The Gravity Probe B SQUID Readout Detector

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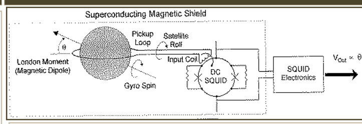
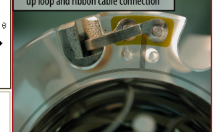
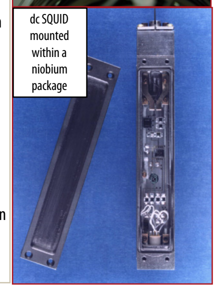
Abstract

We describe the DC SQUID-based readout system used on-orbit to measure the spin axis orientation of the GP-B gyroscopes. This system uses thin-film four-turn superconductive pickup loops to inductively couple the London moment signals of the spinning gyroscopes to the SQUID detectors. The SQUID detectors were mounted within niobium packages that provided magnetic shielding and allowed for active temperature control of the SQUIDs. EMI mitigation techniques were used to isolate the SQUIDs from spacecraft and ambient RFI noise sources. We discuss the design and construction of the readout system hardware and describe the extensive testing of the system prior to launch. We present on-orbit SQUID noise results demonstrating a gyroscope spin axis orientation resolution of 1 marc-sec in less than 10 hours of integration time, sensor harmonic distortion of less than 0.01%, SQUID bias and gain temperature sensitivity coefficients, and calibration results. The experiment error associated with the measured SQUID noise is less than 0.2 marc-sec/yr.

The London Moment




Quartz gyro housing with niobium pick-up loop and ribbon cable connection


dc SQUID mounted within a niobium package

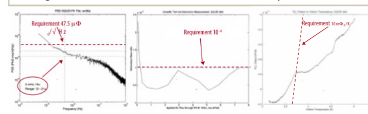
As predicted by physicist Fritz London in 1948, a spinning superconductor develops a magnetic dipole – the London Moment - which is exactly aligned with the instantaneous spin axis and whose magnitude is proportional to the spin speed.

$$B_{London} = -\frac{2mc}{e}\omega_{spin} = -1.14\times10^{-7}\,\omega_{spin}\,(\mathrm{G})$$

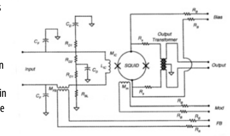
A thin superconducting layer of niobium (1.2 μm) over the quartz gyroscope rotor allows GP-B to use this magnetic pointer to mark the spin axis of the near-perfect gyroscopes without affecting the geometry or mass distribution. In order to read out the London Moment, a four-turn thin film niobium pick-up loop (0.4 μm thick x 50 μm wide trace) is deposited on the quartz gyroscope housing and is coupled to a dc-SQUID through a shielded niobium ribbon cable.

SQUID Package Design & Test

The GP-B SQUID package provides the interface to the Quantum Design SQUID sensor including a superconductive connection to the pick up loop cable and normal conductors for the output signal, dc bias current, modulation, and feedback signal. EMI pick-up is mitigated through filtering within the cold electronics which limits the input bandwidth to 1 MHz. Materials with high thermal diffusivities are used allowing micro-Kelvin temperature control in the presence of milli-Kelvin disturbances. These materials include high purity (low oxygen content) niobium, a sapphire SQUID carrier, and ultra-high purity copper attaching the SQUID package to the science instrument assembly. The niobium case combined with a lead-tin alloy foil gasket provide ac magnetic shielding for the SQUID. Pre-launch verification testing included measurements of noise, linearity, thermal control, EMI immunity, and scale factor stability.

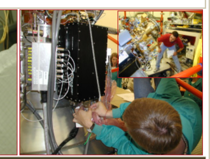

Low frequency noise spectrum — Linearity — Bias Temperature Coefficient

The SQUID input and output circuits (i.e. cold electronics) are shown in detail. Note the feedback coupling into the SQUID input circuit. Inductors, capacitors and resistors in the input and output networks are chosen as to minimize EMI pick-up in the measurement band, limiting the input bandwidth to 1 MHz.

