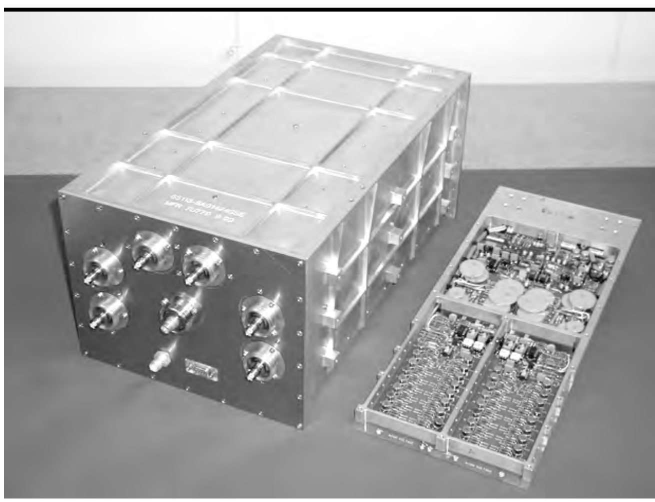
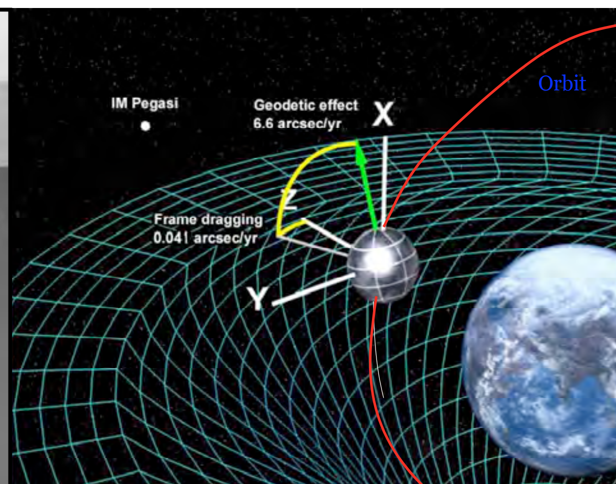
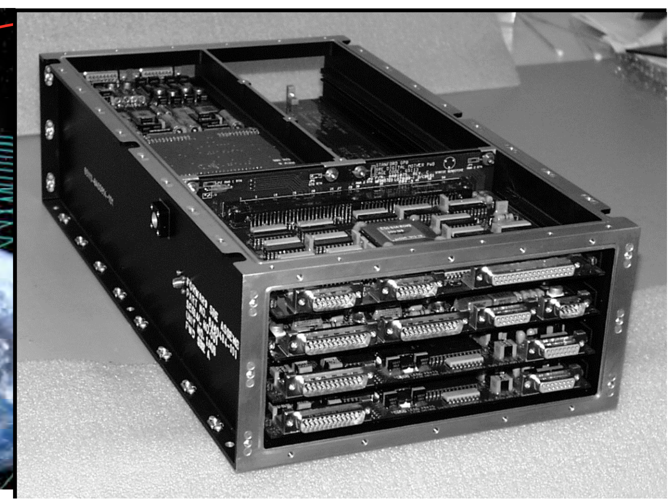
GP-B Payload Electronics

John Mester

Stanford University







Payload Electronics

- Overview
- Telescope Readout Electronics
- Experiment Control Unit
- Global Positioning System Receivers
- Proton Monitor
- ATC
- SQUID Readout Electronics
- Gyroscope Suspension System

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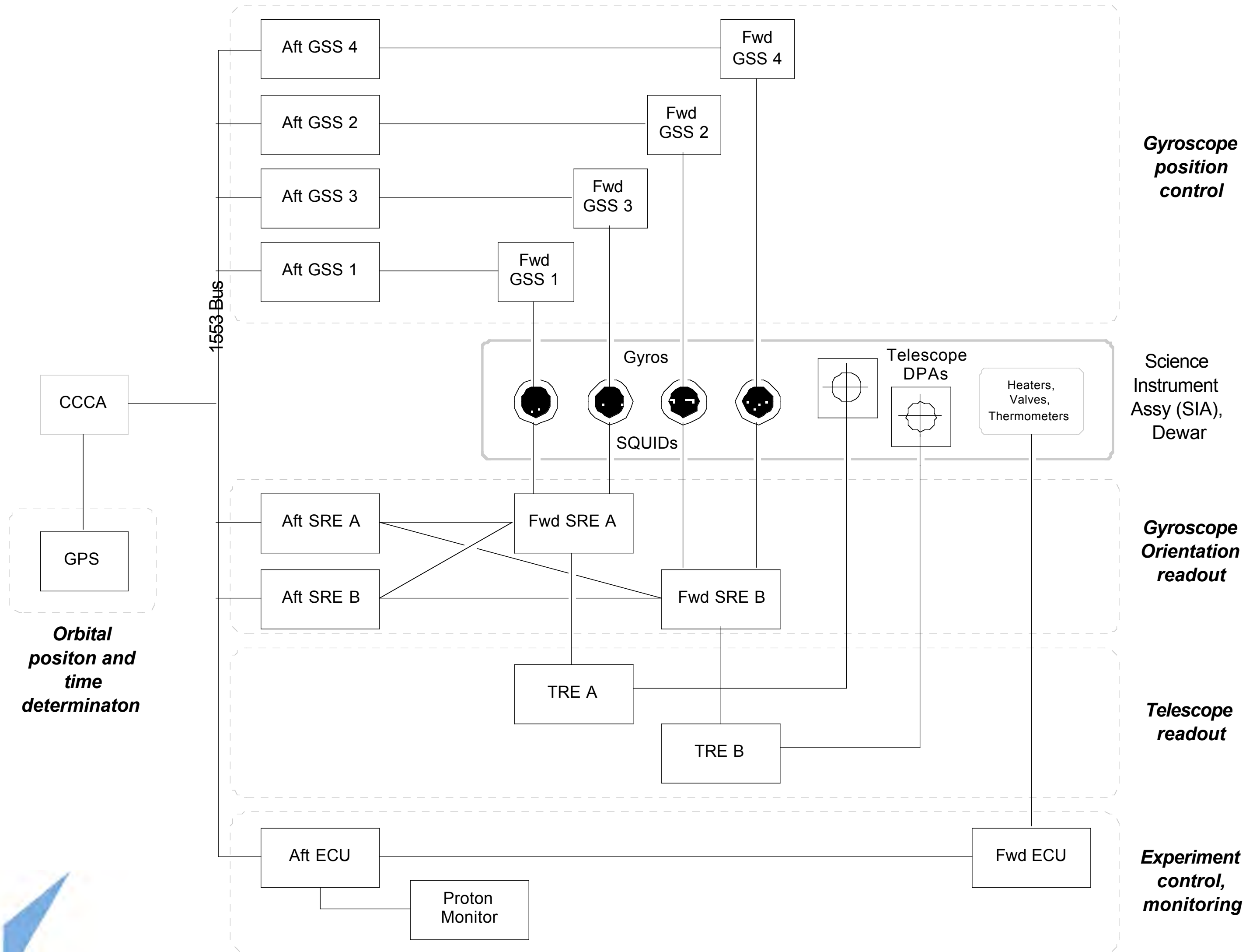
Payload Electronics Functions

- Telescope Readout Electronics (TRE) - 2 Fwd boxes.
  - Measures orientation of space vehicle boresight relative to guide star.
- Experiment Control Unit (ECU) - 1 Aft + 1 Fwd box.
  - Measures payload temperatures and status signals.
  - Controls heaters and valves: payload instrument interfaces.
- GPS Receiver (GPS) - 2 Aft boxes + 8 antennas.
  - Provides ephemeris position, velocity and time data for orbit trim and science data reduction. Time transfer.
- Proton Monitor (PM) - 1 Aft box.
  - Provides on-orbit radiation data; correlates with gyroscope heating, charging.
- Attitude Control Electronics (ATC) - 2 boxes 19 boards
  - magnetic torquer drivers, star tracker readout, magnetometer readout, thruster driver, RAV valve driver, power supply, 1553 Board
  - Payload/Spacecraft integrated functions.
- SQUID Readout Electronics (SRE) - 2 Aft + 2 Fwd boxes.
  - Measures gyro spin speed and orientation.
- Gyroscope Suspension System (GSS) - 4 Aft + 4 Fwd boxes.
  - Suspends and maintains precise centering of gyroscope rotors in their housings.
  - Provides backup analog control in the event of a GSS computer failure.

Payload Electronics System Block Diagram



Payload Electronics Suite:

- 6 Computers
- 18 Boxes
- ~110 Cables
- ~120 PWAs

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Spacecraft Bus and CPU

- Payload and Spacecraft Controlled by RAD6000 Spacecraft CPU driving 1553B Bus (2 for redundancy A and B sides)
- RAD6000 radiation-hardened 32bit single board computer, based on the IBM RISC Single Chip CPU, .
- > 200 RAD6000 processors in space on a variety of NASA, United States Department of Defense and commercial spacecraft, including:

* Spirit and Opportunity Mars rovers
* Mars Pathfinder lander
* Deep Space 1 probe
* Mars Polar Lander and Mars Climate Orbiter
* Mars Odyssey orbiter
* Spitzer Infrared Telescope Facility
* MESSENGER probe to Mercury
* STEREO Spacecraft
* IMAGE/Explorer 78 MIDEX spacecraft
* Genesis and Stardust sample return missions
* Phoenix Mars Polar Lander
* DAWN Mission to the asteroid belt using ion propulsion

