, which require a great deal of time to warm up and change samples. If a CMN thermometer is connected in series with the unknowns, their impedances may be measured as a function of temperature using only one SQUID system. This important feature is an exclusive capability of the MPS Multipurpose Measuring System; dc susceptibility measurements require a separate SQUID system for each unknown and the thermometer.

SYSTEM COMPONENTS

A complete MPS Multipurpose Measuring System consists of the following units:

a) The Model MFP SQUID Probe carries at its lower end the nulling mutual inductor and the SQUID. Excitation terminals and superconducting potential terminals are provided for the unknown, which can be connected to the probe by means of a twisted pair of insulated superconducting potential leads with a length of up to 1m. The lower end of the probe operates submerged in liquid helium at or below 4.2K. The upper end of the probe contains rf decoupling components and connections to the room temperature parts of the bridge.

b) The SQUID electronics (Model 300X RF Head or equivalent) connects rigidly to the room temperature end of the probe and provides all signals necessary for operating the SQUID null detector. The output of the Model 30 control unit may be displayed using an amplifier having a noise level of less than 1 μV per root cycle of bandwidth, referred to its input.

c) The RBU Bridge Unit, connected to the Probe by means of a flexible multicore cable, contains the room-temperature bridge components and the excitation oscillator. The unit is powered from the ac line by means of an internal power supply.

d) The SHE Model BPD Biphase Detector is used to detect both the in-phase and numerous characteristics matched specifically to the RBU provide the full precision and operational ease available from the RLM System. An oscilloscope or tunable, narrow-band null detector, but both convenience and accuracy will be sacrificed.

e) The Model CCS constant current supply provides a low-noise wide range (1mA to 100mA) current source allowing four-terminal dc resistance measurements when used with the Model MFP probe. See Model PMS Picovolt Measurement Systems for details.

SPECIFICATIONS

The sensitivity of the measuring system is limited inherently of Johnson noise in the resistive components of the unknown (including the potential connections) and by device noise in the SQUID. Assuming a typical value of SQUID noise and that the unknown impedance is at a temperature of 4.2K the following sensitivities are obtained:

"R" Mode: 0.001% for $10^{-4}\ \Omega < R < 10^{-2}\ \Omega$
0.01% for $2 \times 10^{-6}\ \Omega < R < 0.5\ \Omega$
where R is the total unknown resistance including contact resistance.

"L, M" Mode: 0.001% for 2×10^{-8} H < L < 2×10^{-4} H
0.01% for 2×10^{-9} H < L < 2×10^{-3} H
0.001% for 6×10^{-7} H < M < 10^{-3} H
where L is a superconducting inductance and M has a superconducting secondary with L < 10^{-4}H

Operations with reduced resolution is possible outside these ranges.

ABSOLUTE ACCURACY, STABILITY AND DRIFT

The system is calibrated to 1% absolute accuracy. Short term stability of this calibration is 0.001% in the "L, M" mode, and 0.01% in the "R" mode. Long term stability may be degraded by an order of magnitude over these figures. Temperature drift in the "L, M" mode is less than 5 ppm/°C.

RANGE

The full 1% accuracy of the system is maintained for the following range of unknowns:

$2 \times 10^{-8}\Omega < R < 1\Omega$
2×10^{-11} H < L < 10^{-3} H
2×10^{-11} 1 H < M < 10^{-3} H (with secondary L < 10^{-4} H)

Operation with reduced accuracy is possible outside these ranges.

LINEARITY

Departure from linearity in the in-phase balance setting will be less than 0.02% of reading plus 0.04% of the quadrature setting.

POWER DISSIPATION

The oscillator output to the bridge is variable in 10 steps (1-2-5 sequence). The sensitivities listed above are obtained with the following power dissipation (or excitation current):

(R) When measuring resistance at 80 Hz the power dissipation P is always below one picowatt:

$P = 4 \times 10^{-15}/R$ watts for $R > 10^{-3}\ \Omega$

$P = 4 \times 10^{-9}\ R$ watts for $R < 10^{-3}\ \Omega$

(L & M) For self or mutual inductance measurements the excitation current I is given by:

$I = 2 \times 10^{-10}/L$ Ampere for L or M > 10^{-16} H
$I = 2 \times 10^{-4}$ Ampere for L or M < 10^{-16} H

FREQUENCY RANGE

The internal oscillator at switch selected angular frequencies of 100, 20, 500 and 1,000 radians per second (approximately 16, 32, 80 and 160 Hz.

MODEL BPD BIPHASE DETECTOR

The SHE BPD Biphase Detector shown in Fig. 1 is a lock-in amplifier designed especially for use in balancing the SHE RLM Measuring System. The Model BPD features a simultaneous double meter display of the in-phase and quadrature components of the out-of-balance signal. The unit contains a signal amplifier having a medium impedance (10KΩ) semi-floating input connection and microvolt sensitivity. The reference channel also uses a semi-floating input connection to eliminate ground loops and employs a linear phase shift circuit and servo quadrature generator. Phase-shifted reference signals and detector outputs are provided.

The gain of the Model BPD may be changed by a factor of 1000 in a 1-2-5 sequence to simplify both the coarse and fine balance of the bridge. Selectable output time constants from 0.03 to 10 sec may be chosen to shorten response time or reduce noise.
Fig. 3 The model MFP Probe top housing (left) and cryogenic tip with niobium shield in raised position to expose terminals (right). The cryogenic tip shows the terminals used to connect the unknown impedence and the threaded boss which may be used to attach a sample holder

SQUID PROBES FOR THE LABORATORY

<u>FEATURES</u>
- Easy to install
- Multiple Measurement Capability
- Immersion Operation

SHE manufactures three basic SQUID probes for general laboratory use. These probes provide the basic capability for a variety of ultrasensitive measurements such as:

- Magnetic fields and field gradients
- Static magnetic moment and susceptibility
- Electric and magnetic fluctuations
- DC voltage and resistance
- Low frequency ac resistance and self-inductance
- Low frequency mutual inductance and susceptibility

All probes are designed to be used while immersed in a liquid helium bath. Probes are available separately for upgrading older SQUID systems or for expanding the capabilities of a more recently purchased system.

Standard model SQUID probes are shown in Fig. 1. All are hermetically sealed at the room temperature end. An rf transmission line runs from the room temperature end to the SQUID sensor, which is mounted within a removable superconducting shield at the opposite, low temperature end.

Rapid access to the sensor is gained by loosening a threaded retaining collar and sliding a niobium shield upward along the probe shaft. When lowered, the niobium provides magnetic shielding of the sensor input terminals. Input leads, usually a shielded, twisted pair of superconducting wires, are easily passed through a hole in the niobium bottom cap and attached to the sensor input terminals. This bottom cap terminated in a threaded post which may be used to attach input coils or other mechanical appendages.

In all SHE probes, construction materials are non-magnetic and carefully selected to minimize conduction of heat into the helium bath. All probes are doubly shielded against rf interference and other electrical transients that may affect the SQUID operation.

Fig. 1 SQUID probes (left to right): Model MFP, Model SP, Model SPD, Model DP

PROBES

The following choice of probes allows you to select only those capabilities required by your experiment.

Model SP -- Basic magnetometer probe
Model SPD -- Two-piece, semi-flexible, basic magnetometer probe
Model MFP -- Multi-function probe with DC picovoltmeter and magnetometer capabilities AC bridge and magnetometer probe

The standard length of these probes in 36 inches, but any length between 26 and 46 inches may be special ordered. Other dimensions are shown in Fig. 1 of this data sheet.

Models SP and SPD Magnetometer Probes

The Model SP magnetometer probe, shown in Fig. 1, is supplied with the Model BMS basic system and is most commonly used as a magnetometer or galvanometer.

The SP probe is a rigid probe designed for direct immersion. A room temperature O-ring seal can be made on the 5/8" diameter surface (see Fig. 3) to allow pumped dewar operation. For

installations requiring a slightly flexible probe shaft, a 1/16" diameter version, the Model SPD, is available. In the Model SPD, the SQUID housing is easily separated from the probe shaft to allow for installation through small holes.

