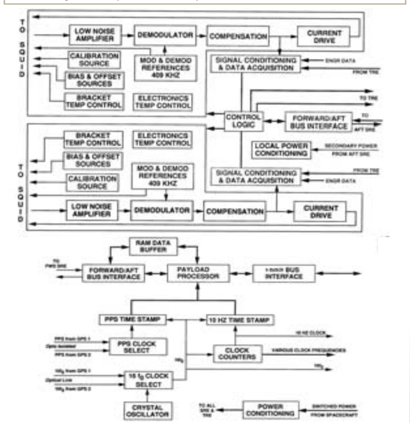
SQUID Control, Temperature Regulation & Signal Processing Electronics for GP-B

James Lockhart, San Francisco State U. and Stanford U.
Terry McGinnis, Peter Boretsky, Lockheed Martin Corp.
Barry Muhlfelder, Bruce Clarke, Jie Li, Stanford University
Gregory Gutt, Boeing Company

SQUID Electronics Overview

SQUID Readout Electronics Functions

- Operate four dc SQUIDs (Superconducting Quantum Interference Devices) in flux-locked-loop (FLL) configurations with 409 kHz flux modulation and
  - High stability at 5 mHz science signal frequency (satellite roll freq.)
  - Very large dynamic range to handle trapped flux signals/interference
- Provide anti-alias filtering, analog-digital conversion, and digital filtering
- Monitor & control SQUID temperatures <5 μK fluctuation @satellite roll freq
- Provide precision calibration signal for injection into SQUID input circuit
- Provide high-stability master clock synchronized to GPS clocks



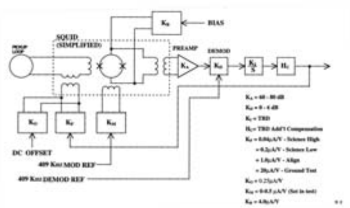
SQUID Control & Readout

Design Goals for SQUID Control Electronics

- Very low noise figure (<2 dB)
- Low drift; low temperature sensitivity
- High linearity to deal with gyro spin-frequency signals
- Provisions for flux-quantum-slipping fundamental calibration
- High bandwidth/EMI immunity to on-board interference sources
- Compatibility w/ space environment -- particle radiation

Features

- Preamp: Cascode FET, < 1 nV/√Hz at 409 kHz flux mod. freq.
- Demodulator: Balanced FET switches
- Single pole integrator; 100 kHz bandwidth w/70 kHz peaking response
- Feedback current sent to flux transformer in SQUID input circuit
- Calibration Signals [ROM-table sine waves; precision multiplying D-A converter with stable reference voltage; injected into SQUID input.
- Active integral temperature control of critical SQUID electronics circuits
- RAD6000 CPU for digital filtering, digital PID SQUID temperature control, timing synchronization
- Oven-controlled swept-quartz crystal oscillator for master clock



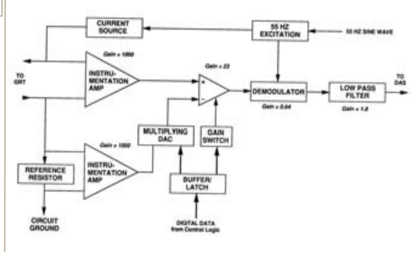
SQUID Temperature Control

Design Goals for SQUID Temperature Controller [See Ref. 5]

- Monitor and control temperatures of SQUID sensors to less than 5 μK fluctuation at the satellite roll frequency. Allow thermal defluxing of SQUID.

Features

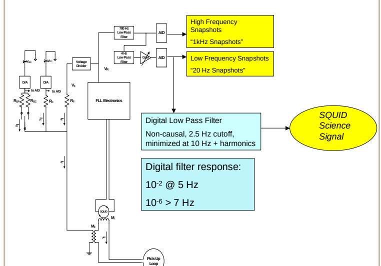
- Analog ac resistance bridges (55 Hz) with phase-sensitive detection
- Sensor excitation < 1 nW
- Bridge output compared to output of a setpoint DAC; difference signal digitized to drive precision digital temperature controller.
- Digital temperature controller implemented in RAD6000 computer; control law incorporates gain peaking at satellite roll frequency. Provision to optimize the control law on orbit.
- AC heating power (110 Hz sine) used to avoid stray magnetic coupling in the spectral region of our 5 mHz gyro signal
- Temperature data from 2 control & 2 independent monitor thermometers, plus heater power data sent to telemetry.
- Deflux mode of temperature controller allows thermal degaussing of SQUID