Payload Boxes SRE and GSS contain 6 RAD6000s

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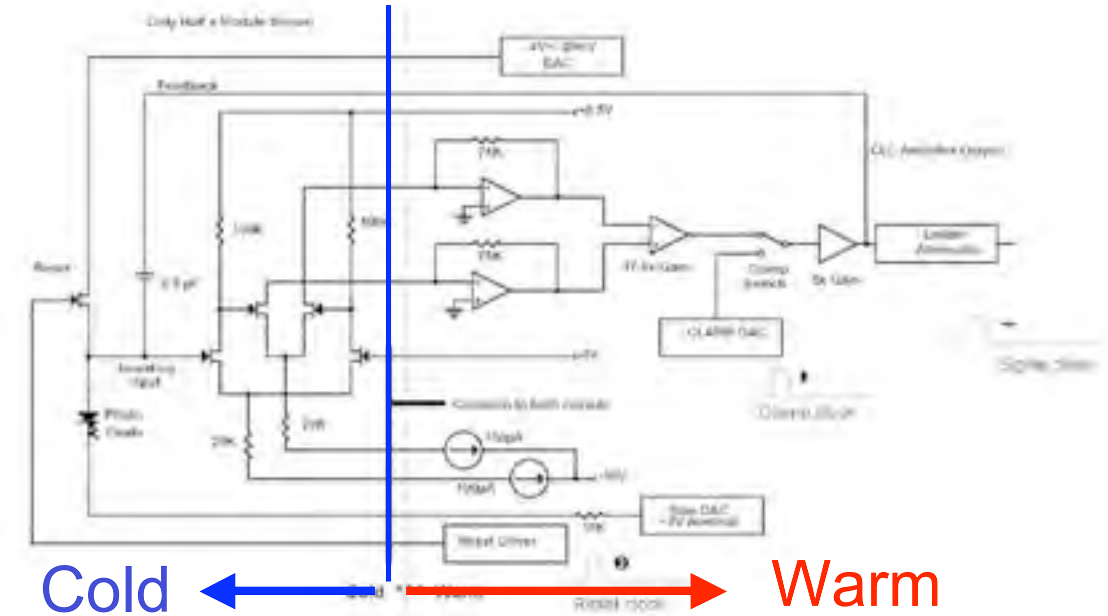
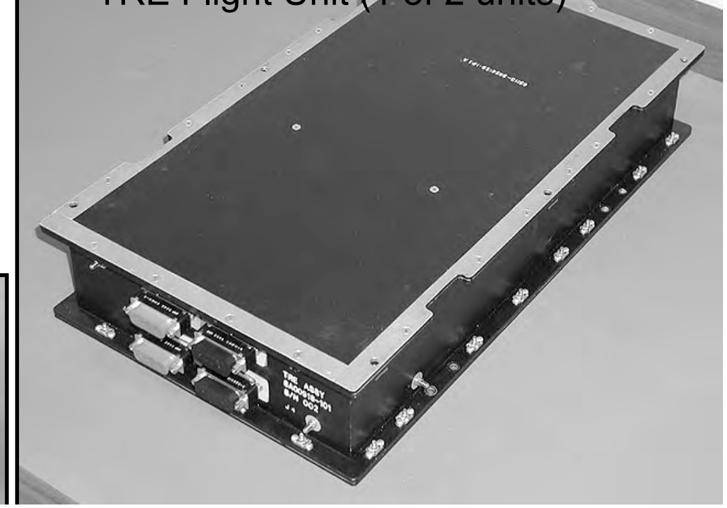
TRE

- Reads out Cryogenic Detectors

Detector



TRE Flight Unit (1 of 2 units)



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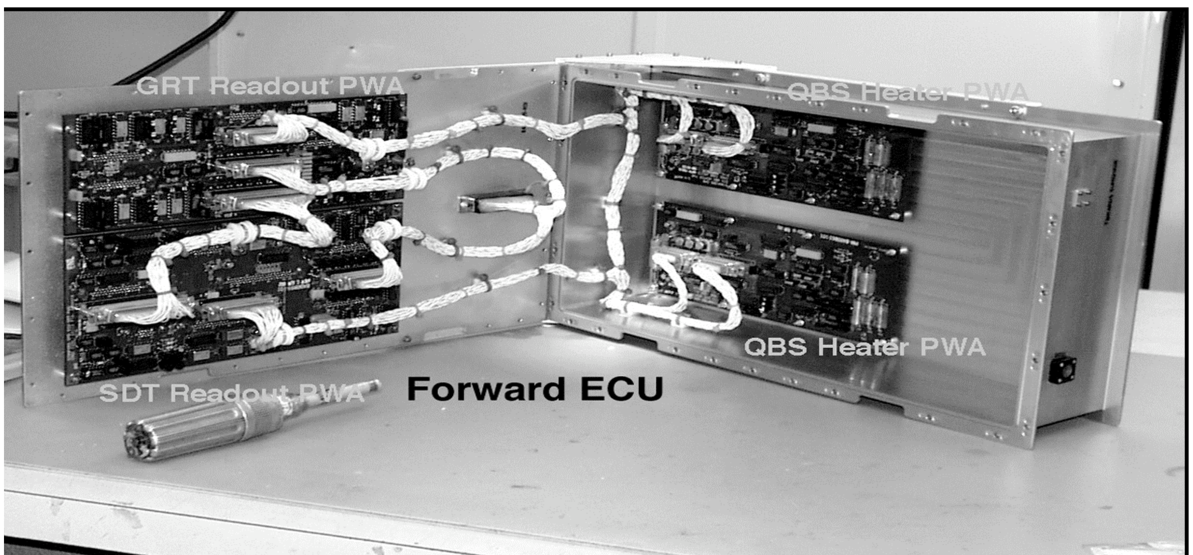
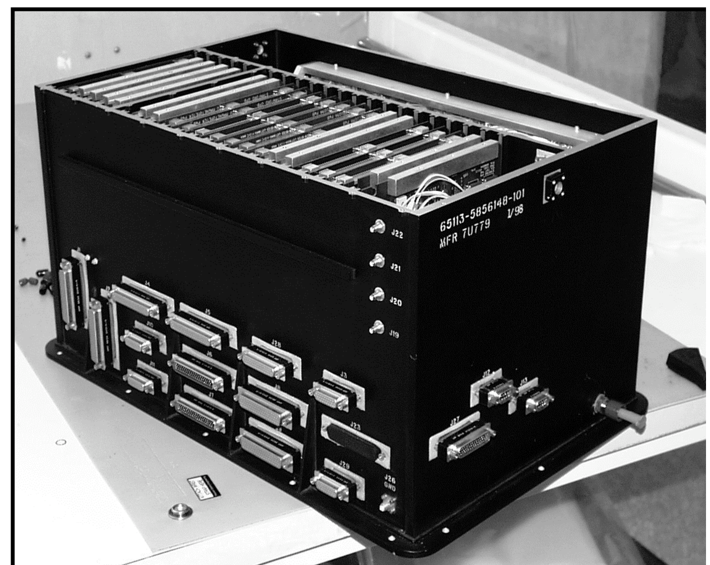
ECU

- GP-B ECU has 29 boards to control and monitor experiment functions such as dewar and probe temperature controls, Gas Management and probe pump-out,
- UV Light source lamps (2) and drivers for 8 fiber optic switches for Charge Control



ECU Fwd Unit


ECU Aft Unit

GPS

2 redundant sets. Each composed of a Trimble TANS Vector III GPS receiver and four matching Trimble antennas, modified for space use by Stanford

- Orbit determination for ephemeris and science data analysis
- Time Transfer via a pulse per second (PPS) signal output by the receiver reconciling vehicle time (Vt) with Coordinated Universal Time (UTC).

Position accuracy: 2.5 m (rms)

Velocity accuracy: 2.2 mm/s (rms)

Time transfer accuracy: 2 micro-s.

GPS Pathfinder unit with antenna array

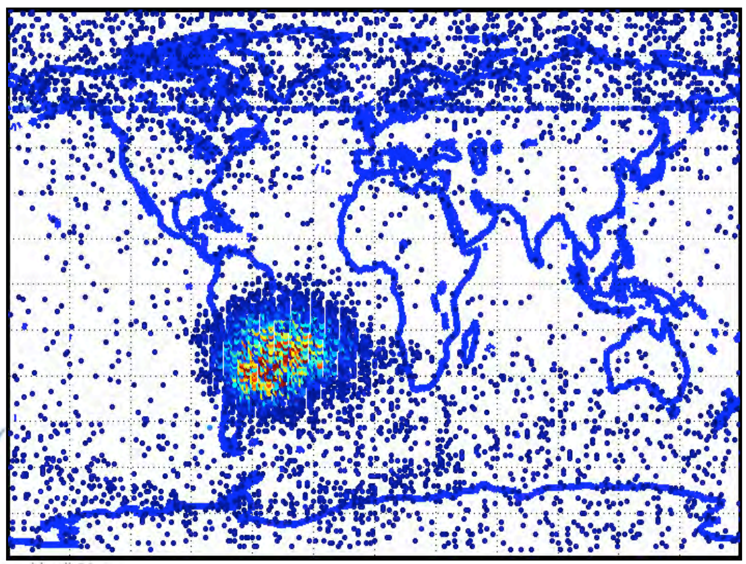
Proton Monitor

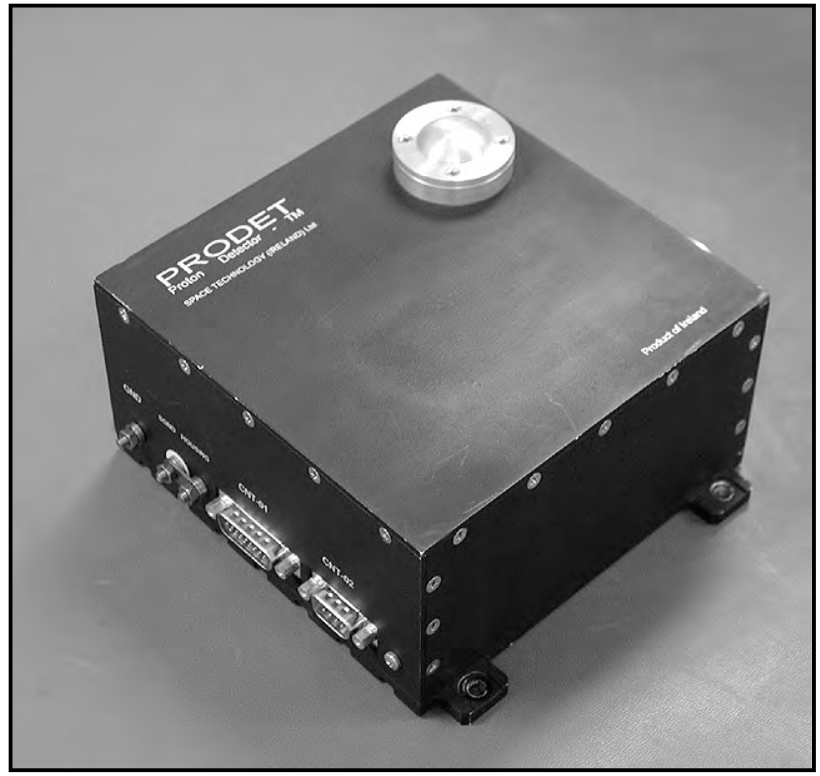
- Integrated with spacecraft and aft ECU.