To use the Model SP as a magnetometer, it is necessary to attach a suitable pickup coil to the input terminals of the SQUID. To optimize sensitivity, the inductance of this pickup coil should be matched to the 2 μH inductance of the input coil in the SQUID. For example, a 5 cm diameter single loop of 0.025 cm wire has an inductance of about 0.17 μH. Since the inductance is proportional to the square of the number of turns, a three-turn loop would have an inductance of about 1.5 μH. By attaching this coil to the input of the Model SP probe, a sensitivity to external fields of better than 10^{-10} gauss can be obtained with a one hertz bandwidth. Technical assistance for the design of other pickup coils, such as gradiometer coils, small sample susceptibility coils, or thermometer coils is available from SHE.

Model MFP Multi-Function Probe

The Model MFP probe is the most versatile of all SHE SQUID probes. It combines the full picovoltmeter, magnetometer, and ac bridge capabilities in a compact, easy-to-use design. The probe itself, shown in Fig. , is similar in design to the Model SP with a few important exceptions. These include additional room temperature circuitry located directly beneath the type N connector in a vacuum sealed housing. Also, the SQUID sensor housing is longer to accommodate a cryogenic resistance standard and small terminal board required for voltage measurements. Rewiring of the probe to change its function is easily accomplished by moving a few jumper wires located on the cryogenic terminal board. Its great versatility makes this the recommended probe when a variety of future applications is required.

ACCESSORIES

Probe Accessory Pack

Each SHE probe is supplied with a package containing the following often-used items:

a) Superconducting .010 tubing, approximately .030" (0.76 mm) O.D. x .010 (0.20 mm) I.D. x 10 ft (3 m). Composition 60% Pb, 40% Sn, other compositions available on special order. Useful for shielding input leads in fields up to 1,000 gauss.

b) Lead foil, 12" x 12" x 0.005" (305 mm x 305 mm x 0.13 mm). Useful as superconducting shielding in magnetic fields up to 800 gauss.

c) NbTi wire, 0.005" (0.13 mm) diameter x 50 ft. (15.2 m) with heavy formvar insulation. Useful for SQUID signal coil circuitry, terminal board jumper wires, and other applications requiring superconducting wires.

d) Assorted spare #0-80 UNC machine screws and flat washers.

Model SEC Remote Terminal Board

In many experimental arrangements, the signal to the SQUID is derived from a source within a vacuum can immersed in liquid helium. The SEC Remote Terminal Board (Fig.) enables input signals from within the vacuum can to be transferred to the SQUID probe located outside.

The SEC consists of a terminal board containing six terminals enclosed within a small housing. The terminals are niobium-titanium, permitting superconducting contacts to be made when a superconducting wire is held against a terminal by means of a brass screw and washer. A removable superconducting cover screws onto a threaded stud projecting from the bottom of the housing. A hole through this stud is used for bringing in shielded input leads.

Attached to the top of this housing is a long brass tube with a threaded outer diameter. Niobium-titanium leads from the terminals, shielded in superconducting tubing, pass through a low temperature epoxy seal and up through the brass tube. These leads are brought out as three separately shielded twisted pairs and are 30 cm long.

A small brass disc threads onto the brass tube and is soft-soldered into any available port in the cryostat's vacuum can. The standard outer diameter of this disc is 11/16", with other diameters available as an option.

To install the SEC, one simply slips the threaded brass tube through the port in the cryostat from below and threads on the brass disc. The vertical position of the housing is adjusted at this time. The brass disc is then soft-soldered into the port and onto the threaded tube to complete the installation.

Fig. 2 Model SEC Remote Terminal Board

SPECIAL MATERIALS

SHE maintains a supply of materials which are useful in cryogenic work. These are available in small quantities. Included are PbSn superconducting tubing, lead foil, NbTi wire, copper-nickel tubing, fiberglass sleeving, indium wire, manganin wire, niobium tubing and soap-glycerine sealing compound. A complete listing of currently available items may be found in the price list.

A valuable tool for

- Mineral and Geothermal Prospecting
- Geomagnetic Research

using MT, IP and controlled source EM techniques

FEATURES su superconducting ss SQUID mm magnetometer lh liquid helium mg GMSX

- 10^{-5} γ resolution
- Frequency response to 250 Hz
- Enormous 134 dB Dynamic Range
- Low Sensitivity to Interference
- Rugged Portable, Easy to use

The BTi Model GMSX is a field-proven rugged, highly sensitive superconducting SQUID magnetometer designed for geophysical exploration and measurement. This system resolves field changes of 4 x 10^{-5} γ (in a 1 Hz pass band) in the presence of steady fields more than 100 times the earths field. The system output voltage lies between ± 10 V and sensitivities ranging from 0.1 to 6 V/γ are available. The system resolution is independent of frequency above 10^{-2} Hz **(??? more like 40 -50 mHz)** and can easily be used to dc. Its compact size and easy set-up make it ideal for use in hostile terrain. Figure 1 shows the elements of the GMSX consisting of the magnetometer probe within the liquid helium dewar, the interconnecting cables, and the electronic controller.

The GMSX magnetometer offers several important advantages when compared to other magnetometers. It is a vector magnetometer, in contrast to the proton precession device which responds only to the magnitude of the field. With a three-axis vector magnetometer both the magnitude and direction of the field can be determined. Its performance is not impared by the presence of large gradients and, unlike fluxgate devices, SQUID magnetometers do not saturate. In comparison to large induction coils the GMSX is not awkward or cumbersome in deployment and use, operates to dc and avoids giving undue emphasis to high frequency phenomena such as the ubiquitous lightening induced sferics.

The system resolution below 10 Hz to dc exceeds any other magnetometer , and is essentially flat. High resolution measurements can be made in large background fields or gradients which can prevent the use of other systems.

These characteristics make the SQUID magnetometer the superior instrument in magnetotelluric and controlled source measurements. In low level measurements over several frequency bands noise in the measurement can severly compromise or destroy the usefullness of the data. The use of a SQUID magnetometer as a remote reference device to provide a measure of uncorrelated noise to be compared with the output of a similar magnetometer at a magnetotelluric measurement site has been extremely successful. The results of these measurements have been superior determinations of the electromagnetic impedence ot the earth showing internal consistancy levels never before achieved. No other magnetometer is sufficiently noise free and sensitive to allow such excellent measurements to be made.

SYSTEM DESCRIPTION

A SQUID magnetometer is shown schematically in Figure 2. The standard BTi geophysical magnetometer system comprises the following major elements:

Liquid helium dewar

magnetometer insert assembly
Model 300X rf head, one per axis
Model 30 control unit, one per axis
Connecting cable, one per axis

The removable insert resides in the liquid helium space of the dewar. Three SQUID sensors are contained within tubes located above the cylindrical form at the bottom on which the three sense coils are mounted. Slender rf transmission lines passing alongside the central support tube are terminated at the room temperature end by N-type rf connectors. The three rf heads attach at this point. The dewar is refilled with liquid helium via the specially insulated port shown at the top of the insert assembly. This port is normally capped during operation and the gas escaping from the boiling helium is vented through a separate opening located behind the fill port.

TECHNICAL SPECIFICATIONS

The liquid helium dewar is a fluid container designed to provide the thermal isolation necessary to maintain a temperature difference of approximately 300°C between its interior, which is filled with liquid helium, and the exterior. Liquid helium is required to maintain the magnetometer in its superconducting state. Thermal insolation is achieved by proper insulation and choice of materials. The Model LPD-25X dewar, standard with the GMSX requires liquid helium refills once every twenty one **(???)** days in stationary use. The dewar and all other parts of the GMSX are designed using nonmagnetic materials to avoid magnetic interference. A low profile design is used to allow easy handling and excellent stability; these are useful features when the system is used in rough terrain and where wind caused vibration can introduce unwanted interference. The dewar and probe weigh 36 kg when filled. Carrying handles are provided.

The sensing element of the magnetometer consists of a superconducting pickup coil coupled inductively to a SQUID. Changes in the magnetic field at the pickup coil generate changes in the system output voltage which are linearly proportional to the field changes. The linearity of the system is better than 10 ppm.

The system output voltage is the voltage drop across the feedback resistor in a negative feedback loop controlled by the SQUID electronics. The feedback signal is generated in response to changes in the output signal of the SQUID sensor. The output of the SQUID sensor is periodic in the field at the pickup coil and the negative feedback technique is used to produce the linear output of the magnetometer. When operated in this mode the system is in a flux locked loop.

Specifications of the magnetometer are determined by the properties of the SQUID sensor itself, the geometry of the pickup coils and the control electronics.