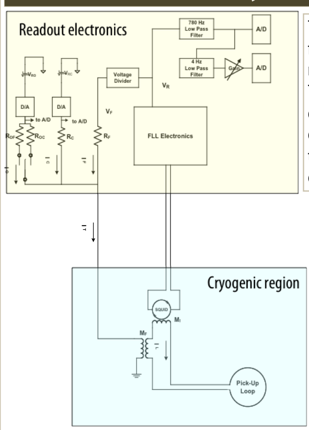


Integration

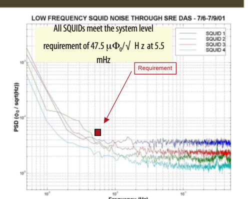
The four SQUID packages (one for each gyroscope) are mounted on the probe assembly and well-coupled thermally to the liquid helium bath. The superconducting ribbon cable connection to the SQUID package is made after the gyroscopes are installed within the Science Instrument Assembly (left and center). The SQUID Readout Electronic (SRE) is mounted on the exterior of the dewar (right).

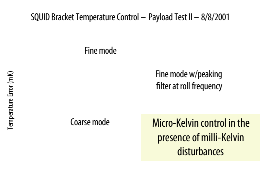


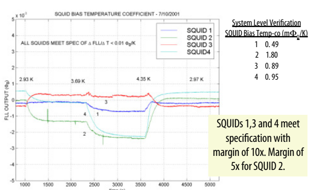
System Ground Test Performance



The SQUIDs are operated in a flux locked loop with feedback into the superconducting input circuit in order to minimize reaction currents in the gyroscope pick-up loop. Thermal control of both the cryogenic and the warm electronics minimizes thermally induced signals in the experiment measurement band. System level verification testing included measurements of noise, linearity, thermal control, EMI immunity, and scale factor stability.







System Level Verification
SQUID Bias Temp-co (mΦ0/K)

1	0.49
2	1.80
3	0.89
4	0.95

On-Orbit Performance

On-orbit verifications included measurements of noise, thermal control and scale factor stability. The output of each SQUID is scaled into equivalent pointing (arc-sec) using the orbital aberration as a calibrator. 3 of the 4 gyroscopes met the pre-launch on-orbit pointing noise specification of 190 marc-sec/√Hz at the satellite roll frequency (12.9 mHz), a measurement resolution of 1.0 marc-sec in 10 hours of integration time. See table to right.

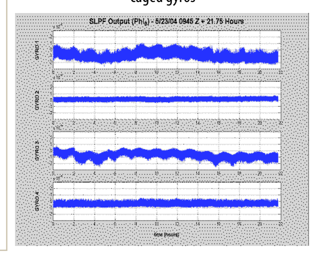
Using the measured gyro pointing noise and the full covariant analysis for the experiment (error tree), the SQUID readout noise limit on the overall experiment error is:

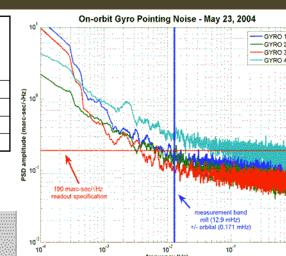
Gyro 1	0.189 marc-sec/yr
Gyro 2	0.176 marc-sec/yr
Gyro 3	0.158 marc-sec/yr
Gyro 4	0.347 marc-sec/yr

Based on 365 days of integration time.

SQUID	Noise @ 12.9 mHz ($\mu\Phi_0/\sqrt{Hz}$) SPEC=47.5 $\mu\Phi_0/\sqrt{Hz}$	Noise @ 12.9 mHz (marcs/$\sqrt{Hz}$) SPEC=190 marcs/$\sqrt{Hz}$
1	28	168
2	20	157
3	25	140
4	24	344

Readout noise measurement with caged gyros





References

1. Barry Muhlfelder, J.M. Lockhart, and G.M. Gutt, "The Gravity Probe B Gyroscope Readout System," *Adv. Space Res.*, in press.
2. J.M. Lockhart, "SQUID Readout and Ultra-Low Magnetic Fields for Gravity Probe B (GP-B)," *Proc. of the SPIE*, vol. 619, p. 148, 1986.

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This research supported by NASA on contract NAS8-39225