50Mev-1Gev Protons from

- Cosmic Rays
- South Atlantic Anomaly
- Solar Flares

Correlates w/ telescope detectors hits

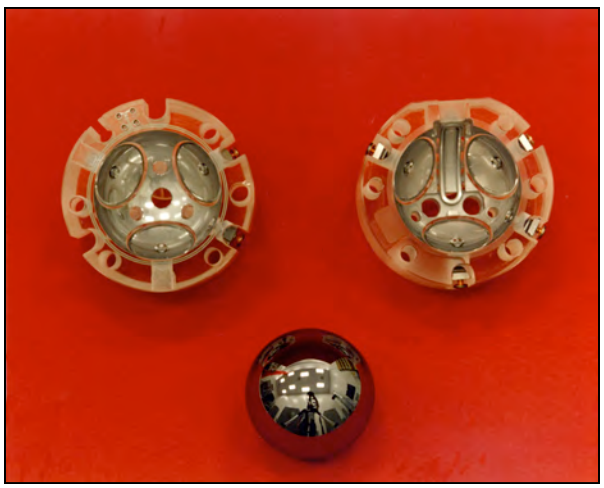


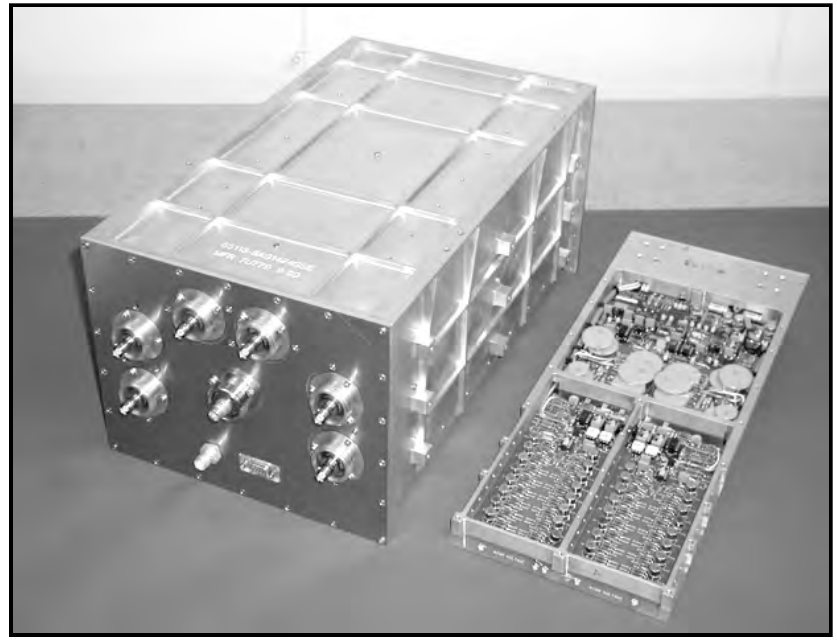


1 of 2 Proton Monitors, ready for spacecraft integration.

GSS

- 4 Forward and 4 Aft Boxes
- Provides gyro position sensing and centering (nm)
- Sensor for Drag-free control
- Charge measurement
- Special modes for gyro spinup and spin axis allignment





GSS Forward flight-equivalent unit with HV Amp/Bridge assembly

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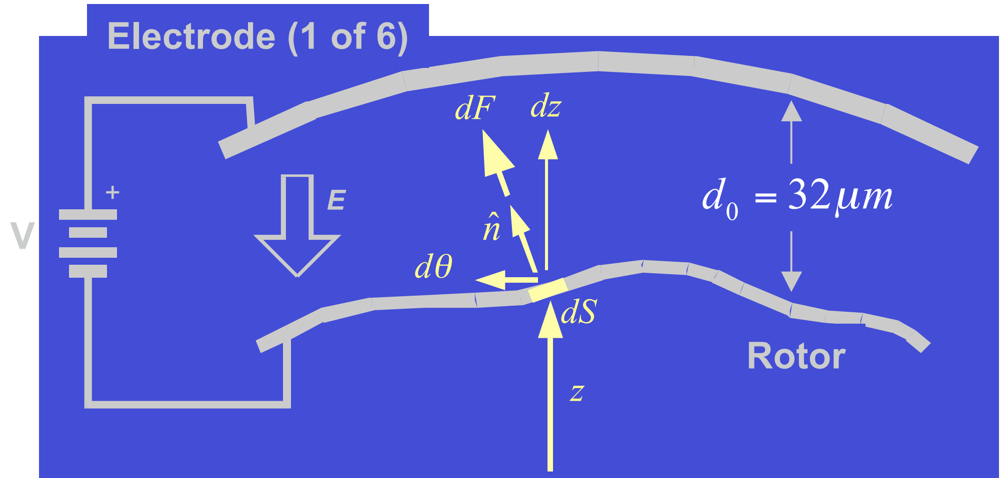
Physics of Electrostatic Suspension



Electric Field:

$$\mathbf{F} = \frac{\varepsilon_0}{2}\iint_S |\mathbf{E}|^2\, \hat{\mathbf{n}}\; dS$$

$$\tau = \frac{\varepsilon_0}{2}\iint_S |\mathbf{E}|^2\, (\mathbf{r}\times\hat{\mathbf{n}})\; dS$$

Stored Energy:

$$\mathbf{F} = -\frac{\partial}{\partial \rho}\left[\tfrac{1}{2}CV^2\right]$$

$$\tau = -\frac{\partial}{\partial \eta}\left[\tfrac{1}{2}CV^2\right]$$

Per-axis forcing relationship (1 of 3):

$$F_z = K\frac{(V_{z1}-V_r)^2}{(d_0-z)^2} - \frac{(V_{z2}-V_r)^2}{(d_0+z)^2}$$

Plant Characteristics:

- Open-loop unstable!
- Nonlinear!
- Multi-input/Multi-output!
- Torques and forces a function of applied voltages!

Suspension System Design Drivers

Minimize Torques

"Do Nothing"

- Slow response/bandwidth
- Low suspension voltages/forces
- SQUID compatible – minimal EMI.
- Science-tuned controller.
- "Zero force" drag free control.

Protect the Rotor

"DO NOT let the rotor crash"

- Fast response/bandwidth.
- High suspension voltages/forces.
- High position bridge SNR (amplitude/frequency).
- Robust control algorithm.
- Ground test and spinup control.

Spaceflight compatible

- Implement with slow computing resources and electronics.
- Endure vibration, shock, EMI, radiation, thermal, vacuum environment
- Operate semi-autonomously with low drift and tight power budget.

Many conflicting requirements makes for a challenging design!

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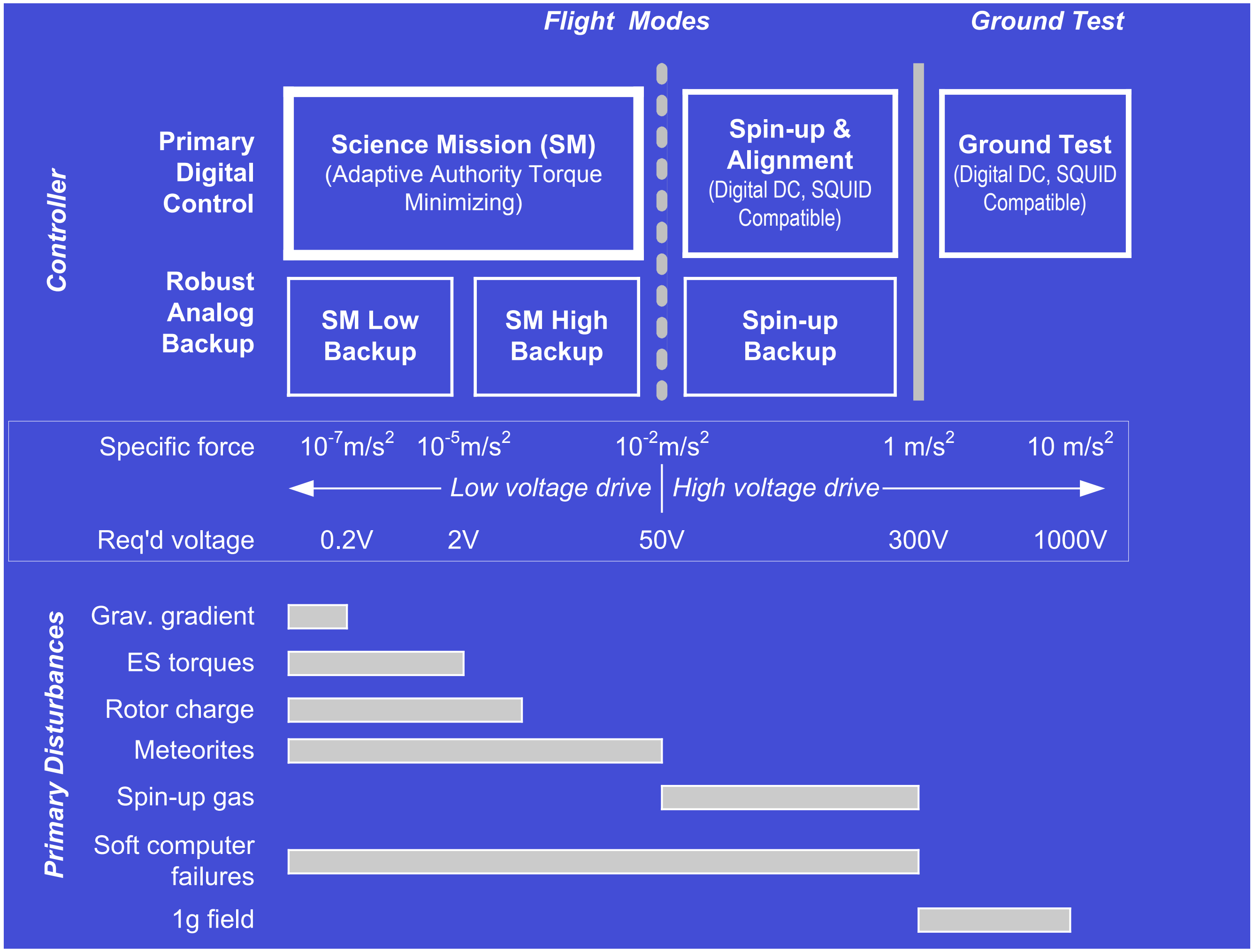
Gyro Suspension System Modes



- Suspension forces span 8 orders of magnitude
- All modes tested on high fidelity simulator prior to launch.
- Sequenced bring up of controller on orbit to confirm performance and protect gyroscope.
- All primary and backup modes tested and function well on orbit.

