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A ROBUST SQUID SYSTEM FOR SPACE USE

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We describe a dc SQUID measurement system developed for use in space. The SQUID system has two main elements. The cryogenic hardware consists of a niobium SQUID package containing a SQUID die mounted on a sapphire carrier. Flux-lock loop electronics bias the SQUID and linearize its output. The flight design meets all requirements including noise performance and the ability to reject environmental influences in polar orbit. The flight hardware, based upon this design is now in final assembly and test.

1 Introduction

SQUIDs (Superconductive Quantum Interference Devices) are recognized as the most sensitive detectors for frequencies below approximately 10 MHz. Because of their sensitivity, several space-based experiments rely on them as the heart of precision measurement systems. These experiments include Gravity Probe B [1] (GP-B), the Satellite Test of the Equivalence Principle [2] (STEP), and various liquid helium lambda point experiments [3]. Although the specific SQUID requirements vary, these experiments share three concerns: noise performance, gain stability and bias stability. Noise performance dictates the amount of integration time required to achieve a given signal resolution. For the GP-B experiment the system noise must be less than 1×10^{-28} J/Hz or 50 $\mu\Phi_0/\sqrt{Hz}$ at the primary signal frequency of 5.5 mHz. Spurious bias or gain variations may corrupt the primary science signal. For the GP-B experiment spurious bias (offset) variations must be limited to less than 20 $n\Phi_0$ at 5.5 mHz. A drift in gain or change in gain at the orbital or annual frequency must also be limited to 1 part in 10^5 per year. Note that gain in this context is $\partial V/\partial\Phi$ where V is the flux-lock loop output voltage and Φ is the magnetic flux applied to the SQUID loop.

2 First Generation dc SQUID System

Initially, the focus at GP-B was to develop a SQUID system with very low intrinsic noise. This task was carried out in a simple facility thus allowing rapid progress. There were no significant environmental factors which might degrade SQUID noise performance or cause coherent bias or gain variations. We chose to use a SQUID and SQUID carrier manufactured by Quantum Design Inc. Both commercial SQUID electronics and in-house laboratory-grade electronics were used to operate the SQUIDs. Our results were very satisfactory when this SQUID was operated in this quiet environment. The spectral density of the noise at 5.5 mHz was 4 times better than the required level of performance. In addition, adequate bandwidth (100 kHz) and linearity (better than 0.01%) were successfully demonstrated.

Next, this commercial SQUID carrier housed within a GP-B SQUID package was used in a large-scale, payload-like test configuration. Here we successfully verified the coupling strength between the SQUID and the GP-B gyroscope [4]. In addition, we verified good low frequency magnetic shielding. Some concerns however remained about the SQUID system. Although the noise specification was met, there was little margin. In addition, the SQUIDs were very sensitive to electromagnetic interference (EMI) and electromagnetic compatibility (EMC) of the SQUIDs with the other electronic subsystems could not be demonstrated. It was not possible to provide adequate temperature control because of the poor thermal conductivity of the carrier substrate. Finally, the SQUID electronics did not provide a temperature control function and it could not be operated autonomously as required in-flight. To meet these needs, we embarked on an effort to develop a specialized SQUID carrier/package and SQUID electronics.

3 Experiment Considerations

EMI/EMC, thermal, and proton bombardment effects must be managed to maintain the inherent SQUID noise performance and to ensure that spurious gain and bias variations are adequately controlled. There are two aspects of the work to limit these effects. First, the SQUID and SQUID electronics has been designed to be as tolerant of the environment as possible. Second, the environment has been made as benign as possible through overall experiment design.

The task to attain adequate EMC performance for the GP-B SQUID system has been challenging. We require extremely low SQUID noise and therefore must achieve superior EMC performance. GP-B is a complex experiment with many electrical subsystems. To give a scale of the experiment, approximately 250 cables penetrate the probe and subsequently terminate near the SQUIDs. Good SQUID EMC performance has been achieved by implementing a long list of features. All of the non-SQUID electrical subsystems (including most importantly the gyroscope suspension electronics) have been specifically designed to be SQUID-compatible. All subsystems operate off of a single clock to eliminate beating phenomena. rf conducted on cables into the probe is required to be less than 50 μV rms at spot frequencies above 1 MHz. The experiment grounding is tightly controlled. Finally, all cables which enter the probe are low-pass filtered.

EMI mitigation presents its own set of challenges. First, there is uncertainty about the on-orbit GP-B EMI environment. Next, since a telescope is required for the GP-B experiment, the associated 20 cm optical bore potentially allows a direct EMI path for frequencies above 1 GHz to the cryogenic portion of the probe. Advanced optical coatings [5] applied to the outermost telescope window allow more than 50 dB of attenuation from 1 GHz to 100 GHz with less than 1 dB of loss in the desired optical signal. Lastly, the enclosure which houses all of the sensitive electronics including the SQUID electronics provides 30 dB of EMI attenuation.