• The system is a differential vector magnetometer; i.e., the system output for a given axis is proportional to the change in the magnetic field perpendicular to the plane of the pickup coil corresponding to that particular axis. A three-axis system consists of three orthogonal pickup coils and total field changes can be obtained by combining the changes of the components.

• The smallest increment of field change that can be resolved by the superconducting magnetometer is determined by the system noise. For frequencies above 0.01 Hz **(??)** the noise spectrum is independent of frequency. The rms noise amplitude is proportional

to thhe square root of the measuring bandwidth, which is normally determined by output filters or by the recording instruments. Below 0.01 Hz the rms noise amplitude in a 1 Hz bandwidth varies as $(1/f)^{1/2}$, f being the frequency.

• The resolution of the magnetometer is defined to be the change in field input giving rise to an output voltage change equal to the rms noise per root herts of bandwidth centered at the signal frequency. Note that the resolution is dependent on the bandwidth of the measurement. With an output bandwidth of 1 Hz the standard GMSX will resolve field changes as small as 4×10^{-5} γ. Below 0.01 Hz the resolution decreases, varying as $(1/f)^{1/2}$.

• The resolution is varied by means of a superconducting range switch located on the Model GMP probe. This switch can be changed only when the probe is removed from the dewar. The two standard resolution values for the GMSX are given in the specifications. These values are intended to allow appropriate resolution for both magnetotelluric and controlled source measurements. Other applications requiring different sensitivities can also be accommodated.

• Three ranges x1, x10, x100 are provided to give increased output (volts per gamma) at the expense of the maximum signal that can be followed without resetting the magnetometer's output. The resolution remains the same for all three ranges. For the standard GMSX these values range approximately in volts per gamma from 0.01 to 1 for the lesser sensitivity and 0.06 to 6 for the greater sensitivity. The maximum output is ± 10 V for each axis, but the reset capability described below allows an almost unlimited extension of dynamic range.

• For each axis all set-up and test controls and output signals are located in a single unit which may be located and operated as far as 100 m from the dewar without compromising performance. The GMSX is normally provided with 50 m cables.

•The frequency response of the GMSX is nominally flat from dc to 250 Hz. The roll-off at 250 Hz is determined by input filters built into the magnetometer. These are very effective in preventing degradation in performance due to man-made rf sources such as radio transmitters, switching arcs, electrically noisy motors or generators, or from naturally occurring high frequency phenomena such as sferics. For special applications, a magnetometer response can be extended to 20 kHz as a factory option. Such a system is recommended only in exceptional circumstances because of the performance loss due to increased sensitivity to high frequency interference.

• Four low-pass and one line frequency notch filter are provided to reduce noise at the output. Theese filters filter only the output and have no effect on the noise in the flux-locked loop. The low pass filters roll-off at 12 dB per octave with -6 dB points at 100 Hz, 10 Hz, 1 Hz, and 0.1 Hz. The notch filter may be used independently or in combination with one of the low pass filters. Long decay transients associated with switching filters are avoided by having the filters track the output voltage at all times.

•The system is intended to be used over the wide range of temperature variations commonly experienced in the field. Guaranteed values of the temperature coefficients of the systems components are given in the specifications.

• Operating modes designated FAST, MED, and SLOW provide a match of the magnetometer's response to the frequency and amplitude to magnetic and electric signals

at the measuring site. In the FAST mode, line frequency signals as large as 1000 γ can be tracked. The SLOW mode allows system rejection of high frequency electrical noise or short lived transients.

• The system has an auto reset capability which allows almost unlimited extension of the dynamic range. Reset can be brought about either by a front panel pushbutton, internal automatic circuitry, or an externally generated signal (System Interface), which brings about reset whenever system output exceeds a pre-set value. Reset does not compromise resolution. The reset process changes the output to a voltage value very near zero.

The rf biased SQUID response is periodic in the field. Stable operation in a flux-locked mode is possible for lock points located in every cycle of the periodic response. The system output voltage for operation at these different lock points differs by precisely known amounts. The reset circuitry changes the lock point to that cycle of the periodic response which corresponds closest to zero volts output. The net effect of reset is to shift the output zero by a precisely known integer multiple of the field period. Continuous measurements are not compromised.

A TTL compatible signal is provided at the Model 30 system interface connector giving complete information regarding the reset operation.

For those unfamiliar with the use of liquid helium and SQUID systems, BTi provides a one day training session at our facility, without charge, to purchasers of the GMSX. Typically only a few hours are required for the training, providing complete familiarity with the system.

The BTi magnetometer is available for both purchase and lease. We urge you to contact us to discuss your measurement and the possible use of SQUID magnetometers.

GEOPHYSICAL TRIAXIAL MAGNETOMETER SYSTEM GMSX

SYSTEM COMPONENTS

1. Model GMP SQUID Probe with three HYBRID SQUID™ Sensors

2. Three sets Model 330X SQUID control electronics

3. Three 50 m interconnecting cables

4. Model LPD-25X dewar with helium level guage and remote readout

5. Helium transfer tube

6. Two complete sets of operating manuals

SYSTEM SPECIFICATIONS

ORIENTATION: Magnetic orthogonality between axes better than .01 radian.

CALIBRATION: Absolute calibration of sensitibity to betyter than 1%.

EM SHIELDING: Built-in 18 dB/octave roll-off with -9 dB frequency of approximately 250 Hz. Other values available on request.

RESOLUTION: Two switchable resolution values. Standard values are 4 x 10^{-5} γ and 1.2 x 10^{-4} γ in a 1 Hz bandwidth (rms). Other values between 8 x 10^{-6} γ and 2 x 10^{-3} γ available on request.

OUTPUT:

	RANGE	FULL SCALE OUTPUT	OUTPUT VOLTAGE
	ξ1	± 170 γ	0.06 V/γ
High Resolution	x10	± 17 γ	0.6 V/γ
	x100	± 1.7 γ	6 V/γ
	x1	±1000 γ	0.01V/γ
Low Resolution	x10	±100 γ	0.1V/γ
	x100	±10 γ	1V/γ

LINEARITY: Linearity better than 10 ppm.

TEMPERATURE COEFFICIENT: Output drift due to temperature changes of the rf head of less than 2.5 x 10^{-5} γ/°C. Output drift due to temperature changes of the control unit of less than 10^{-4} γ/°C under typical operating conditions.

DIMENSIONS AND WEIGHT: Dewar and Magnetometer Probe Assembly: Diameter 42 cm Height 90 cm Weight 40 kg

CONTROL UNIT: 8.7 cm H x 21.5 cm W x 33.6 D Weight 3.6 kg

RF HEAD: 3.7 cm x 7.6 cm x 9.5 cm Weight 0.5 kg

CABLE: Length 50 m Weight 3.5 kg

POWER REQUIREMENTS: 115 Vac (75 mA) or 230 Vac (37 mA) 48-400 Hz; or ±24 V dc (150 mA per axis)

Model DBS
Dynabias™
dc SQUID
System

Features:

- **Lowest Noise**
- **Large Dynamic Range**
- **Novel 1/f Noise Reduction Circuitry**
- **Computer Controllable**
- **Unsurpassed Reliability**
- **Multi-channel Control**

The Model DBS DYNABIAS™ dc SQUID System combines a double-junction Superconducting QUantum Interference Device and a novel bias and demodulation scheme to realize the lowest noise SQUID system ever offered. It is intended for applications that demand the best available performance from a SQUID. The price and specifications of the Model DBS complement BTi's best-selling Model 330X/HYBRID SQUID™ system

DYNABIAS
ELECTRONICS

It is well known that dc SQUIDs can be more sensitive *(i.e., have lower noise)* than rf SQUIDs at frequencies above about 100 Hz. However, this improvement is often accompanied by a relatively large 1/f noise contribution that completely dominates at the lower frequencies. Since most SQUID applications involve very low frequencies, the potential performance of the dc SQUID has been difficult to obtain in practice.

BTi has changed this situation. The Model DBS incorporates the novel DYNABIAS noise reduction circuitry* for detecting and amplifying signals presented to the input of the dc SQUID. Noise in the 1/f regime is significantly reduced compared to operating the same SQUID using conventional dc biasing techniques. DYNABIAS together with the Model DSQ double junction HYBRID SQUID sensor can give up to a 20 dB improvement in noise over the entire frequency range for the Model DBS SQUID System.