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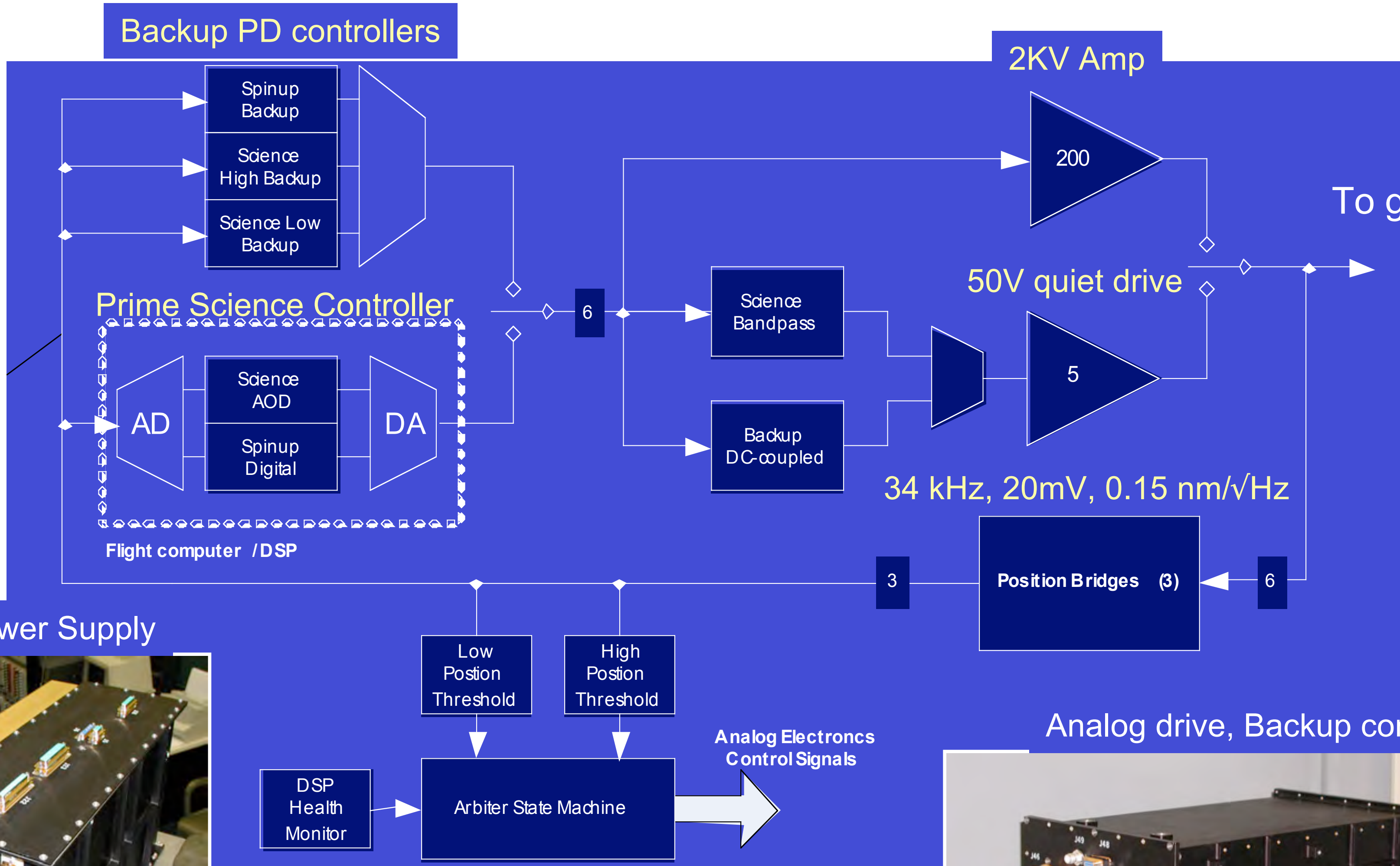
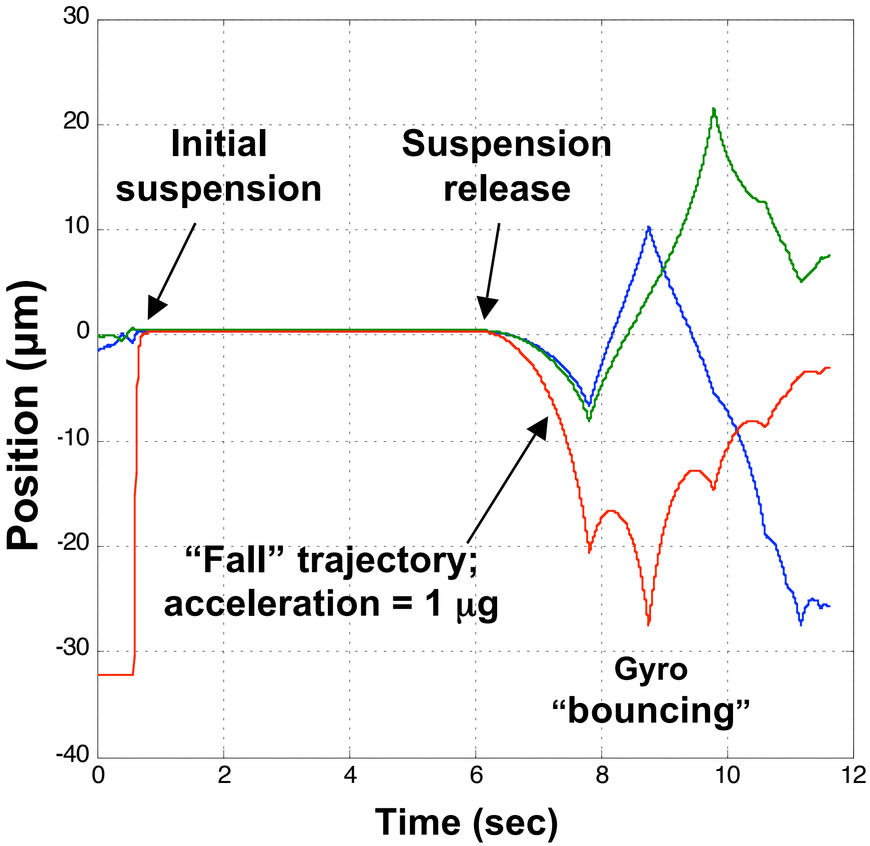
Control System Hardware



DSP + Power Supply

Analog drive, Backup control

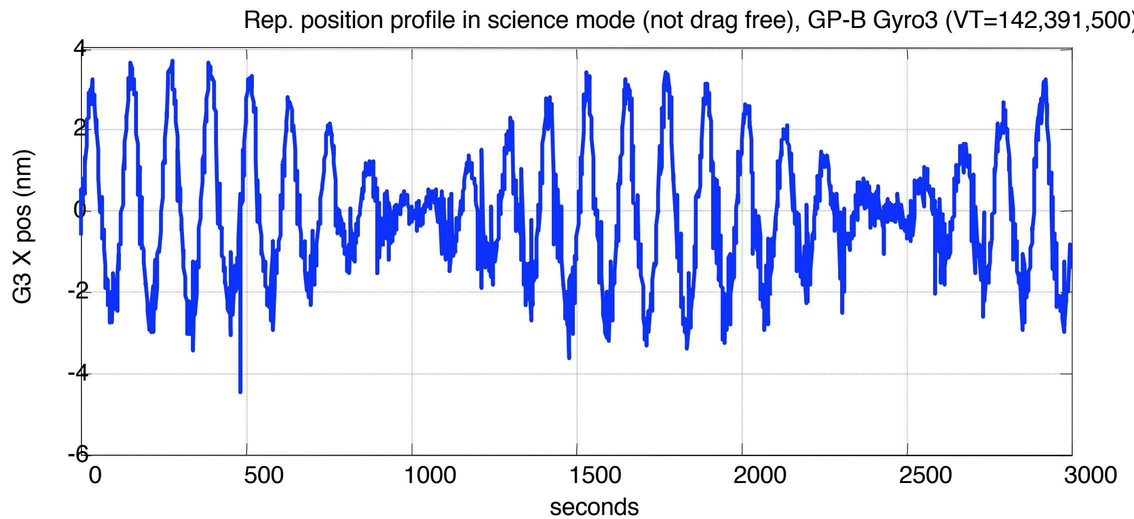
Initial "Backup" Suspension on Orbit



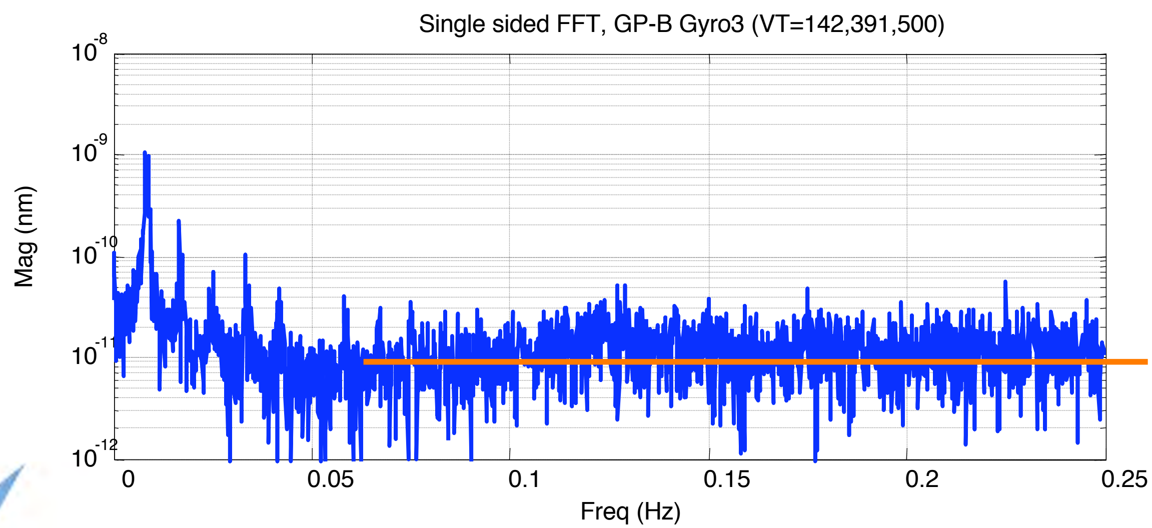
- Gyro first suspended with high science level analog backup controller (PD architecture)
- Suspended for 5 seconds then released.
- "Fall" trajectory and subsequent bounces clearly seen in position data (~1 μg acceleration)
- Robust backup system
  - 3 sets of of PD controllers
  - Computer health monitor.
  - 5 μm safety radius around center.

