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OVERVIEW OF APPLICATIONS OF SQUIDS

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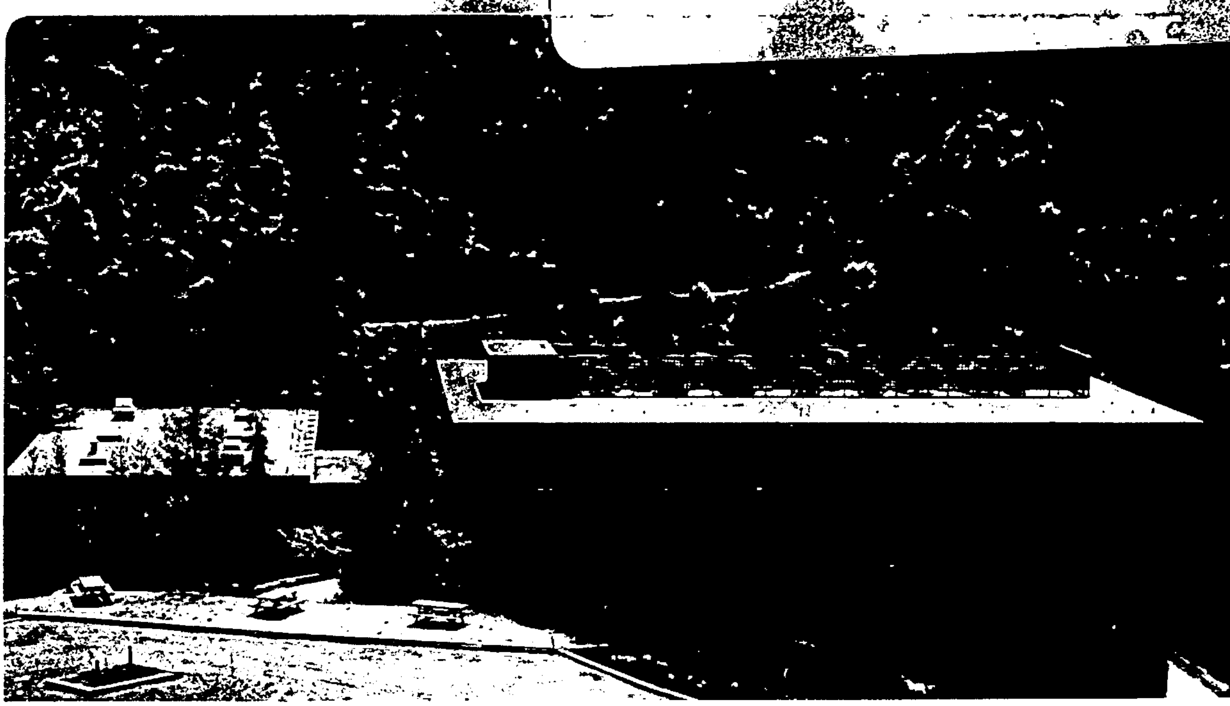

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Proceedings of SQUID Magnetometry Workshop
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OVERVIEW OF APPLICATIONS OF SQUIDS

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The applications of SQUIDs can be conveniently divided into the five following categories, in each of which is listed a number of representative examples:

Cryogenic Sources:

- Thermoeletric Voltages
- Hall Voltages
- Quasiparticle Charge Imbalance
- Flux Creep
- Resistivity
- Static Susceptibility
- NMR

Geophysics

- Magnetotellurics
- Electromagnetic Sounding
- Atmospheric Physics
- Rock Magnetism--Paleomagnetism
- Piezomagnetism
- Tectonomagnetism
- Location of Hydrofractures
- Internal Ocean Waves
- Gravity Gradiometers
- Airborne Magnetic Gradiometers

Standards

- Comparing Josephson & Standard Volts
- h/m
- Noise Thermometry

Biomagnetism

- Magnetocardiology
- Spontaneous/Evoked Brain Activity
- Eye Movements
- Location of Magnetized Particles

"Extraterrestrial" (ET)

- Gravity Wave Detectors
- Monopole Detectors
- Orbiting Gyro Test of General Relativity

The performance and limitations of SQUIDs can be broadly characterized as follows:

Determined by SQUID

White Noise

1/f Noise

Drift

Determined by Electronics

Frequency Response

Slew Rate

Dynamic Range

Determined by Environment

60 Hz

Radio & Television

Low Frequency Magnetic Noise: Cars and Elevators

Fluctuations in Earth's Field

Tilt of Magnetometer in Earth's Field

Etc.

The last category applies only to SQUIDs or pick-up coils that are not magnetically shielded from their environment, for example, geophysical magnetometers and biomagnetic gradiometers, while the first two categories apply to both shielded and unshielded devices. We now briefly examine these limitations in the light of the various applications.

White noise It is convenient to characterize the noise of a SQUID in terms of the equivalent flux noise energy, $\varepsilon/1\text{Hz} = S_\Phi(f)/2L$, where $S_\Phi(f)$ is the spectral density of the equivalent flux noise, and L is the inductance of the SQUID loop. A typical rf SQUID, for example the SHE toroidal SQUID, has a noise energy of roughly 10^{-29} JHz^{-1}. The noise energy of dc tunnel junction SQUIDs is given approximately by[1] $16k_BT(LC)^{1/2}$, where C is the junction capacitance. A typical planar device, efficiently coupled to a spiral input coil,[2] has a noise energy of the order of 10^{-32} JHz^{-1}. In the case of the dc SQUID, there appear to be relatively few experiments in which the white noise is a serious limitation: one example is the transducer for gravity wave detectors, where a quantum limited amplifier will eventually be needed. The white noise of the rf SQUID is more often a limitation: one example is in gradiometers.

