Pergamon
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doi: 10.1016/S0273-1177(03)00829-9

THE GRAVITY PROBE B GYROSCOPE READOUT SYSTEM

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ABSTRACT

We describe the superconducting gyroscope readout system to be used for measuring to a precision of 1 marcsecond in 10 hours of integration time the spin axis orientation of the Gravity Probe B (GP-B) gyroscope. The cryogenic portion of the readout system uses a dc SQUID to measure the gyroscope's London magnetic moment. Room temperature electronics appropriately bias the dc SQUID, allowing the detection and amplification of the gyroscope signal. We will describe recent advances in the system hardware including improved electronics and packaging. We will show flight quality noise performance and will discuss measurements of the system's rejection of simulated on-orbit environmental influences. © 2003 COSPAR. Published by Elsevier Ltd. All rights reserved.

INTRODUCTION

The GP-B experiment requires a determination of the gyroscope drift rate with an error of less than 0.3 marcsec/yr. The readout system described here provides this function. The basis of the readout system is as follows: The gyro rotor generates a magnetic dipole, known as the London moment, which is perfectly co-aligned with the spin axis of the rotor. Any change in the orientation of the spin axis causes a change in the orientation of the London moment. A pickup loop, placed in close proximity to the rotor, intercepts this changing London moment. A superconductive signal cable connects the pickup loop to a dc SQUID (Superconducting Quantum Interference Device). Since the magnetic flux threading the pickup loop circuit is conserved, a current is generated in that circuit when the London moment changes orientation. Also, since the pickup loop is tied to the spacecraft body, all of the gyroscope drift information is upconverted to the spacecraft's roll frequency. Using a conventional, flux-locked loop configuration, the SQUID detects and amplifies the current signal.

Figure 1 gives the GP-B readout system schematic diagram.

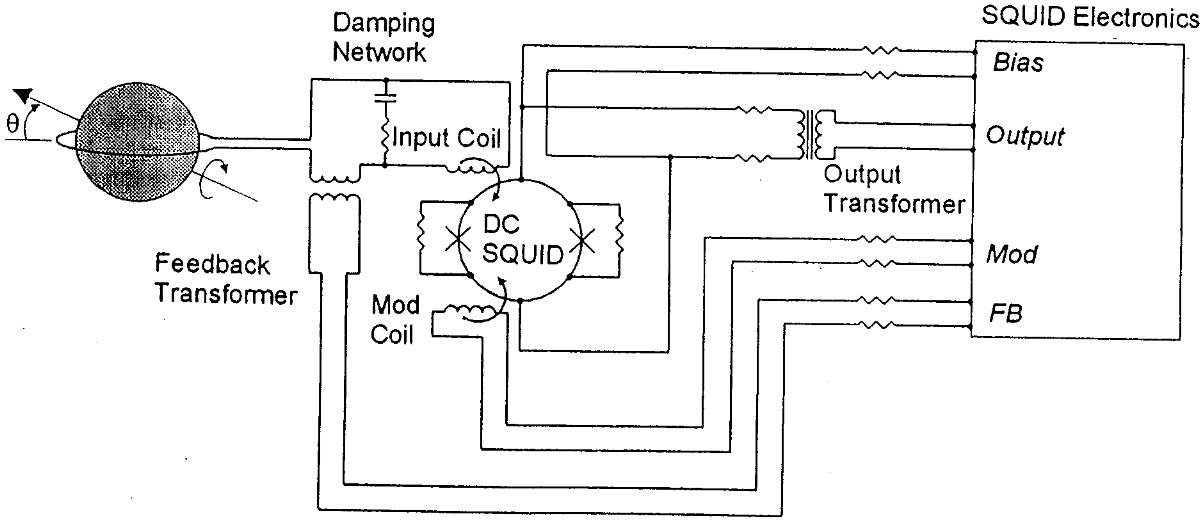

Fig. 1. Superconducting gyroscope readout system.