Demonstrated performance: < 0.5 nm RMS positioning

Position Measurement Performance



Representative gyro position trace showing non drag-free gravity gradient effects in Science Mission Mode



Measurement noise 0.45 nm rms

Noise floor

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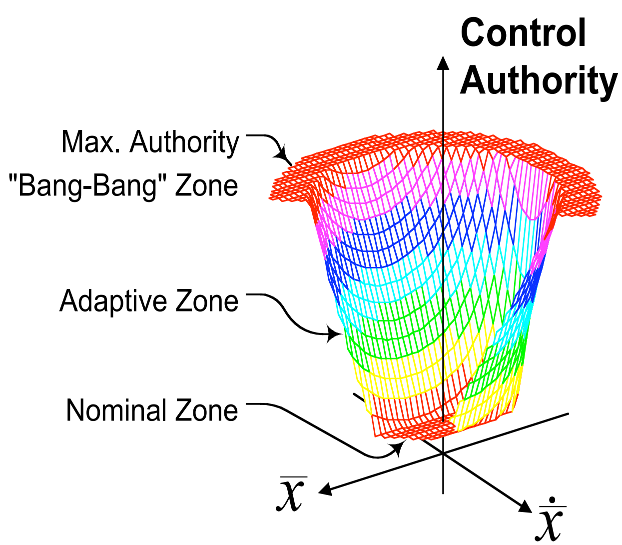
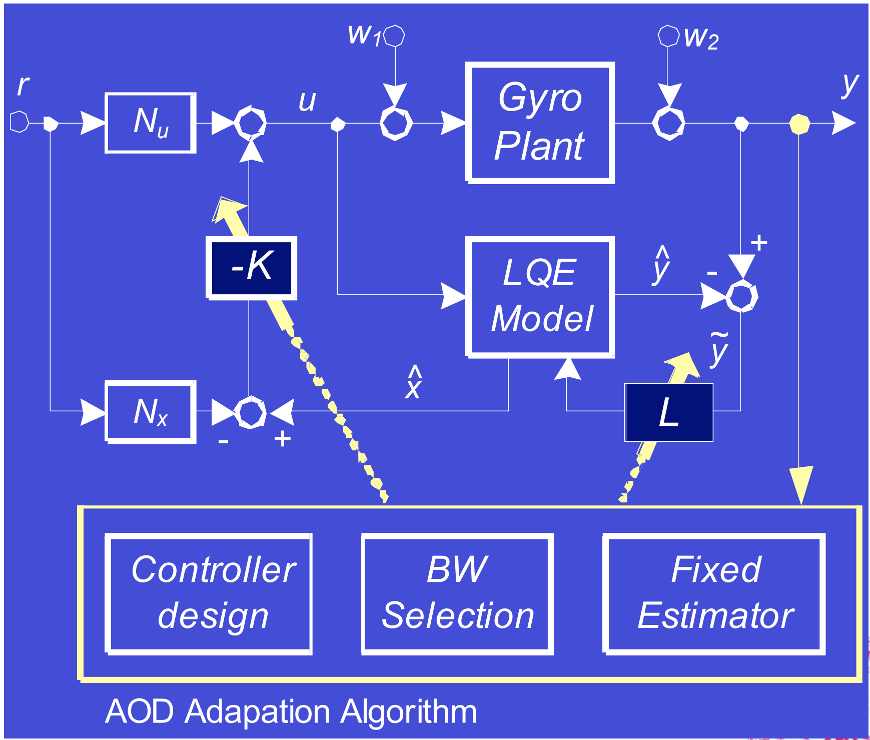
Variable Authority Control for Low Torque

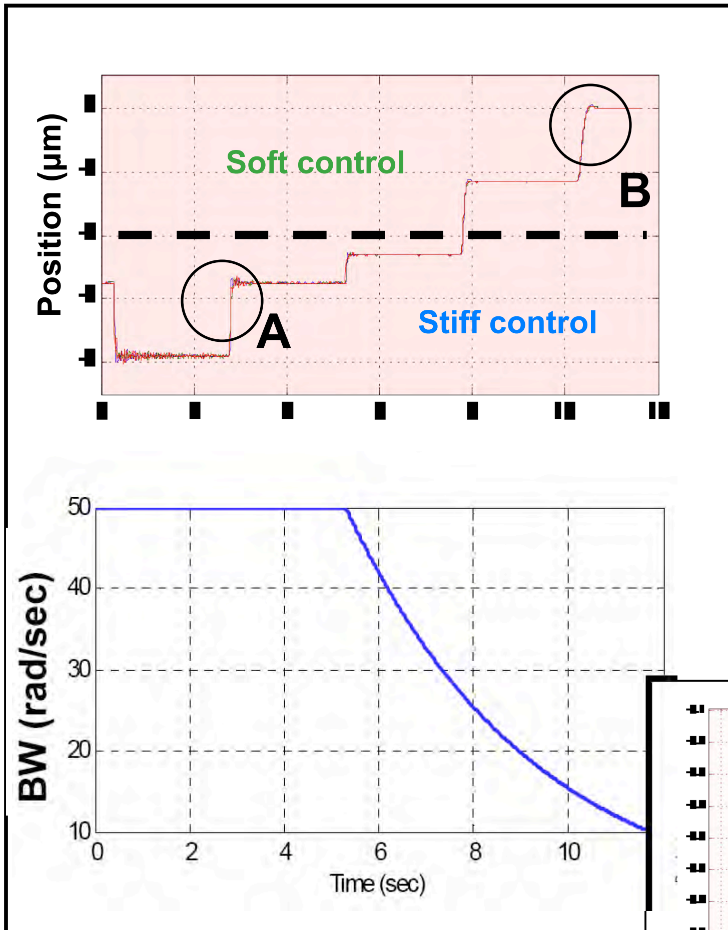
- High control authority ⇨ High voltages ⇨ High torques
- Nominal Operations: Low authority/voltage used when rotor is centered.
- Fast attack adaptation as rotor moves away from center
  - Respond to micrometeoroid impacts, etc.
  - Adapts based on estimates of position and velocity.
- Authority decays after rotor is re-centered and transients die away

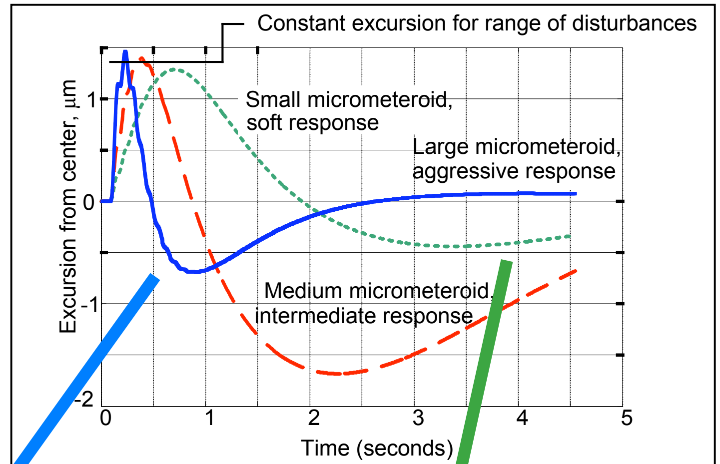


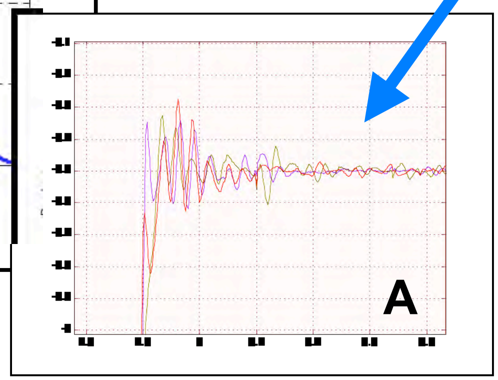


Variable Authority in Action On Orbit

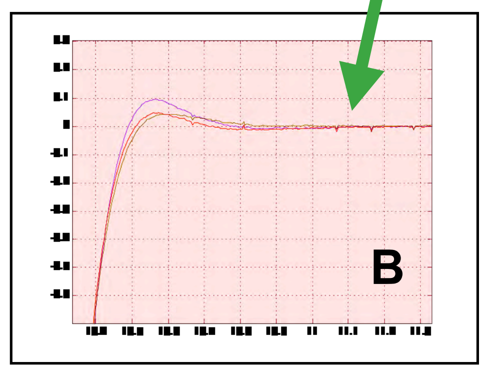
- Disturbance-dependent control authority keeps the gyro safe while minimizing torques.







High BW (50 rad/sec)



Low BW (3 rad/sec)

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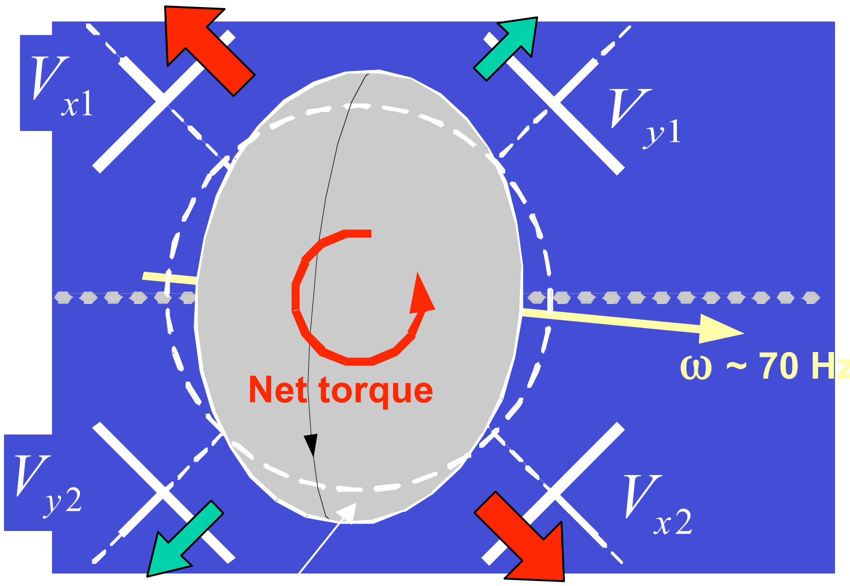
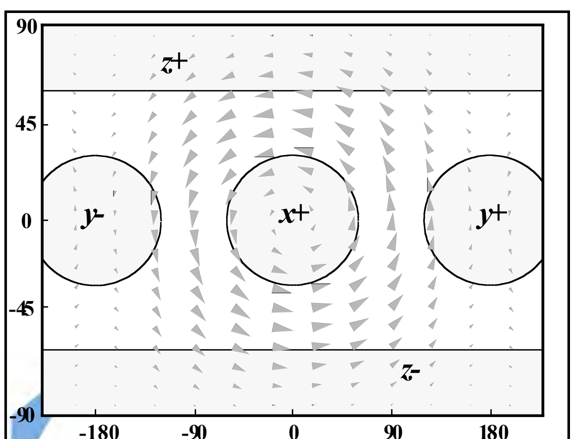
Amplifying Torques for Spin Axis Alignment