In addition, the relative amount of 1/f noise can be dependent on the ambient magnetic field when the SQUID sensor is cooled. When cooled in the earths magnetic field, the 1/f knee (the point where the 1/f contribution [extrapolated from very low frequencies] is equal to the white noise) for the Model DBS is typically 1 - 3 Hz. Cooling the SQUID sensor in low ambient magnetic fields (on the order of milligauss) may inprove the 1/f performance by as much as an order of magnitude.

The DYNABIAS dc SQUID electronics is contained in two modules, a Bias/Feedback unit located close to the cryostat containing the SQUID, and a bench or rack mounted control unit that can be located up to 100 meters from the cryostat.

The Model 400 Feedback/Bias unit provides the necessary voltages to properly bias a double junction SQUID sensor. Normally, internal feedback is applied to the SQUID sensor to maintain a flux-locked loop. For applications requiring feedback directly to the input circuit, the model 400 contains the circuitry needed for external feedback. The

Model 400 connects to a 10 pin jack at the room temperature end of the cryogenic probe via a 60 cm long flexible cable.

The model 40 is a half-rack size unit that controls the operations of the Model DBS DYNABIAS dc SQUID System. Front panel controls allow the user to select four sensitivity ranges, to set either of the two feedback loop responses, and to reset the operating point of the flux-locked loop. The NORMAL and FAST loop response selection allows the user to alter the feedback loop to achieve the best compromise between speed (maximum slew rate for linear operation) and stability. In the FAST mode, a high speed analog feedback circuit capable of tracking over 10^6 Φ_o/sec (100 mA/sec) is activated. This is nearly 100 times faster than flux-counting SQUID systems and far exceeds anything previously available.

Multi-channel applications are accomodated by the Model 48 dc control electronics. This unit, similar in function to the Model 40, allows simultaneous control of up to eight Model 400 Feedback/Bias units. Like the Model 40, it allows remote operation of the Model 400 Feedback/Bias units, but at a significant savings in cost.

An analog panel meter on the control electronics normally monitors the output voltage and is also used in conjunction with self-contained test circuitry activated in the SET mode to optimize SQUID performance. Precise set-up adjustment is possible even in the presence of input noise or signals having slew rates as great as 10^6 Φ_o/sec.

THE DYNABIAS PRINCIPLE

A substantial contribution to the 1/f noise in dc SQUIDs can arise from the presence of the dc bias current. By chopping the dc bias in combination with the conventional flux modulation technique, BTi engineers have devised a novel scheme for operating a dc SQUID. This DYNABIAS double modulation approach successfully separates the original signal waveform from the noise associated with the dc bias, and is responsible for the outstanding performance of the Model DBS in the very low frequency regime.

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dc HYBRID
SQUID SENSOR

The low noise BTi Model DSQ dc SQUID sensor is based on the HYBRID SQUID™ design* that has proved to be so successful in the original rf biased version, the most popular SQUID ever made. The same critical manufacturing techniques employed for the rf HYBRID SQUID are used in the Model DSQ dc SQUID sensor. The excellent coupling and self-shielding of a toroidal SQUID body is combined with two tough niobium thin film junctions that are immune to repeated thermal cycling and prolonged room temperature storage. The reliability of this SQUID sensor is unsurpassed, yet it retains the low noise, exceptionally low drift, and freedom from small, subquantum flux jumps that were previously available only from comparitively delicate point-contact devices. The toroidal geometry protects the weak links from exposure to stray magnetic fields and improves the coupling to external pickup coils, giving a greater usable sensitivity. The SQUID itself resides in a hermetically sealed inner chamber filled with shock absorbing material for added protection and filled with high-purity helium gas to avoid corrosion. This prevents damage from mechanical shock, condensation, ice, or excessively fast temperature changes. Superconducting niobium terminals are provided to facilitate making connections to the signal coil which is permanently installed inside the SQUID.

CRYOGENIC PROBE

The basic Model DP cryogenic probe(similar to the BTi Model SP rf SQUID probe) is intended for general laboratory use by direct immersion in a liquid helium bath. It is hermetically sealed at the room temperature end and employs nonmagnetic construction materials selected to minimize conduction of heat into the helium bath. The probe is doubly shielded against crosstalk, rf interference, and other electrical or magnetic transients that may affect the SQUID operation. The Model DSQ dc SQUID sensor and its input terminals reside within a superconducting shield at the bottom of the Model DP probe. Rapid access to the sensor is gained by loosening a threaded retaining collar and sliding the niobium shield upward along the probe shaft. When lowered, the shield allows operation in fields up to several hundred gauss. Input leads , usually a shielded twisted pair of superconducting wires, are easily passed through a hole in the niobium bottom cap and attached to the sensor input terminals. This bottom cap terminates in a threaded post which may be used to attach input coils or other mechanical appendages. Nonstandard probe lengths may be special ordered. *Note that non-standard length probes may affect system noise.* Contact BTi for details.

FILTER BOARD OPTION

To assist in removing unwanted noise from the output, the Model 40F Filter option for the single channel Model 40 control electronics has both high-pass and low-pass filters with 24 dB/oct rolloff. The high-pass filter has three selectable cut-off frequencies between 0.03 Hz and 10 Hz, with the low-pass filter having three selectable cut-off frequencies between 30 Hz and 10kHz.

Sophisticated comb filter circuitry is provided to reject noise at the powerline frequency and its harmonics. The filter frequency switches are mounted directly on the filter board which is located inside the Model 40 housing. Switching transients produced by the comb filter are removed by a 6 dB/octave low-pass filter starting at 1.2 kHz.

An additional two stages of amplification are provided with switch selected gains of x 10 or a user adjustable gain between 1 and 10 (factory set at x 1). The amplification stages are located at the outputs of the low-pass and high-pass filters. The comb filter has a programmable gain of x1, x 2, and x 5, set either manually or by a suitable TTL signal via the system interface connector on the rear panel of the Model 40.

SYSTEM INTERFACE

Both the Model 40 and Model 48 control units accept TTL compatible inputs via a rear panel system interface connector to change the range, to reset the feedback loop, and to select slew rates. To facilitate operation by an automatic data acquisition system, information about the range and mode status is also presented at the system interface connector. An auto reset feature resets the output of the Model 40 whenver the full scale range is exceeded.

APPLICATIONS

By virtue of its exceptional low noise and wide bandwidth, the Model DBS is well suited for many applications, including laboratory, biomagnetic, and geophysical measurements. It may be possible to substitute the Model DBS for an existing SQUID system. Upgrading an existing BTi or SHE magnetometer system for geophysical and biomagnetic use is

facilitated by retrofit kits available from BTi. BTI application engineers should be consulted for additional information concerning upgrading existing magnetometer systems for geophysical and biomagnetic measurements.

SPECIFICATIONS

SENSOR Niobium thin-film double junction SQUID. Nominal 4.2 K operating temperature.

INPUT Two niobium screw terminals suitable for superconducting connection to input coil. Input coil inductance: 2µH. Current sensitivity: 0.1 µA/Øo corresponding to 20 nH mutual inductance between input coil and SQUID. (1 Øo = 2.07 x 10^{-15} Webers.)

OUTPUT Front and rear panel floating BNC jacks. ± 10 V full scale, output impedence 47 Ω, panel meter monitors output voltage in NORMAL and FAST modes.

NOISE Less than 1.5 x 10^{-12} A(rms)/√Hz. [15 µØo/√Hz], referred to input, in the frequency range 10 Hz to 50 kHz.

RANGE Four sensitivity ranges selected by pushbutton. The table gives input current and equivalent flux change for full-scale deflection (FSD). Relative accuracy of the scale factor is within 0.5% of the nominal value.

FREQUENCY RESPONSE
dc to 50 kHz (-3 dB) in FAST mode
dc to 5 kHz (-3 dB) in NORMAL mode

MAXIMUM INPUT AMPLITUDE Maximum amplitude for reversible locked-loop operation is limited by the maximum slew rate of the feedback amplifiers as shown in Figure 6. Performance on downsloping portions of graph will be degraded by any additional (external) noise.

MAXIMUM SLEW RATE Greater than 100 mA/sec (referred to input) in the FAST mode.

RESET CONTROLS Reset may be initiated by front panel pushbutton, by TTL compatible input at the system interface connector, or automatically when the output exceeds a predetermined level that may be set anywhere from one volt to full-scale output. Minimum time required for remote reset varies between 35 µsec and 100 µsec depending on the voltage change between reset points and on the operating mode (NORMAL or FAST). Automatic reset time may optionally be specified as short as 20 µsec (consult the factory regarding possible operational limitations). On the Model 40, TTL compatible outputs needed to operate an up/down (digital flux) counter are provided by the auto-reset circuitry and are available at the System Interface connector.
DETECTOR AND SYNC OUTPUTS Provided for monitoring and troubleshooting purposes.