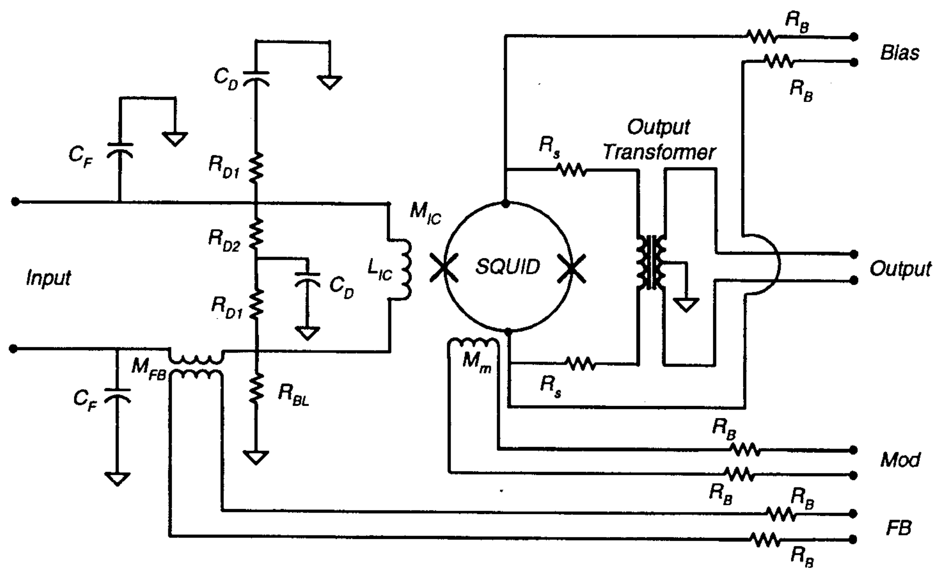

Figure 1: GP-B Flight SQUID Configuration

4 Flight dc SQUID System

Even with all of the measures described above, the GP-B experiment requires SQUID operation in a somewhat noisy environment. To reduce the impact of this noisy environment, four features have been implemented in the SQUID package. Figure 1 is a schematic diagram of the SQUID configuration. A balanced, 10 nF feedthrough filter capacitor C_F, is placed at the SQUID's input. When combined with the 2 μH SQUID input coil L_{IC}, this capacitor limits the input bandwidth to 1 MHz. Next, to allow improved rejection of common-mode signals, the secondary coil of the SQUID's output transformer has a center-tap to ground and the damping network at the SQUID input has been made more balanced. The damping network is comprised of resistors R_{D1} (10 Ω), R_{D2} (100 Ω) and capacitors C_D (2 nF). Buffer resistors R_B (100 Ω) reduce the amount of rf reaching the SQUID and isolate the carrier from cable capacitance. In addition to these four EMI/ESD features, a feedback transformer with mutual inductance M_{FB} (0.4 μH) allows the feedback signal to be applied to the SQUID's input circuit. This value of M_{FB} has been chosen because when combined with the mutual inductance M_{IC}, it gives a coupling to the SQUID similar to the modulation coil to SQUID mutual inductance M_M (1.4 nH). The primary coil of the SQUID's output transformer has series resistors R_S (0.6 Ω) to reduce the amount of dc current flowing through the output transformer. Finally, a bleed resistor R_{BL} provides a ground reference for the input circuit.

The SQUID electronics and SQUID cables have been designed to reject EMI. The cables have solid shields and the SQUID electronics has balanced drivers and receivers.

The expected on-orbit thermal environment has been a significant design driver for the GP-B SQUID system. We must control the temperature of the SQUIDs to 5 μK to limit variations in SQUID bias. This is achieved by nesting a SQUID temperature control system within a probe temperature control system. Thermally conductive construction materials are used in the SQUID package to minimize the temperature difference between the control system's thermometer and the SQUID. The SQUID die is mounted on a sapphire carrier. The carrier is in turn housed inside a niobium package which has been specially treated to enhance its thermal conductivity. The SQUID electronics is also susceptible to thermal influences. A shroud is placed over the SQUID electronics to prevent direct illumination by the sun. This shroud reduces temperature variations at 5.5 mHz to less than 50 mK. A SQUID electronics temperature controller further stabilizes the temperature of critical board regions to 1 mK.

The GP-B spacecraft will be exposed to high energy protons as it passes through the South Atlantic Anomaly (SAA) and during times of solar flare activity. 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 selected SQUID die which are proton-tolerant. To prevent charge buildup, R_{BL} (5 $M\Omega$) grounds the input circuit of the SQUID. See Fig. 1. Proton bombardment tests[6] indicate that the thermally conductive sapphire carrier will attenuate proton induced offsets to an acceptable level. The SQUID electronics is also susceptible to proton bombardment. To reduce the impact of proton bombardment, the SQUID electronics box is thickened in critical locations. We have chosen components which are known to be proton-tolerant and have tested the stability of our voltage references for proton-induced drift. The results of these tests combined with calibration techniques described later in this paper demonstrate adequate tolerance to proton bombardment.