Adv. Space Res. Vol. 32, No. 7, pp. 1397–1400, 2003

Printed in Great Britain
0273-1177/$30.00 + 0.00

The coupling between the gyroscope and SQUID is (Lockhart, 1986):

$$\text{SQUID Flux} = \frac{MN^{*}B_{L}\pi r^{2}\sin\theta}{L_{T}} \qquad (1)$$

where M is the mutual inductance between the SQUID and its input coil, N* is the effective number of turns in the pickup loop, B_L is the equivalent magnetic field associated with the London moment, r is the radius of the rotor, θ is the angle formed by the gyroscope's spin axis and the pickup loop and L_T is the sum of the pickup loop inductance, SQUID input coil inductance and any stray inductance. For the GP-B configuration, the gyroscope spin axis lies nearly in the plane of the pickup loop and sinθ can be approximated by θ, yielding a simple, linear relationship between gyroscope angle and SQUID flux.

Readout noise is a significant component of the total measurement error of the GP-B experiment. Computer simulations (Haupt, 1996) predict that the gyroscope's readout noise must be better than about 0.2 arcsec/√Hz or equivalently, a resolution of 1 marcsec in 10 hours of integration time. Using the linear relationship between gyroscope angle and SQUID flux, we can express the gyroscope readout noise as a SQUID magnetic flux noise. Doing so, we find that the SQUID flux noise must be $\leq 50\ \mu\Phi_o/\sqrt{\text{Hz}}$. This noise performance must be achieved at the roll rate of the spacecraft, ≥ 5.5 mHz.

In addition to SQUID noise as described above, readout gain and bias variations contribute to readout error. Spurious bias variations synchronous with the relativistic signals must be limited to 0.1 marcsec or 20 $n\Phi_o$ (Haupt, 1996). As discussed below, we have considered various environmental factors which might lead to small biases. We have designed and tested the hardware to ensure that these bias effects are kept adequately small. Gain variations must also be controlled. The initial gyro signal (due to spin axis misalignment) will be of order 10 arcsec. A slow, constant drift in readout gain would mimic a constant drift rate in the gyroscope. We must limit or measure gain variation in the readout system to 1 part in 10^5 per year (equivalent to 0.1 marcsec/yr drift rate uncertainty). Although we have designed and tested the hardware to limit gain drift, we have implemented a readout calibration system to measure the system's gain, and if necessary, to compensate for gain drift.

The performance attributes of noise, bias stability and gain stability have played a central role in developing the hardware. To achieve adequate performance, several environmental factors must be considered including magnetic and electromagnetic interference, thermal variations, and proton bombardment. As will be discussed in the next section, the hardware has been designed to tolerate these conditions.

HARDWARE DESCRIPTION

The SQUID carrier lies at the heart of the readout system and contains a Quantum Design dc SQUID die, an output transformer, a thinfilm feedback transformer, blocking resistors, and a resonance damping network. Photolithographically patterned Nb traces allow for superconductive connections. Au-Nb pads located near the SQUID and feedback transformer allow ultrasonic wedge bonds using Pb-In-Au wire. At other locations on the carrier, Cu-Nb pads allow us to solder resistors, a damping network and an output transformer onto the carrier. The resistors isolate the SQUID from cable capacitance. The RC damping network helps to control parasitic interactions between the SQUID and its input coil. Finally, the output transformer better matches the output of the SQUID to the input of the room temperature electronics. The SQUID carrier is housed inside a SQUID package. Through use of Ge resistance thermometers, heaters and high thermal conductivity sapphire and niobium construction materials, precision temperature control is possible.

The pickup loop is a thinfilm structure and is fabricated on the parting plane of the gyroscope's housing. 400 nm thick Nb is sputtered onto the housing using a dc magnetron system and patterned into a 4 turn loop using photolithographic techniques. The signal cable connects the loop to the SQUID using spring loaded joints at each end. These joints have been designed to remain loaded during launch and thermal cycling. The signal cable has a solid Nb shield and passes through a 10 nF feedthrough filter to protect the SQUID from EMI.

