

SQUID CONTROL, TEMPERATURE REGULATION & SIGNAL PROCESSING ELECTRONICS FOR GP-B



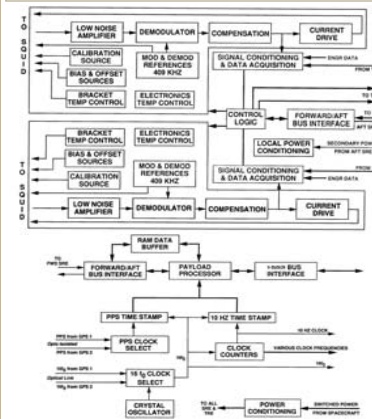
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SQUID Electronics Overview

SQUID Readout Electronics Functions

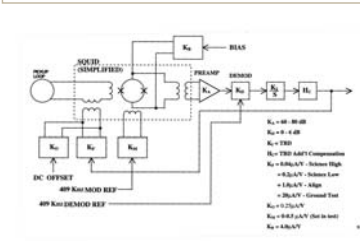
- Operate four dc SQUIDs (Superconducting Quantum Interference Devices) in flux-locked-loop (FLL) configurations with 409 kHz flux modulation and
 - High stability at 5 mHz science signal frequency (satellite roll freq.)
 - Very large dynamic range to handle trapped flux signals/interference
- Provide anti-alias filtering, analog-digital conversion, and digital filtering
- Monitor & control SQUID temperatures <math> < 5 \mu\text{K}</math> 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

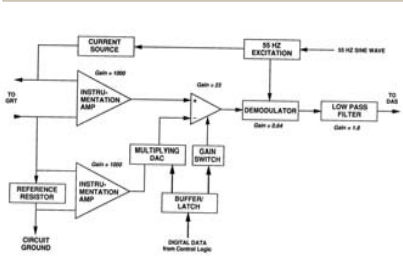
- Very low noise figure (<math> < 2 \text{ dB}</math>)
- Low drift; low temperature sensitivity
- High linearity to deal with gyro spin-frequency signals
- Provisions for flux-quantum-slipping fundamental calibration
- High bandwidth/EMI immunity to on-board interference sources
- Compatibility w/ space environment -- particulate radiation
- Features**
 - Pre-amp: Cascode FET, <math> < 1 \text{ nV}/\sqrt{\text{Hz}}</math> 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]

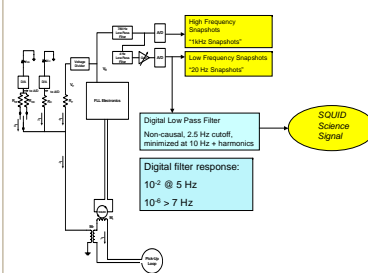
- Monitor and control temperatures of SQUID sensors to less than $5 \mu\text{K}$ fluctuation at the satellite roll frequency. Allow thermal defluxing of SQUID.
- Features**
 - Analog ac resistance bridges (55 Hz) with phase-sensitive detection
 - Sensor excitation <math> < 1 \text{ nW}</math>
 - Bridge 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, with heater power data sent to telemetry.
 - Deflux mode of temperature controller allows thermal degaussing of SQUID



Signal Processing

SQUID Signal Processing

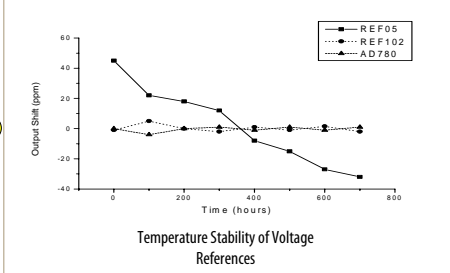
- FLL output lowpass anti-aliasing filtered (800 Hz corner).
- One feed from the lowpass output goes both directly to the ADC multiplexer, where it is sampled at 2200 Hz
- Second lowpass feed goes to 2-pole lowpass filter (4 Hz corner) which attenuates large spin-frequency signal
- Adjustable-gain amp 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 <math> < 0.3 \text{ marcs}</math> [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 <math> < 1 \text{ PPM}</math>)

- 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.



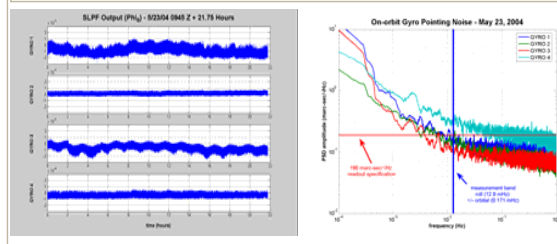
Features for Space Operation

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; <math> < 100 \text{ ppm}</math> 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

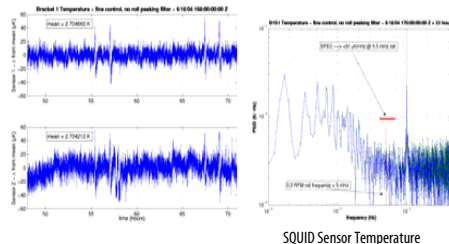
On-Orbit SQUID Control Performance

- 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



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.



References & Acknowledgements

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