SYSTEMS INTERFACE CONNECTOR
Provides TTL compatible (5V) pinouts for external control of control electronics (both models 40 and 48) including mode, range, reset, and front panes status. Model 40 outputs also include auto reset and reset sign.

POWER 115/230 Vac (±10%), 48-400 Hz, 20VA max.

SIZE & WEIGHT Model 40 Control Unit: 100 mm H x 216 mm W x 357 mm D (4 x 8.5 x 14 inches). Height with feet removed: 87 mm (3.44 inches). Weight is 3.6 kg.
Model 48 Control Unit: 192 mm H x 432 mm W x 438 mm D (7.56 x 17 x 17.25 inches). Height with feet removed: 178 mm (7 inches). Weight is 3.6 kg.
Model 400 Feedback/Bias Unit: 45 mm H x 128 mm W x 203 mm D (1.75 x 5 x 8 inches). 710 mm (28 inch) flexible section connects to probe. Longer flexible sections are available on special request. Weight is 1 kg.
Model DP Cryogenic Probe: Weight is 1 kg.

MODEL40F **FILTER UNIT SPECIFICATIONS**
High-pass filter: 24 dB/octave with switch selectable cut-off frequencies of 0.1 Hz, 0.3 Hz, and a user adjustable frequency between 0.03 Hz and 10 Hz, factory preset at 0.03 Hz. Filter gain is x 10 or user adjustable between x 1 and x 10, factory preset at x 1.

Low-pass filter: 24 dB/octave with switch selectable cut-off frequencies of 100 Hz, 1 kHz, and a user adjustable frequency between 30 Hz and 10 kHz, factory preset at 30 Hz. Filter gain is x 10 or user adjustable between x 1 and x 10, factory preset at x 1.

Comb Filter: Attenuates at the line frequency and all harmonics up to the 63 rd. Attenuation at the fundamental is 45 dB and 25 dB at the third harmonic. The -3 dB notch width is 0.4 Hz at the fundamental.

Specifications are subject to change without notice.

◊ *The filter frequency switches are mounted directly on the filter board inside the Model 40F housing, accessible by sliding back the top cover. User adjustable frequencies (and gain - see below) are set by changing a resistor mounted on the circuit board. These frequencies are preset at the factory to 1 Hz (high pass) and 3 kHz (low pass).*

Owing to a fundamental noise contribution that is inherent in SQUID sensors, there exists a low frequency contribution to the system noise that departs from flat frequency response as the frequency decreases. It should be noted that this low frequency noise is roughly the same for all types of SQUID sensors (rf vs. dc, thin film vs. point contact, etc.). The point at which this low frequency noise becomes significant is related to the relative noise levels of the frequency independent (white) noise and the 1/f noise. Defining the "knee" or transition from flat response to be the point where the 1/f contribution (extrapolated from very low frequencies) is equal to the white noise, the Model DBS Dynabias dc SQUID system has a 1/f knee below 3 Hz, with the 1/f energy noise being on the order of $4 \times 10^{-30}/f$ (joules).

A substantial contribution to the 1/f noise in dc SQUIDs can arise from the presence of the dc current bias. By chopping the dc bias in combination with the conventional flux modulation technique, BTi engineers have devised a novel scheme for operating a dc SQUID. This DYNABIAS double modulation approach successfully separates the original signal waveform from the noise associated with the dc bias, and is responsible for the outstanding performance of the Model DBS in the very low frequency regime.

In addition, the relative amount of 1/f noise can be dependent on the ambient magnetic field when the SQUID sensor is cooled. When cooled in the earths magnetic field, the 1/f knee is typically 1 - 3 Hz. Cooling the SQUID sensor in low ambient magnetic fields (on

the order of milligauss) may inprove the 1/f performance by as much as an order of magnitude.

INTRODUCTION

Electrical measurements of physiological potentials are well established in clinical diagnostics. Analogous measurements of physiological magnetic fields, however, are relatively unknown to researchers and clinicians. These measurements are proving to be of considerable significance and are the subject of a great amount of current research.[1-2]

This research encompasses many of the major organs of the body, including the heart, brain, liver, lungs and muscles. several new diagnostic procedures and instruments have resulted from this work. BTi provided the equipment used in many of these experiments--equipment now available to you.*1

Essentially every phenomenon in electrophysiology has a magnetic analog since a magnetic field is associated with every electric current. Magnetic measurements offer several advantages when compared to electrical measurements:

- They require no contact with the subject and are thus immune to changes in the skin, such as resistive changes resulting from perspiration.

- Magnetic fields penetrate resistive media such as the skull with minimal distortion, unlike the surface electric potentials which can be greatly distorted.

- Since the magnetic fields emerge undistorted from the body, they can be used to determine the location of their sources, a feature of great significance in encephalography. The magnetic field distribution outside the head can be used to construct a three dimensional map of the functionally active areas of the brain, accurate to within a few millimeters in some cases.

Magnetic measurements, including those of sources deep within the brain, are performed noninvasively.

In addition, magnetic measurements can be made for which there are no electrical analogs. These are measurements of static magnetic fields produced by ferromagnetic materials inhaled, injected or ingested into the body, and measurements of the magnetic susceptibility of materials in the body. Examples of these are magnetic dusts inhaled and retained in the lungs and paramagnetic compounds such as ferritin and hemosiderin which occur naturally in the body. The concentration of ferritin and hemosiderin in the liver has been measured and correlated with chemical analysis of biopsy samples with remarkable accuracy using a superconducting biosusceptometer (Fig. 1).

Biomagnetic phenomena could not be studied or used as indicators of physiological conditions until instruments were developed with sufficient sensitivity for measuring these extraordinarily small magnetic fields. The most intense magnetic fields normally emitted from the human body are those from the heart. These have an intensity of only 50 picoTesla (1 pT = 10^{-12} Tesla = 10^{-8} Gauss), while those from the brain are 50 to 1000 times less intense. Consequently, it was not until superconducting SQUID+1 magnetometers became available in the early 1970's that practical measurements of these fields could be made (Figs. 2 and 3).

Although these techniques are in their infancy, measurements already have been made of magnetic phenomena associated with the heart (magnetocardiograms, MCG), the brain, (magnetoencephalograms, MEG), magnetic susceptibility of inhaled materials

(magnetopneumograms, MPG), magnetic susceptibility of accumulated paramagnetic and ferromagnetic substances in the body, isolated nerves, plus many more.

Most of these measurements have been performed using standard or modified BTi instruments. If your research could benefit from magnetic instrumentation, our experience and design capabilities are available to you as well. Call us for consultation with our design engineers.

MEASUREMENT TECHNIQUES

Magnetic fields associated with different physiological functions and conditions vary widely in their intensities, frequencies and spatial distributions. consequently different techniques and instruments must be used in their measurement.

As shown in Figure 4, the frequencies of interest range from essentially d.c. to several hundred Hertz, and the field intensities range from about 50 fT (50×10^{-15} T = 5×10^{-10} Gauss) to 10^6 fT (10^{-5} Gauss). The sources of these fields vary from localized groups of neurons in the brain, to more dispersed muscle tissues in the heart, to magnetic particles distributed throughout the lungs.

Electrically Active Sources. Magnetic fields from active electrical sources in the body are measured completely passively and external to the body by placing the detector in close proximity to the body's surface. This technique is applicable to the heart, brain and skeletal muscles.

It has been shown in the case of the brain, for example, that a neuron can be modeled as a current dipole which generates a well defined magnetic field profile. Measurement of this profile can be used to infer the location of the neuron with considerable accuracy. Using evoked response techniques, the location of signal pathways and information processing centers in the brain can be mapped at different delay times (latencies) following the stimulus. For this purpose, the field is mapped around the surface of the head, as in Figure 2. To date, such measurements have been made by moving a single detector around the head.

A new system, recently developed by BTi, will accelerate this process and improve its accuracy by simultaneously making magnetic field measurements at five locations. In addition, this system will cancel magnetic noise with greater precision by measuring the ambient magnetic field vector and field gradient using four additional magnetic sensing channels. the ambient noise will be electronically subtracted from each of the five active measurement channels to greatly increase the overall system sensitivity.