5 Recent Results

We have verified all flight SQUID requirements by carrying out laboratory tests in a payload-like system and separately, by subjecting the SQUIDs to simulated on-orbit environments.

Recently, we completed the final GP-B integrated system test prior to payload integration and test. The primary purpose of this test was to verify adequate EMI/EMC SQUID performance in a payload-like configuration. Based upon a series of pretests, two different SQUID configurations were installed and tested in the integrated test facility. Unlike previous integrated system tests, both types of SQUID packages tested here had the 10 nF input filter and the 100 Ω buffer resistors described earlier in this paper. One of the SQUID carriers (SQUID carrier A) was configured as shown in Fig. 1. The other (SQUID carrier B) had an unbalanced damping network and lacked the bleed resistor and center-tap to ground on the output transformer.

Both of these SQUID carriers passed EMC testing, and thereby demonstrated a significant advance over our previous measurements. We attribute this result to the SQUID's input filter and buffer resistors because other than for these attributes one of the SQUID carriers (SQUID carrier B) was electrically similar to previous carriers which had failed EMC tests. As part of the recently completed test we demonstrated the required SQUID noise performance while operating the gyroscope suspension electronics. Tests were also carried out where calibrated rf signals were injected into the integrated system probe using the experiment's existing cabling. These tests confirmed that for frequencies below 500 MHz (where EMC rather than EMI is our main concern) the two SQUID carriers exhibited similar and acceptable performance.

EMI tests were performed by radiating signals though the telescope bore. Below 1 GHz neither SQUID showed any significant response to EMI. This is consistent with our expectations that very little of this rf penetrates the telescope bore. Above 1 GHz we found that SQUID carrier A had at least 20 dB more rejection of rf than SQUID carrier B. We expect that on orbit, SQUID carrier A will operate satisfactorily whenever the incident EMI is less than 10 V/m. We expect this condition to be satisfied more than 99% of the time. This fully meets the duty cycle requirement.

We have measured the thermal sensitivities of the SQUID system. Specifically we have measured the bias and gain temperature coefficients of both the cryogenic hardware and the flux-lock electronics. The measurements described here were made in the temperature range of 2 K to 4 K. We have measured the bias temperature coefficient of isolated SQUIDs and typically find a coefficient of less than 10 $m\Phi_0/K$ (we have seen as low as 1 $m\Phi_0/K$). Although we do not fully understand the cause, in some cases the bias temperature coefficient of the complete readout system can degrade to as much as 1 Φ_0/K. In those cases, temporarily raising the temperature of the SQUID above its transition temperature restores the temperature coefficient to its original value. Raising the temperature of the superconductive input cable above its transition temperature has no apparent affect on the bias temperature coefficient. We have measured the gain temperature coefficient of isolated SQUIDs. We repeatedly find that the gain temperature coefficient is less than the measurement noise of $3 \times 10^{-6}/K$. This is nearly 100 times better than our requirement. We have also successfully operated the SQUID and probe temperature control systems. The 5 μK temperature control combined with the thermal sensitivities quoted above confirm that thermally induced bias variations will be less than 20 $n\Phi_0$. To date, we have achieved an electronics bias temperature coefficient of 50 $m\Phi_0/K$ and expect to reach 20 $m\Phi_0/K$ by using electronic components with minimal temperature sensitivity. We have measured the gain temperature coefficient of these electronics and have achieved better than 10^{-5} K^{-1}. This is a factor of 10 better than the required gain temperature coefficient.

6 Calibration

The GP-B experiment requires a measurement to 1 part in 10^5 of both the SQUID system gain and the SQUID system gain stability during the 16 month experiment duration. The absolute SQUID system gain is determined using naturally occurring signals whose amplitudes are known to better than 1 part in 10^5. We have developed a stable calibration source to measure any drift in the system's gain. The output of an AD588 voltage reference is converted into a current and then inductively coupled to the SQUID. Since we have verified the stability of this calibration signal to better than 1 part in 10^5 per month, any excessive changes in this signal as observed at the output of the SQUID are a measure of SQUID gain drift.

We have also developed a method to measure on-orbit drift in the AD588 output. Using this technique, in which the calibration source injects a flux quantum into the SQUID loop, the SQUID gain stability has been demonstrated to 4 parts in 10^6. The method is as follows. The SQUID is first flux-locked and the output zeroed. Next, the SQUID is unlocked and a current is fed through the feedback coil. This current nominally couples one flux quantum into the SQUID loop. The SQUID is then relocked. If the AD588 is stable, the flux-locked output of the SQUID will remain zeroed. A non-zero SQUID output indicates a change in the calibration of the AD588. Although we might be able to reduce the error in this measurement with increased averaging, the present result satisfies the GP-B need.

7 Conclusion

The tests we have discussed here confirm that the SQUID hardware and electronics meet all requirements. We are currently assembling the flight SQUID system and expect it to be ready for final test in 1998.

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