The SQUID is operated in a flux-locked loop using low noise, analog electronics. Four circuits are used with each SQUID to provide flux modulation current (at 420 kHz), dc bias current, feedback current (100 kHz bandwidth), and to receive the SQUID's output voltage. A constant amplitude ac current source is summed into the feedback line to provide a calibration o the system's gain. The feedback current contains the relativity and other information. A signal proportional to this current filtered, digitized, stored, and ultimately sent to the ground. The electronics are located within a large enclosure to preve direct exposure to the sun. The enclosure has been designed to passively stabilize the temperature without causing excessi heat build-up. In addition, key electronic components are temperature controlled.

A previous paper (Lockhart, 1986) described a multi-layered shield designed to reduce both dc and ac magnetic fields at GP-B gyroscope. We have now implemented that design. This shield has been designed to limit the magnetic field trappe the rotor to a uniform equivalent field of ≤ 1 μG. This shield also attenuates ac magnetic fields, which are coupled into the pickup loop as it passes through the earth's magnetic field, by a factor of greater than 10^{12}.

All of the GP-B electronics have been designed to be as quiet as possible to limit the amount of EMI reaching the readout system. The readout system itself is very well shielded; its cables are filtered and are nearly light tight. We have also considered EMI sources external to the experiment. Although the probe and dewar make an excellent electrostatic shield, a window must be provided for the telescope to view the guide star. We reduce the leakage through this window by metalizing it and by using EMI absorbing materials in the telescope's sunshade. Together, these measures will provide at least 40 dB of attenuation to 10 GHz.

TEST RESULTS

We have performed readout system noise measurements in both isolated, quiescent conditions as well as in the full GP-B payload configuration. Several years ago (Lockhart *et al.*, 1994), we achieved a single-sided SQUID noise of 30 $\mu\Phi_0/\sqrt{\text{Hz}}$ (equivalent to 120 marcsec/$\sqrt{\text{Hz}}$) at a frequency of 5.5 mHz. We have now met the readout noise requirement of 190 marcsec/$\sqrt{\text{Hz}}$ (equivalent to 50 $\mu\Phi_0/\sqrt{\text{Hz}}$) in the full GP-B configuration. Improved EMI rejection allowed us to eliminate a lossy SQUID input filter which had been used in earlier tests. Removing this filter reduced SQUID noise and increased gyroscope coupling efficiency. Both of these effects translate into improved readout noise performance. In addition, the SQUID packages were temperature controlled to limit thermally induced drift and the use of normal metal near the pickup loop was limited to minimize Johnson noise.

We have also experimentally verified Eq. 1. These tests confirm the coupling between the rotor's London moment and the output of the readout system. Furthermore, we have simulated on-orbit environments to ensure that the readout system will continue to perform adequately. Specifically, we have tested the readout system for magnetic and electromagnetic effects, thermal sensitivities, proton induced upsets and nonlinear behaviors.

The earth's magnetic field may couple into the readout system to mimic the science data. We have demonstrated flux trapping in the gyro rotor of less than 1 μG (uniform field equivalent). This performance meets our need. Some of our earlier tests have shown that the attenuation of ac magnetic fields were limited by leakage into the SQUID package. In tests of an isolated SQUID package, a Pb-Sn gasket placed between the SQUID package and lid reduced this leakage by a factor of 50, yielding a residual leakage of approximately 1 $m\Phi_0/G$. An end-to-end readout system ac shielding test has demonstrated adequate performance.