5 nm centrifugal bulge @ 70 Hz



Torque field around an electrode

- Suspension constraints: 4

$$F_x = k\left[\left(V_{x1} - V_r\right)^2 - \left(V_{x2} - V_r\right)^2\right]$$
$$F_y = k\left[\left(V_{y1} - V_r\right)^2 - \left(V_{y2} - V_r\right)^2\right]$$
$$F_z = k\left[\left(V_{z1} - V_r\right)^2 - \left(V_{z2} - V_r\right)^2\right]$$
$$V_r = 0 = \sum_i V_i$$

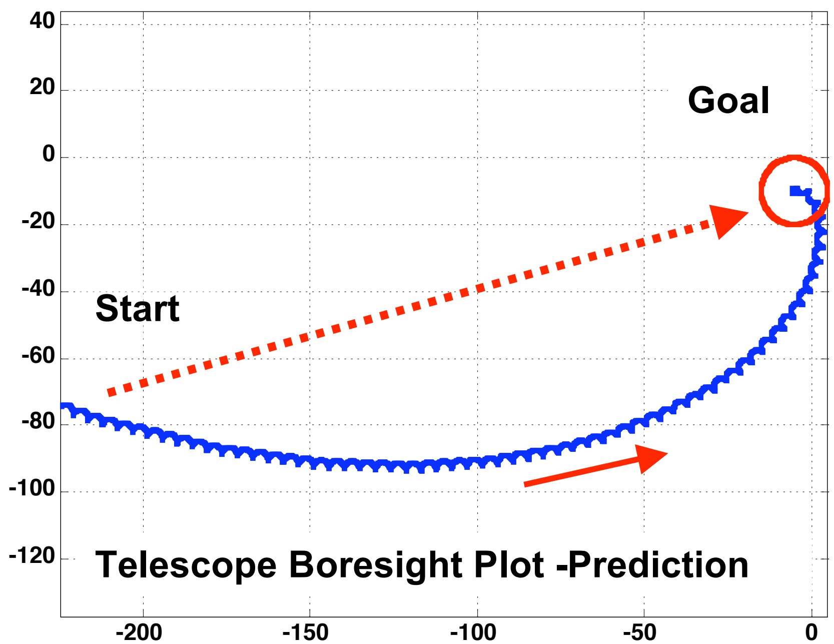
- 6 voltages ⇨ 2 open DOF in V

Differences of voltages constrained, sum of voltages is not!

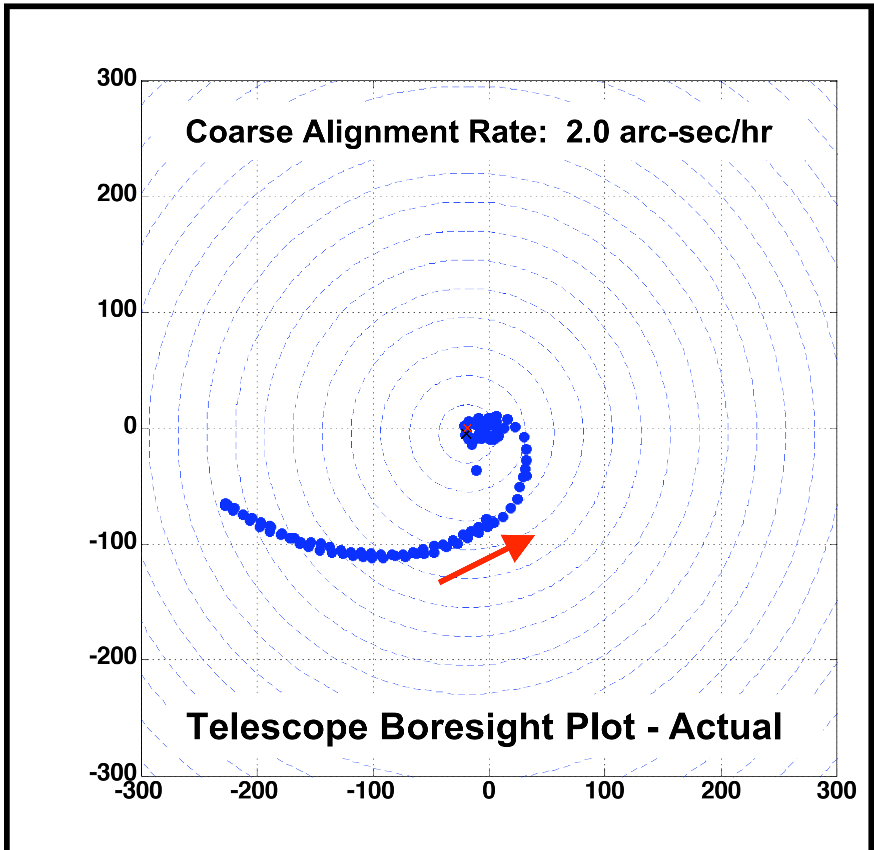
$$s_x = \left[V_{x1}^2 + V_{x2}^2\right], \quad s_y = \left[V_{y1}^2 + V_{y2}^2\right]$$

Unbalancing the "common mode" pull between axes gives rise to a controllable torque against the rotor centrifugal bulge

Spin Axis Alignment on Orbit



- Residual suspension torques on rotor shape used to effect alignment.
- Provides an early calibration of a primary error source – found to be 20% of pre-launch predicts!



Demonstrated performance: final alignment to within 10 arc-sec of goal.

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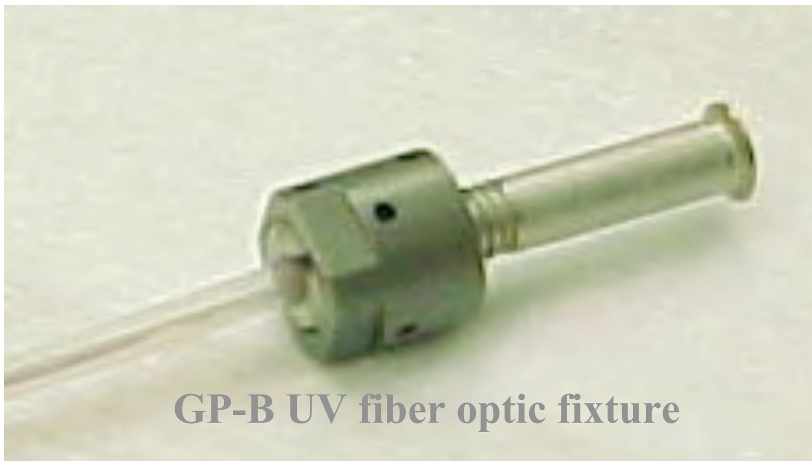
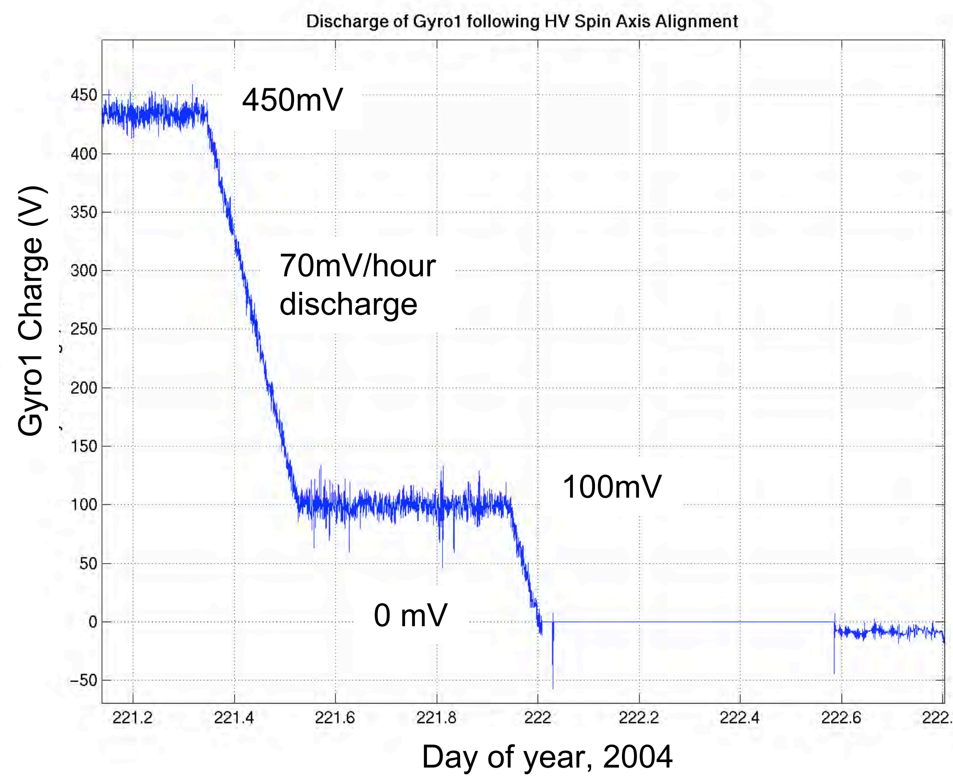
UV Charge Control

System Components: UV Light source, fiber optic, and bias electrode
GSS Charge Measurement