Para/Diamagnetic Sources. Fields from paramagnetic or diamagnetic materials are measured while a low intensity external magnetic field is applied to a local region of the body and compared with the background field when the subject is removed from the sensitive range of the instrument. Information on the depth of these materials can be obtained by using magnetization and detection coils of differing sizes in the same instrument or by measuring the field as a function of distance from the body.

Ferromagnetic Sources. The location and quantity of ferromagnetic materials in the body, typically due to contaminants in the lungs, are determined by measuring the magnetic field external to the body before and after a low intensity magnetic field (typically 0.01 Tesla) is applied to magnetize the ferromagnetic material. the distribution of these materials can be determined by applying the field to only a small region of the body at a time.

Action Potential Sources. Yet another type of biomagnetic measurement made with BTi instruments is the measurement of magnetic fields generated by currents flowing in isolated nerves or muscle fibers. To observe the details of the magnetic fields from action potentials requires that the sample fibers be in close proximity to the detector. This is done by threading the nerve or muscle fiber through a small ferrite cored toroidal coil. The signal is transmitted by means of a flexible coaxial conductor to the superconducting detector located in a conventional liquid helium storage dewar.

Instruments used for measuring biomagnetic fields must discriminate the biomagnetic signals from naturally occurring or environmentally generated magnetic fields. these fields can be vastly more intense than the signal of interest. The most intense naturally occurring fields in the steady field of the earth, which, with an intensity of 5×10^{10} fT (0.5 Gauss), is 10^4 to 10^9 times as great as typical biomagnetic fields. This field, fortunately, is quite stable and can be discriminated against rather easily, as will be shown later.

Superposed upon the constant field of the earth is an additional field resulting from fluctuating electric currents in the ionosphere. the amplitude of this ac field is frequency dependent, generally decreasing in amplitude as the frequency increases. The remaining external fields are primarily manmade. These can be caused by the following: structural steel and other localized magnetic materials such as furniture and instruments that distort the earth's field and result in field gradients; moving vehicles that generate transient fields; electric motors; elevators; radio; television and microwave transmitters; and the omnipresent powerline magnetic field and its harmonics. Typical noise levels are shown in Figure 5.

Rejection of the signals from these various sources of noise is accomplished in a variety of ways. One of the better, but also one of the less convenient, ways of shielding the sensor from these sources of noise is to construct a room of highly permeable magnetic shielding materials in which the sensor and subject are placed. Fortunately, other methods are available that are almost as successful and permit even MEGs to be made in a typical clinical/laboratory environment.

High frequency shielding of the sensor coils is readily accomplished by surrounding the pickup coils with a conducting shield that attenuates the response of the system to high frequency signals (eddy current shielding). Signals from the power line can be reduced to manageable levels electronically by the use of notch filters. Consequently, the environmental magnetic noise of greatest significance is in the frequency band from d.c. to a few hundred Hertz.

The sensitivity of the system to external magnetic noise is greatly affected by the design of the detection coil array. The detection coils used in superconducting magnetometers are composed of one or more loops of superconducting wire (Fig. 6). A single closed loop of superconducting wire has the unique characteristic that any change in the magnetic field threading through the loop results in a change in the current flowing in the loop. Unlike its resistive counterpart, the current in a superconducting loop persists indefinitely as long as the magnetic field is not changed. The superconducting magnetometer responds only to changes in magnetic field through the detection coils. Consequently, constant fields, even if hundreds of times greater than the earth's magnetic field, do not affect the ability to resolve the biomagnetic fields.

Connecting in series two such identical and exactly parallel loops wound in opposite senses provided a coil that is insensitive to changes in the spatially uniform background field (Fig. 6b). The two loop coil however, responds to changes in any gradients in the magnetic field since a gradient results in different amounts of flux in each loop. Hence its name--magnetic gradiometer.

If the source of the signal of interest is near one of the loops, it will result in a greater change in field in the near loop than in the more remote loop, resulting in a net change in output. In effect, one loop is used a magnetometer and the second as a compensating loop to cancel variations in the background field. Used in this manner, the gradiometer is a uniform field canceling magnetometer.

Unfortunately background fields are rarely uniform. However, if their sources are sufficiently remote, the gradient in the field over the sensing coils is both small and uniform. In this case, it is possible to use two gradiometers connected in series opposition to further minimize the response of the system to these sources (Fig. 6f). This technique greatly reduces the sensitivity of the instrument to environmental magnetic noise. Again, however, a source placed sufficiently near one loop of one of the gradiometers results in a net current in this 2nd order magnetic field sources, but cancels uniform fields and linear field gradients from remote sources. This technique can increase the signal-to-noise ratio by about a factor of 10^6 above that achieved with a single loop magnetometer. This configuration has enabled the recording of magnetic encephalograms in an unshielded urban environment.

This technique can obviously be extended to higher orders by connecting in series opposition two 2nd order gradiometers, etc. Doing so, however, reduces the sensitivity of the instrument to the signal of interest and does not necessarily improve the signal-to-noise ratio further.

BTi's standard biomagnetic system incorporates a 2nd order gradiometer that is highly sensitive to nearby sources of magnetic fields while rejecting ambient magnetic noise with great precision. Higher order gradiometers and other geometries are provided on request. Examples of coil configurations are shown in Figure 6.

LIQUID HELIUM & DEWARS

Helium, an inert gas with a boiling point of 4.2K (-269°C), is used for cooking SQUID sensors and superconducting detection coils to their operational temperatures. Liquid helium is readily available from commercial vendors throughout the United States and in most foreign countries. It is usually supplied in storage containers (dewars) having capacities of 25, 30, 50 or 100 liters and is delivered to the customer's site. The liquid is readily transferred from the storage dewar to BTi magnetometer dewars by means of a flexible vacuum insulated transfer tube. Transferring is accomplished by inserting the transfer tube into the storage and magnetometer dewars and applying a slight overpressure (1-2 psig) to the storage dewar. A liquid helium level meter in the BTi dewar indicated the amount of liquid transferred. the process can be completed in about 15 minutes.

Dewars are used to store liquid helium with the minimum possible boil-off rate and to maintain the coil array and SQUID detector in the superconducting state. Dewars for biomagnetic measurements are constructed of specially designed and selected materials to minimize their magnetic interaction with the system. They are constructed of shatterproof fiberglass reinforced epoxy and are quite safe to use. They require no routing maintenance and require refilling only once or twice a week.

BTi BIOMAGNETIC INSTRUMENTS

Although most biomagnetic systems are custom designed for specific applications, BTi has developed "standard" instruments for measuring all of the biomagnetic fields discussed earlier:

- Model 600: Used for measuring time varying and static magnetic fields, such as those from the heart and brain, and *in-situ* magnetized ferromagnetic materials.

• Model 605: Five-channel instrument designed for magnetic brain wave recordings at five locations simultaneously. In addition, separate measurements are made of the ambient magnetic field vector and axial field gradient for noise cancellation in the measurement channels. This system represents today's state-of-the-art and permits more accurate, reliable and rapid magnetic brain measurements to be made.

• Model 610: Used fro measuring the fields induced by paramagnetic materials in the body, such as ferritin in the liver. This system includes a superconducting magnet for applying a low intensity magnetic field to local regions of the body, and two sets of detection coils and SQUIDs.

• Model 620: Used for measuring currents in isolated nerve and muscle fibers *in-vitro*.

Model 600 Biomagnetic System

The Model 600 is the most widely used biomagnetic system in the world, affording the capability of conveniently measuring magnetic fields as low as 15 fT/√Hz at frequencies from less than 1 Hz to several hundred Hertz. Two versions are offered, the Model 600A with BTi's standard rf biased HYBRID SQUID™ and Model 600B with the DYNABIAS™ SQUID+2. The latter is recommended where the application require the greatest sensitivity. The former system has an equivalent magnetic field noise of about 35 fT/ç√Hz and is adequate for all but the most demanding applications. The system is shown in Figure 7.

The SQUID detector is installed inside the dewar and the combination comprises the main body of this system. Measurements are made by placing the tail of the dewar containing the detection coil assembly in close proximity to the part of the body at which the signal of interest is to be measured. To maximize the coupling between the source and the sensor, the dewar is constructed so the lowest coil of the detector is not more than 1.1 cm from the outside surface of the dewar. The dewar is 27 cm in diameter, 90 cm long and weighs approximately 15 kilograms in operation. due to the varying requirements, dewar mounts are normally not provided but can be supplied on special order.