Thermal fluctuations of both the SQUID and its electronics correlate with bias variations of the readout system; we therefore control the temperature of both. (Thermal fluctuations also correlate with gain fluctuations, but the associated requirements are straightforward to meet). In addition, we minimize the sensitivity of the system to any residual thermal variations. We must limit to 20 $n\Phi_0$ the bias variations which mimic the science data. We have measured the thermal sensitivity of isolated SQUIDs and have found a coefficient of approximately 10 $m\Phi_0/K$. Although we do not fully understand the cause, in some cases the thermal sensitivity of the complete readout system can be as much as 1 Φ_0/K. Temporarily raising the temperature of the superconductive signal cable above its transition temperature restores the sensitivity to approximately 10 $m\Phi_0/K$. 2 μK temperature control of the SQUID has been achieved using two nested feedback control loops. In addition, the temperature of the liquid helium bath is regulated and there are various passive control elements. We have measured the performance of the electronics temperature control system. This system will limit the expected on-orbit temperature variation at roll frequency of critical circuits to approximately 1 mK. We have also measured the sensitivity of the readout system output to temperature variation in the electronics. Combining this temperature sensitivity measurement of 0.01 arcsec/K with the electronics temperature stability gives an overall bias error of less than 0.01 marcsec/yr.

Nonlinear readout behavior can cause biases which mimic the relativity signals. The signal from the gyroscope is detected by the SQUID and since there is finite gain in the electronics, only a portion of this signal is nulled by the feedback electronics. The associated error interacts with the SQUID's nonlinear voltage vs. flux curve and causes the signal to be distorted and aliased to dc. We have analyzed this phenomenon (Gutt, 1997) and have achieved adequate readout system performance by requiring and attaining adequately linear SQUID voltage vs. flux characteristics (less than 1% deviation from a straight line over the expected operating range of 0.02 Φ_0) and by requiring and achieving sufficiently high open loop gain of the electronics (greater than 100 at 1 kHz).

Tests have also been performed to evaluate the readout system's performance in the presence of EMI. We divide the EMI into two broad frequency ranges: below and above 1 GHz. EMI below 1 GHz was coupled via pickup on cables entering the probe. We were able to reduce readout EMI sensitivity for these frequencies by implementing a variety of cable upgrades including two layers of electrostatic shielding, solid cable shields, and improved cable filters. Signals above 1 GHz were found to pass through the telescope window, reaching the probe interior. Shielding the window significantly reduced high frequency EMI related effects.

The GP-B spacecraft will make repeated passes through the South Atlantic Anomaly (SAA). While in the SAA as many as 10^4 protons/cm^2/s with energies in excess of 10 MeV will pass through the spacecraft. We have bombarded SQUIDs (Muhlfelder *et al.*, 1995) with high energy protons to simulate this environment. The flux-locked loop electronics showed no observable sensitivity to the proton bombardment. Some of the SQUIDs that we tested did show step-like bias shifts. For the SAA situation described above, these shifts corresponded to a few mΦ_0 every five minutes. We have analyzed the impact of these bias shifts upon the determination of the relativistic drift rates and have found that the predicted bias shifts should not cause significant degradation. We also subjected the SQUIDs and electronics to approximately 10 times the total proton dose we expect for the GP-B mission. Neither was damaged by this exposure.

CONCLUSIONS

We have designed, built, and tested the GP-B readout system. Its noise at 5.5 mHz is < 0.2 arcsec/√Hz. The SQUID temperature coefficient is < 10 mΦ_0/K, and the SQUID temperature is stabilized to 2 μK at the spacecraft's roll frequency. The temperature coefficient of the electronics is better than 0.01 arcsec/K and the temperature of the electronics will be controlled to 1 mK at roll frequency. The system has undergone thermal, proton, magnetic and EMI testing. All of the system level performance tests, and all of the environmental tests show that the GP-B readout system meets the flight requirements. The readout system has been integrated into the payload which in turn has been integrated into the space vehicle. The vehicle has been subjected to acoustic test and two thermal vacuum tests. All systems, including the readout system, continue to perform nominally in the space vehicle. Launch of the vehicle from Vandenberg Air Force Base is scheduled for late-2003.

ACKNOWLEDGMENTS

We thank D. Gill and R. Shile for pickup loop and SQUID carrier fabrication and M. Luo for SQUID package fabrication and testing. This work was supported by NASA Contract NAS8-39225.

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