Signal Processing

SQUID Signal Processing

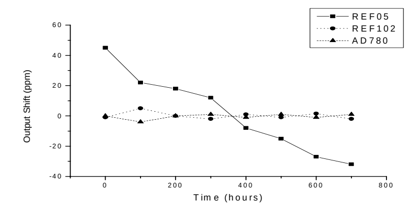
- FLL output lowpass anti-aliasing filtered (800 Hz corner).
- One feed from the lowpass output goes both directly to the ADC multiplexer, where it is sampled at 2200 Hz
- Second lowpass feed goes to 2-pole lowpass filter (4 Hz corner) which attenuates large spin-frequency signal
- Adjustable-gain amp following 2nd filter amplifies the roll-rate signal by up to X256
- Amplified roll-rate signal digitized @ 2200 Hz (X200 oversampled).
- ADC -- Burr-Brown (Texas Inst.) ADS-7805 16-bit successive approximation converter with external voltage reference
- Dither (SQUID sensor white noise) gives X10-20 ADC resolution enhancement, providing gyro angle resolution < 0.3 marcs [Ref. 6]
- Roll-rate signal digitally lowpass filtered (2 Hz corner) and output to telemetry at 5 Hz rate.



Features for Thermal Stability

SQUID Electronics Thermal Considerations (Goal: SQUID electronics drift < 1 PPM)

- Passive control features:
  - →Enclosure design
  - →Location of the forward electronics unit in thermally insulating enclosure
  - →Circuit board layout: large ground & power planes for good thermal coupling.
- Circuit design features for low temperature coefficient:
  - →Components with very low temperature coefficients (5 PPM/°C resistors, etc.)
  - →Use of buried-zener reference voltage devices for A-D and D-A converters
  - →Minimization of the dc portion of the FLL signal path.
  - →FLL demodulator architecture (discrete, highly-balanced FET demodulator).
  - →Operate demodulator at highest possible signal level to further minimize drift.
  - →All amplifiers after the demodulator are low-drift types (OP-27, OP-177).
- Final temperature regulation via closed-loop proportional controllers near critical circuit areas (setpoints from D-A converters)
- Critical circuit temperatures and reference voltages sent to telemetry.



Temperature Stability of Voltage References

Features for Space Operation

Design Goals – Provide Stable Operation in Presence of

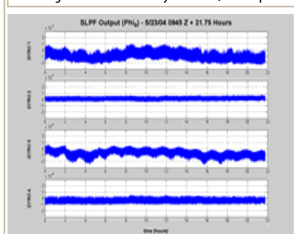
- Energetic Charged Particles (3 kRad (Si)/yr on electronics; mainly protons)
- Solar heat inputs at roll, orbital, and annual rates

Features [See Ref. 4]

- SQUID electronics designed for radiation tolerance (thick-wall Al chassis; Ta shields on integrated circuits; anti-latchup protection)
- Special provisions to refresh critical SQUID D-A converter registers
- Voltage reference devices tested with 10 kRad (Si) 192 MeV protons
  - Analog Devices AD588 was best; < 100 ppm voltage shift
- Accounted for radiation-induced degradation of opto-couplers
- Used radiation-hardened RAD6000 32-bit RISC CPU with backup
- Critical electronics placed in thermally-shielded, insulated enclosure
- SQUID electronics used low-temperature coefficient construction and active temperature control of circuit boards
- SQUID digital temperature controller employed gain peaking at roll frequency to greatly reduce roll-frequency signal drift

On-Orbit SQUID Control Performance

- The SQUID Readout Electronics (SRE) provided highly-stable SQUID operation while adding less than 5% to roll-frequency sensor noise.
- The SRE's high bandwidth allowed low-noise flux-locked SQUID operation in the presence of interference, but added significant non-linearity to the SQUID output due to inadequate filtering of ADC voltage reference

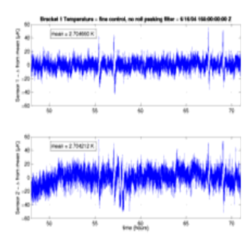


Filtered SQUID Signal Output Showing Low Baseline Drift

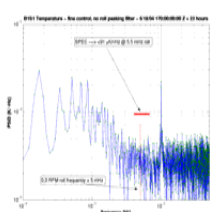
Gyro Readout Noise Spectrum

On-Orbit SQUID Temp. Stability

Plots below show the SQUID sensor temperature stability and fluctuation spectrum obtained with the roll-peaked digital SQUID temperature controller.



SQUID Sensor Temperature vs. Time



SQUID Sensor Temperature Fluctuation Spectrum

References & Acknowledgements

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W. W. Hansen Experimental Physics Laboratory • Stanford University, Stanford, CA 94305-4085 • http://einstein.stanford.edu

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