The magnetocardiogram of Figure 2 and the magnetoencephalogram of Figure 3 were recorded with this instrument.

A one day training course at BTi's facility in San Diego (optionally at user's facility) is included with the system. This course provided familiarization with the proper set up and operation of the system to enable the user to realize its full potential.

Model 605 Neuromagnetometer

BTi's Model 605 Neuromagnetometer is the most sophisticated system of this type ever developed. It offers:

• Simultaneous measurement of magnetic signals at five locations using BTi's newly developed low noise DYNABIAS dc SQUIDs;

• More sensitive, rapid and accurate measurement of the location and intensity of neuromagnetic sources; sensitivities of 20 fT/√Hz are expected in the signal channels;

• Convenient and functional integration of all sensors into a 10 liter, nonmagnetic dewar less than one meter long and contoured to the "average" skull (9 cm radius of curvature);

• Passive magnetic noise cancellation by subtraction of the ambient field and axial field gradient (measured by an integral three axis magnetometer and axial gradiometer) from the signal channels; manual or computer controllable (DEC-UNIBUS DRII-C) interface;

• Active line frequency and harmonic rejection by means of synchronous capacitor comb filters.

The system is supplied with the dewar, a liquid helium level meter, five dc SQUID magnetometer systems, four rf SQUID magnetometer systems, nine-channel comb filters, computer controllable noise reduction unit, and all connecting cables.

Other components necessary for use of the system include: high and low pass filters, nonmagnetic patient support "chair", dewar support structure, data acquisition system and liquid helium transfer equipment. Any of these items not already available can be supplied by BTi.

A training course by BTi personnel is included with the system.

Model 610 Biosusceptometer *2

The Model 610 system is designed for measuring fields from paramagnetic materials in the body. Measurements are made by determining the change in magnetic field at the detector as the subject is moved into and away from the sensitive region of the detector. A small magnetic field is applied during these measurements by a self contained superconducting magnet. the system is illustrated in Figure 8. To simulate the presence of the body during the measurements, water, approximating the natural diamagnetism of the body, is located between the sensor and the body. This water is contained in a "water bag" placed on the subject. The water bag, dewar support and nonmagnetic, movable table for the subject are available on special order.

In the case of liver iron measurements, it is necessary to know the depth of the liver beneath the surface of the body. This depth is determined by ultrasonic means (not supplied).

Two detector channels are included in the system to enable measurements to be made of differing sample volumes and thereby infer the spatial extent of the paramagnetic accumulations in the body.

The system comprises a two channel magnetometer, a low intensity superconducting magnet, a magnet power supply, a Model BMD-25 liquid helium dewar for maintaining the sensors and coils in the superconducting state, a flexible transfer tube for transferring liquid helium into the system from a storage dewar, a liquid helium level meter, and all interconnecting cables.

The dewar with the SQUID detection systems installed is 35 cm in diameter, 134 cm long and weighs 76 kilograms.

As with the Model 600 and 605 system, a one day training course in the proper use of the Model 610 system is included with the system. This course is presented at S.H.E. Corporation in San Diego, or optionally at the user's facility.

The correlation between the magnetic and chemical measurements of the iron concentration shown in Figure 1 was found using this instrument.

Model 620 Action Potential Magnetometer *3

The Model 620 system is designed for measuring the magnetic fields from action potentials in isolated nerve and muscle fibers at ambient temperature. Measurements are made of the magnetic field encircling the nerve by means of a ferrite cored toroidal coil through which the nerve is extended. The standard coil has an inside diameter of 1.2 mm; other sizes can be provided.

This system is illustrated in Figure 9 and contains a HYBRID SQUID with a special probe used to inductively couple the signal from the room temperature toroidal coil to the SQUID. The system has the unique advantage of allowing the specimen to be maintained external to the dewar and at ambient temperatures. The design provides excellent coupling to and spatial resolution of the magnetic field while being insensitive to external magnetic noise.

The system is supplied with the HYBRID SQUID, the toroidal sensing coil and its interconnecting 195 cm long coaxial cable. A typical 30 liter liquid helium storage container (not supplied) with the probe installed will maintain the probe at its operational temperature for two to three weeks.

1. Proceedings of the Advanced Study Institute on Biomagnetism--Frascati, Italy, September 1-12, 1982, Plenum Press, New York (In Press)

2. S.J. Williamson and L. Kaufman, “Biomagnetism”, Journal of Magnetism and Magnetic Materials, 22, 129, 1981. 281 References.

*1 No claims for the clinical efficacy of these instruments are made. Researchers using these instruments are responsible for the interpretation and use of date acquired with them.

*2 U.S. Patent No. 4,079,730

*3 U.S. Patent No. 4,324,255

+1 SQUID is an acronym for **S**uperconducting **QU**antum **I**nterference **D**evice. These devices are universally acknowledged to be the world’s most sensitive magnetic field detectors. Export restrictions apply.

+2 U.S. Patents 4,386,361, 4,004,217 and 4,389,612

MODEL MTS MILLIKELVIN THERMOMETRY SYSTEM

INTRODUCTION

The BTi Model MTS MilliKelvin Thermometry System combines a high resolution low noise SQUID (Superconducting QUantum Interference Device) based measurement system with a compact easily installed CMN (Cerous Magnesium Nitrate) thermometer to form a thermometry system capable of measuring temperatures from above 6 Kelvin down to less than 5 milliKelvin. The Model MTS is designed primarily for use with dilution refrigerators, and is easily installed in most dilution refrigerator systems. Thermometer assemblies are available for temperature measurement directly in liquid helium or for external attachment to an experimental package. The thermometers are easily moved so that they can be used in a variety of experimental configurations.

The Model MTS MilliKelvin Thermometry System comprises the following: CMN thermometer, Model MPS MultiPurpose Measurement System, and Model SEC Remote Terminal Board.

THE SQUID SYSTEM

The BTi Model MPS Multi-Purpose System comprises the Model 330X SQUID electronics, Model MFP Multi-Function Probe, Model RBU ac Impedance Bridge, and the Model CCS Constant Current Source.

The Model RBU RBU ac Impedance Bridge (resistance, self inductance and mutual inductance) is a low power ac impedance bridge in which a SQUID sensor is employed as a null detector. The exceptional current sensitivity of the SQUID enables high resolution (up to 0.001%) measurements to be made while dissipating an almost negligible power in the thermometer (or other impedance being measured).

A key part of this SQUID based system is the Model MFP Multi-Function SQUID Probe. This versatile probe can be used for other measurements in a low temperature cryostat or can be removed from the cryostat and used in other laboratory experiments. For example, it can be used as a picovolt measurement system for measuring extremely small resistances or dc voltages at a resolution better than 10^{-11} Ω or 10^{-13} volt. For resistance measurements, the Model CCS low noise, wide range Constant Current Source is also supplied.

Further information on all BTi SQUID systems and components can be supplied on request.

THE THERMOMETER

The BTi Curie law thermometer uses the well substantiated 1/T Curie law susceptibility of the paramagnetic salt cerous magnesium nitrate hydrate, $Ce_2Mg_3(NO_3)_{12}.24\ H_2O$, (CMN) to create an accurate high resolution thermometer. The thermometer package is designed to be used as an accurate thermometer in the temperature region from 1K down to below 5 mK; similar thermometers have been used as temperature dependent indicators to temperatures below 1 mK.

Figure 1 shows an internal thermometer unit designed for insertion into a liquid helium environment: it then measures the temperature of the liquid helium. Figure 2 shows an external thermometer package which is designed to be firmly attached to the item whose temperature is to be measured: it has a capillary tube (which is connected into the dilution refrigerator plumbing with a simple soft solder joint) for admitting liquid helium, which provides thermal contact between the CMN and the thermometer housing. In both cases a 10 mg CMN powder pill is located in an epoxy form on which are wound two coils, a primary excitation coil and secondary pick-up coil. The susceptibility of the CMN is then monitored by measuring the mutual inductance between the coils using the BTi Model RBU bridge.

Owing to the secondary coil design and to the careful construction of the coils, the mutual inductance between the primary and secondary coils is quite small. This small value allows more precise measurements of changes in mutual inductance, which reflect changes in the susceptibility and thus the temperature of the CMN. The secondary coil is designed to give optimum sensitivity when used with the BTi Model RBU bridge.