Discharge of GP-B Gyro1



GP-B on Orbit operation

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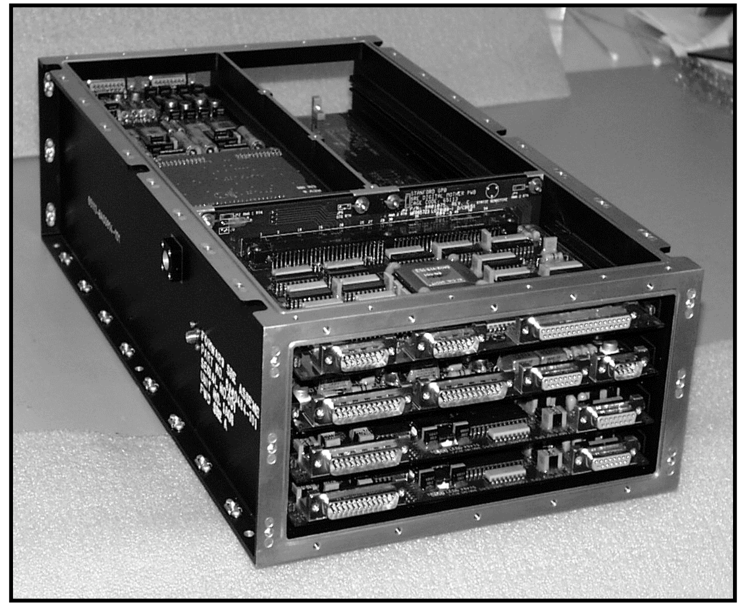
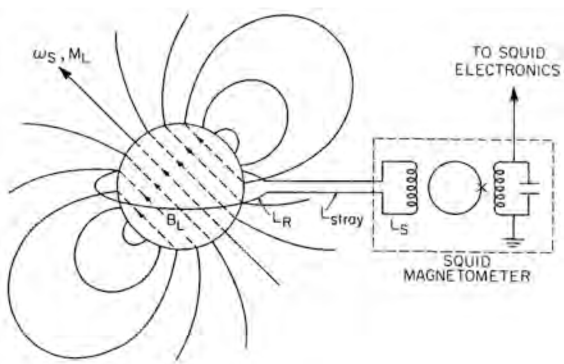
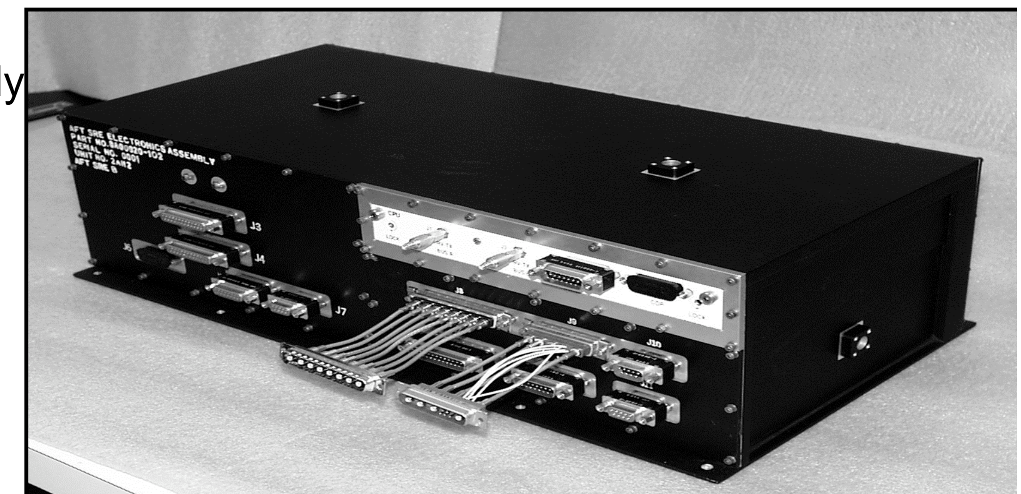
SRE

- Readout system overview
  - Magnetic signal generated by gyroscope
  - Gyroscope signal coupled to pickup loop
  - Signal inductively coupled to SQUID
  - SRE operates SQUID as null detector
    - SRE provides a voltage readout (V) of feedback effort required to null gyro signal
- Primary Gyro Readout - London Moment
- Snapshot data to 2200 Hz
- Bandwidth sufficient to resolve trapped flux at 1-10 harmonics of spin
- => yields measure of instantaneous spin direction and trapped flux fixed to gyro body Enables trapped flux mapping



Assembled SRE Fwd Unit - 1 of 2 units





Assembled SRE aft unit - 1 of 2 units

SQUID

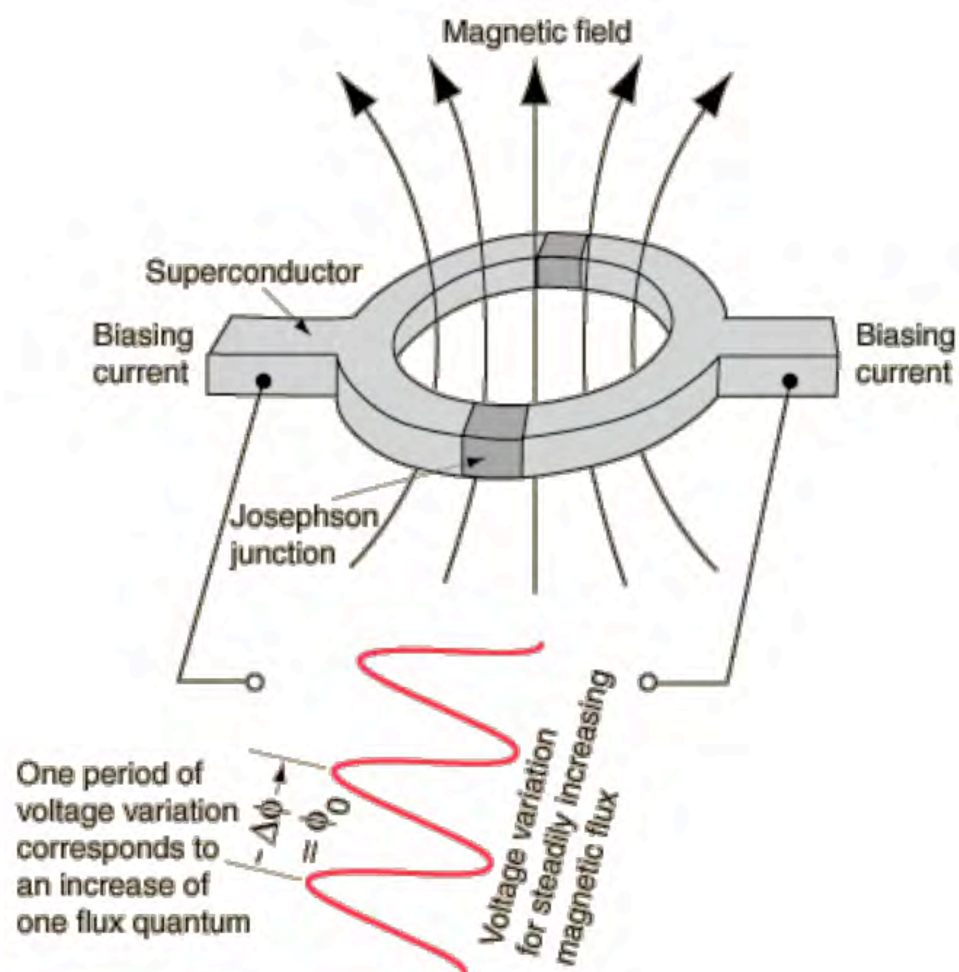
Superconducting Quantum Interference Device

DC SQUID – 2 Josephson Junctions

Current bias -–> Voltage periodic in Φ_0

Analog of 2 slit interference in optics

$\Phi_0 = h/2e = 2.067\ 833\ 636\times10^{-15}$ Wb

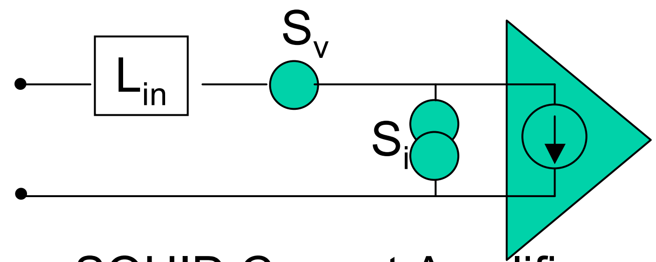


The SQUID Amplifier

L_{in}: Input inductance of SQUID (~ 2 μH for GPB)

SQUID Voltage Noise S_v [typical 10^{-34} - 10^{-36} V^2/Hz]

SQUID Current Noise S_i [typical 10^{-24} - 10^{-25} V^2/Hz]



SQUID Current Amplifier Noise Model

Noise Temperature, $T_n = P_n/k_B B_w$

SQUID Noise Temperature T_n (best measure of noise performance)

$T_n = (S_i S_v)^{0.5}/2k_B$ k_B is Boltzmann's constant

T_n(SQUIDs) < 10^{-6} K for optimally designed circuits (GP-B) white noise)

T_n for best room temperature semiconductor amplifiers ~ 1 K

SQUIDs can have 10^6 lower noise than best room temperature amplifier

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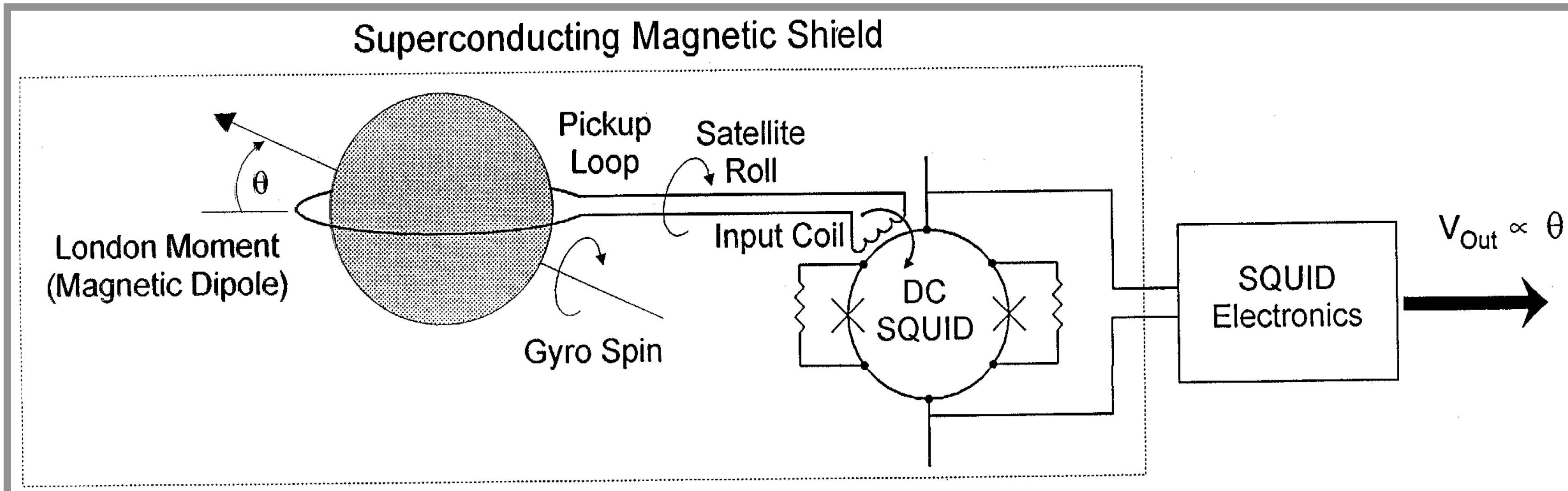
London Moment Readout