Flicker (1/f) noise Both rf and dc SQUIDs exhibit 1/f noise at low frequencies, that is, flux noise with a spectral density that scales approximately as 1/f, where f is the frequency. However, detailed studies of this noise have been made only in dc SQUIDs. It has been established[3,4] that 1/f noise in the critical current of single Josephson tunnel junctions arises from the trapping of electrons in the barrier. In the dc SQUID, the 1/f noise in the critical current of the two junctions gives rise to noise in two ways: an "in-phase mode" in which a 1/f voltage noise is generated across the SQUID, and an "out-of-phase mode" in which a 1/f current noise is generated around the SQUID loop. In the usual flux-modulated scheme in which SQUIDs are operated, only the latter mode contributes to the observed 1/f noise. However, by means of a double modulation scheme in which the bias current as well as the bias flux is alternated, Koch et al.[5] were able to demonstrate the presence of an additional dominant source of 1/f noise, not associated with critical current fluctuations, which they called "flux noise". Furthermore, in a series of five different dc SQUID configurations, they found that this 1/f flux noise was roughly constant at about $(10^{-10}/f)\Phi_0^2\text{Hz}^{-1}$. It should be emphasized that these conclusions are not universal: Some junctions may exhibit a high level of critical current 1/f noise (for example, junctions with high leakage or low barrier height[6]) that produces the dominant 1/f noise in the SQUID, while SQUIDs fabricated with a different technology may exhibit a lower level of 1/f flux noise (for example, a particular batch of SQUIDs fabricated at IBM[7]). The problem of 1/f noise remains a serious one in certain applications, for example, biomagnetic gradiometers, and further investigation is clearly necessary. It is important to identify the origin of the noise if one is to have any hope of reducing it.

Drift The output of a SQUID tends to drift as the temperature is changed. A wide variety of mechanisms can give rise to drift, for example, the temperature dependence of the penetration depth, which leads to changes in the effective area of the loop,[8] the temperature dependence of the magnetic susceptibility of nearby materials that can lead to changes in the magnetic flux,[9] the motion of flux trapped in the body of the SQUID and/or its shield,[10,11] and the temperature dependence of the critical current, which can change the flux linked to the SQUID by the bias current.[10] In the latter case, the drift in a dc SQUID can be greatly reduced by dividing the bias current appropriately between the two arms of the SQUID loop.[10] Kekelis[12] has reviewed other sources of drift.

Frequency response, slew rate and dynamic range These are determined by the electronics used to flux lock the SQUID. The slew rate, in particular, is often inadequate to cope with the transient magnetic fields encountered in magnetometry, for example, in geophysics. The frequency response and slew rate may be greatly improved by increasing the modulation frequency and replacing the single-pole integrator with a two-pole integrator.[13,14] For example, with 500 kHz flux modulation and a two-pole integrator, a dynamic range of $\pm 2 \times 10^7$ $Hz^{1/2}$ ($f < 6$ kHz), a frequency response of 70 kHz (± 3 dB) and a maximum slew rate of 3×10^6 $\Phi_0 s^{-1}$ (at 6 kHz) have been achieved.[14]

Environmental noise In the case of shielded SQUIDs, for example, for voltmeters and susceptometers, the environmental noise can usually be eliminated by the judicious use of superconducting shields, μ-metal cans, shielded rooms and appropriate grounding schemes. On the other hand, for unshielded systems that are used to detect magnetic fields from non-cryogenic sources, for example in geophysics and biomagnetism, environmental noise may well limit the sensitivity of the device. Examples of man-made noise are 60 Hz fields, which can sometimes be reduced by digital filtering if the system has sufficient dynamic range, rf interference, which can usually be reduced to a low enough level by a shield around the cryostat or by a shield between the SQUID and the pick-up loop(s) of a magnetometer or gradiometer, and the fields due to automobiles, elevators or subway cars, which can be reduced by "dynamical balancing".[15] Examples of natural occurring noise are fluctuations in the earth's magnetic field (the "signal" in magnetotellurics) and the tilting of the magnetometer in the static magnetic field of the earth by seismic or wind-induced motion.

The extent to which naturally occurring and tilt-induced magnetic field fluctuation can be reduced between two separated, three-axis magnetometers was recently studied in a collaborative effort between the

Lawrence Berkeley Laboratory and Quantum Design.[16] The magnetometers were equipped with specially designed cryogenic tiltmeters. In one experiment, the vertical component of the magnetic field at the base station, H_z, was predicted from the same component measured at a reference magnetometer 800 m away, H_{zr}, and from various other inputs, for example, tilt components at the base and remote stations, T_x, T_y, T_{xr}, and T_{yr}, and the horizontal magnetic field components at the reference station, H_{xr} and H_{yr}. In a preliminary analysis, the residual between H_z and $H_z^{(p)} = a + bH_{zr} + cH_{xr} + dH_{yr} + eT_x + fT_y + gT_{xr} + hT_{yr} + \ldots$ was minimized in a least square sense. In this way, it was found possible to reduce the magnetic noise due to ambient field and tilt fluctuations by more than three orders of magnitude. It is likely that more sophisticated analysis schemes, for example, using frequency dependent transfer functions, would yield even greater reductions. This result has implications in a number of areas, for example, controlled source electromagnetic sounding and the study of source effects in magnetic field fluctuations at the earth's surface.

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