A niobium shield surrounds the CMN and coils. This shield, a superconductor below 9K, maintains a constant dc magnetic field on the CMN and also shields the coils from environmental magnetic noise. The secondary coils also have a gradiometer design to additionally assist in eliminating magnetic noise from the system.

The small size of the thermometer and the use of CMN powder with liquid helium provide excellent thermal contact between the thermometer and the liquid helium (internal thermometer) or between the thermometer and the thermometer housing (external thermometers) and minimize thermal time constants two very important properties in low temperature research.

The CMN susceptibility is described by a Curie law, $X = C/T$ where C is a constant. The mutual inductance between the primary and the secondary coils is given by

$$M = K_1 + K_2 C/T$$

where K_1 and K_2 are constants determined by the coil geometry, the CMN mass and position, other nearby magnetic materials (such as the Niobium shield), etc. The constants K_1 and K_2C are determined by measuring M vs 1/T in one temperature range and fitting a straight line to the points. then one obtains

$$T = K_2C/(M - K_1)$$

which accurately defines the temperature as a function of the mutual inductance down to temperature below 5 mK. If the Model RBU bridge is used in the INDUCTANCE and MULTIPLY modes with the RANGE set at 0.1, then the mutual inductance is given by $M = \alpha \times (0.1\ \mu H)$ where α is between 0 and 1. α is typically readable to one part in 10^5. (On the Model RBU bridge, α is the dial reading on the IN-PHASE precision ratio transformer.) With these settings, a typical calibration is given by

$T = 4\ mK/(\alpha - 0.60000)$

Thus at T=1 K, $\alpha = 0.60400$ and the resolution of $\Delta\alpha = 10^{-5}$ corresponds to $\Delta T = 2.5$ mK; and a similar resolution at 100 mK corresponds to $\Delta T = 25$ μK. At 10 mK, $\alpha = 1.00000$ (the maximum value for α) and $\Delta\alpha = 0.00001$ corresponds to $\Delta T = 0.25$ μK. For lower temperatures, the precision RANGE transformer β on the Model RBU bridge may be changed to 0.20000; then

$T - 2mK/(\alpha - 0.30000)$

and α at 10 mK now equals 0.50000. (Note: the range may be changed more frequently so as to always maintain sensitivity if this is desired.)

SYSTEM USE

It is recommended that the thermometer be cooled in the earth's magnetic field so that a relatively small field is trapped in the niobium shield surrounding the thermometer. The CMN will function properly in trapped fields up to about 30 Gauss--the M vs. 1/T linearity suffers at the lowest temperatures as the magnetic field increases. Once a field is trapped, the magnetic fields around the thermometer unit may be increased to around 200 Gauss without affecting performance. Because of variation in this trapped field, the thermometer must be recalibrated each time it is cooled down from room temperature of is warmed above 8K. Typically the calibration reproduces within several percent if the thermometer is cooled in the earth's magnetic field.

The accuracy of this thermometer will primarily be limited by the accuracy of the calibration which will depend on the accuracy of the temperature standard. Accuracies of better than 1% are readily achievable. At BTi, thermometers are typically calibrated in the temperature region between 1K and 0.25 K using a previously calibrated germanium resistance thermometer (also available from BTi). Calibrations using the vapor pressure of ^{3}He or ^{4}He, or NBS superconducting fixed points (SRM 767a or 768) are also possible.

The Model MTS system can be used in conjunction with the BTi Model 1000 Potentiometric Conductance Bridge/Controller (not provided in the MTS package) to provide microkelvin temperature regulation at the operating temperatures normally associated with dilution refrigerators.

MULTI-TASKING

The ability of the Model MTS to measure multiple thermometers and/or experimental samples makes it a very unique and highly versatile instrument. The system provides built-in switch selection between two unknowns (more are possible but external switching is then required). This switching capability allows the measurement of temperatures at two different sites using two thermometers or the measurement of the temperature of an unknown sample while at the same time acquiring data from the sample itself (e.g., measuring its susceptibility) - all with a single instrument. This feature is an exclusive capability of the BTi MPS Multi-Purpose System.

External CMN thermometry package
(not to scale)

Curie Law Thermometers

BTi manufactures Curie Law Thermometers using cerium magnesium nitrate (CMN) as the paramagnetic substance. These thermometers are most generally useful in the temperature range from 1K to 2mK. They have been specifically designed to take advantage of the sensitivity offered by SHE SQUID apparatus. Only 10 mg of CMN is typically required to provide adequate resolution over the entire usable range.

The basic thermometer packages which are available are shown in the attached sketch. Model CMNE utilizes pure CMN powder pressed into an epoxy form on the outside of which are located pick-up coils and a niobium shield. It is intended that thermal contact to the CMN be made by immersing the entire unit in liquid helium. The sample whose temperature is being monitored may also be immersed in the helium or may be attached to the outside of the helium vessel. This model is not suitable for direct attachment to that sample.

The model CMNG is basically a mixture of CMN powder and gold powder which is pressed into a copper form. the gold powder serves to make thermal contact between the copper body and the CMN. Pick-up coils and a niobium shield are again located on the outside of the body. The lower end of the copper form is normally provided with a flange for use in clamping it to the sample or a sample holder. Alternatively, a threaded stud (4-40 or 6-32 UNC) or a boss may be provided on the lower end.

The susceptibility of the CMN obeys a Curie law down to temperatures of order 2mK. This susceptibility may be monitored using either a dc or ac technique. For the former, a standard SQUID magnetometer is used in the flux-locked loop mode. The pick-up coils at the thermometer are composed of niobium and are an astaticly wound pair. Consequently, to first order external magnetic disturbances are not detected. The coil leads pass up to the SQUID probe and are attached to the input terminals. These terminals connect to a niobium signal coil located within the SQUID sensor. One now has a completely superconducting circuit. One can apply a magnetic field (up to a few hundred gauss) to the thermometer externally during cooldown and this field is then trapped by the niobium shield when it becomes superconducting. This forms the constant measuring field for the CMN. As the temperature on the CMN changes, its magnetization changes. The magnetic flux linking the pick-up coils thus changes, resulting in a current flow through the flux transformer and signal coil in the SQUID. The flux within the SQUID sensor itself then is changed by an amount proportional to the changes in the susceptibility of the CMN. The magnitude of the signal change corresponding to a given temperature change is proportional to the value of the trapped measuring field and thus greater resolution is available with larger fields. Note that the output of the system is a dc voltage and may be used for regulation, if desired.

For monitoring the susceptibility of the CMN using an ac method, a bridge circuit like that featured in the SHE RLM system is used. The niobium coils wound on the form containing the CMN make up a mutual inductance. The secondary is an astatic wound pair, and over this is wound a uniform primary. The CMN is again centered in one of the astatic pair. The mutual inductance of this system is balanced against that of a standard mutual inductance located elsewhere in the bridge circuit. SHE Model MFP and RMP SQUID probes have this standard mutual inductance built into them. As the temperature of the CMN changes, the indicated value of the mutual inductance enclosing the CMN changes and this value then obeys a Curie law.

It is standard procedure to calibrate either of the above thermometers that is, determine the constants in the equation $T = M \frac{A}{} B$, where M is either the output of the dc magnetometer or of the ac bridge in a higher temperature region by intercomparison with a standard such as the vapor pressure

of helium or a previously calibrated germanium resistance thermometer. The latter are readily available commercially.

The ac method of observation requires a substantially larger outlay for equipment than the dc method. However, it offers several advantages. The measurement system is much less sensitive to external magnetic or electrostatic disturbances and the shielding requirements for the low temperature circuitry are less severe. Magnetic or superconducting transitions at remote points of the circuit will not lead to spurious offset signals. The CMN can be located in a slowly varying field of a superconducting magnet and still indicate an accurate temperature. One must weigh these advantages and possible lost time due to offset errors induced in the dc system signal as a result of magnetic disturbances against the added expense involved in using the ac method.

The accuracy of any of the above thermometers is limited primarily by the accuracy of the customer's calibration. Accuracies of under 1% are readily achievable. The resolution offered by the thermometers at low temperatures is about 1 in 10^5 when using the ac technique. when using the dc method, the resolution depends on the size of the trapped field. If one simply traps the earth's field ($\approx$1/2 gauss), a resolution of 1 in 10^4 at low temperatures is typical. This can easily be increased by two orders of magnitude by trapping larger fields.

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