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

1marcsec in 10 hr integration (2x10^{-13} Gauss)

<8x10–29J/Hz (50μΦ_0/Hz)

	Trapped field (μG)	London Moment Equiv. field (μG)	Trapped field / London Moment
Gyro 1	3.1	57	0.055
Gyro 2	1.3	44	0.029
Gyro 3	0.8	59	0.014
Gyro 4	0.2	47	0.005

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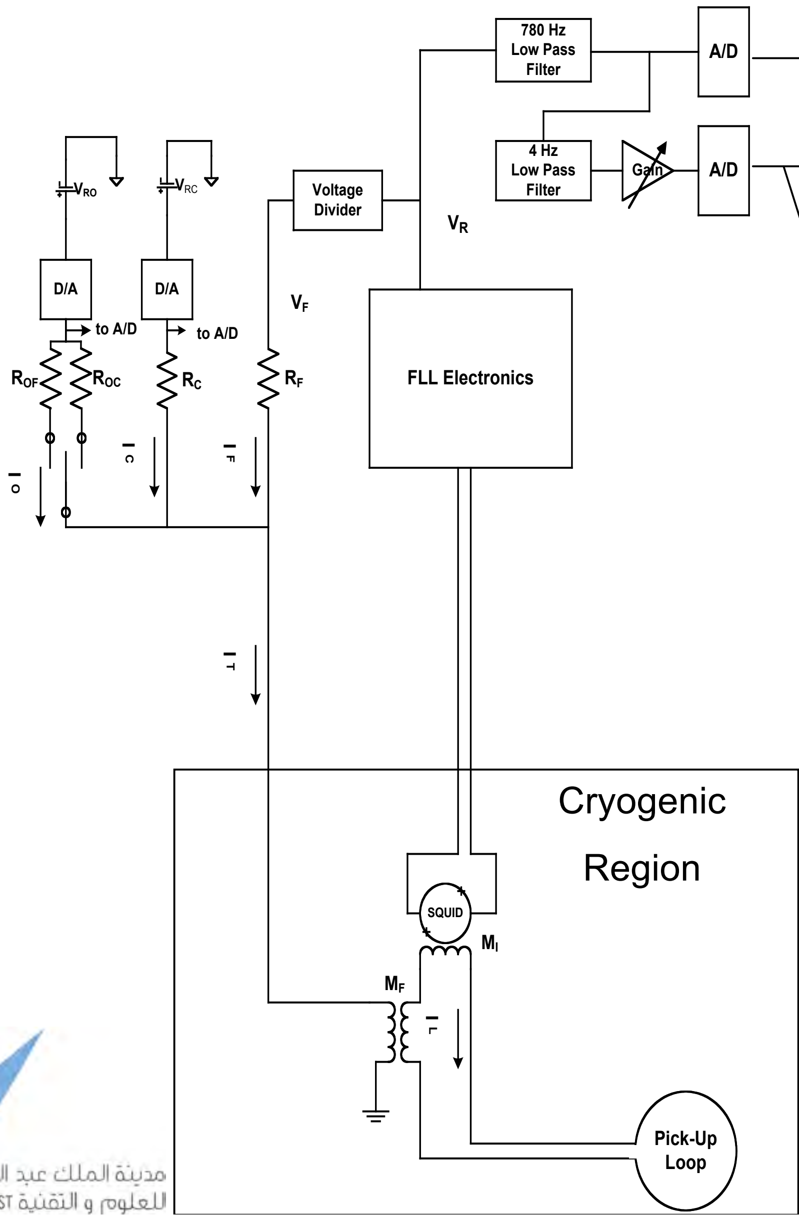
Readout Architecture



High Frequency Snapshots

"1kHz Snapshots"

Low Frequency Snapshots

"20 Hz Snapshots"

Digital Low Pass Filter

Non-causal, 2.5 Hz cutoff, minimized at 10 Hz + harmonics

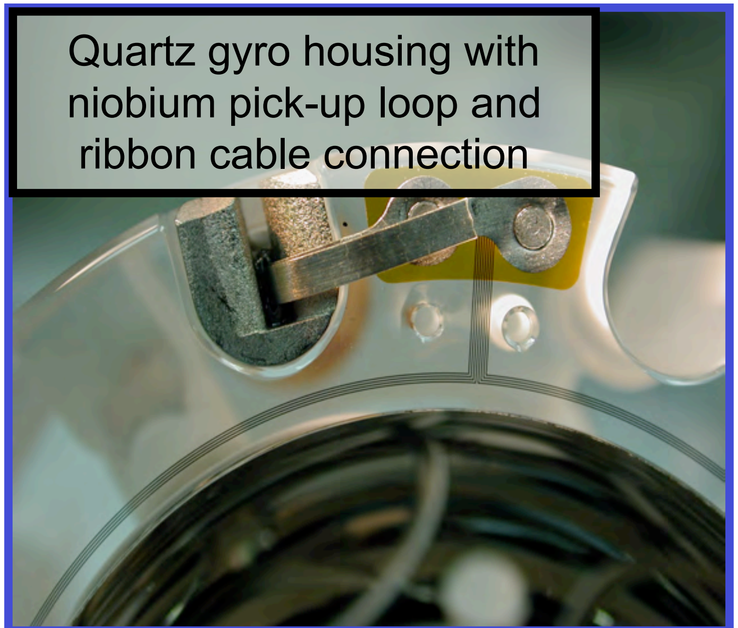
→ *SQUID Science Signal*

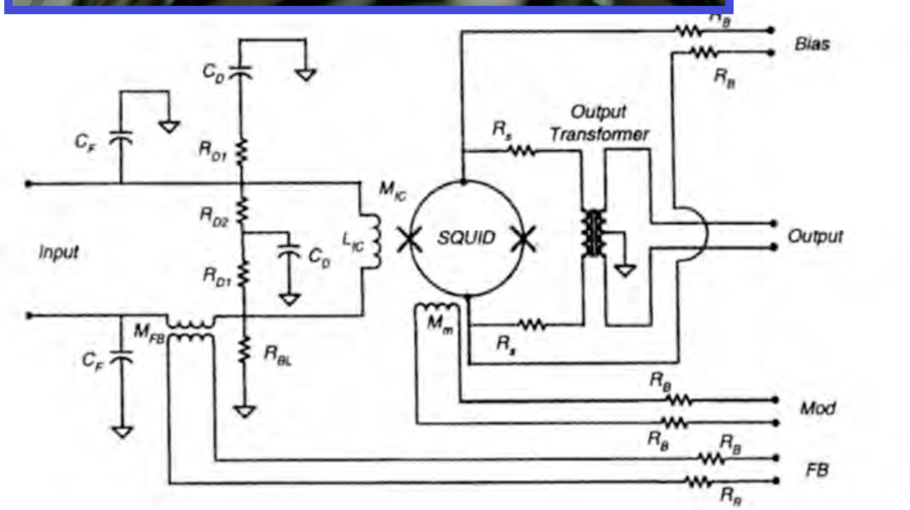
Digital filter response:

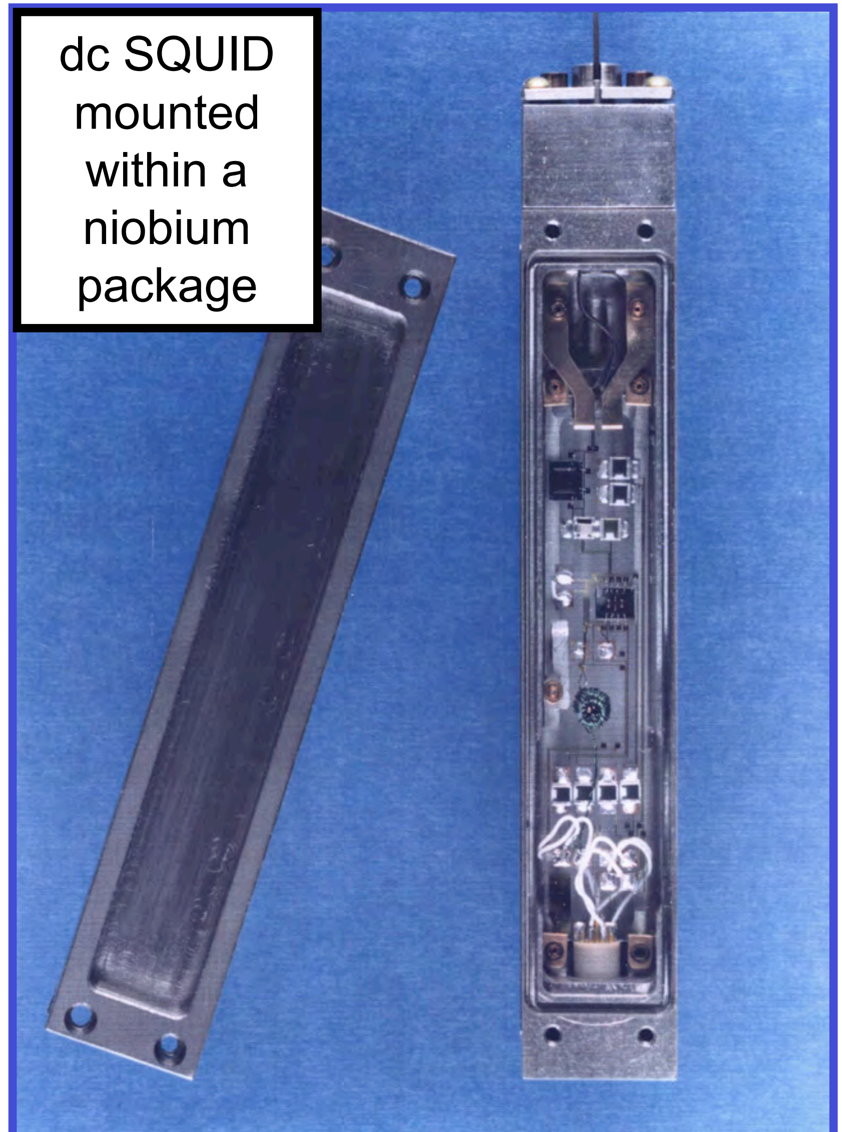
10^{-2} @ 5 Hz

10^{-6} > 7 Hz

Cryogenic Components

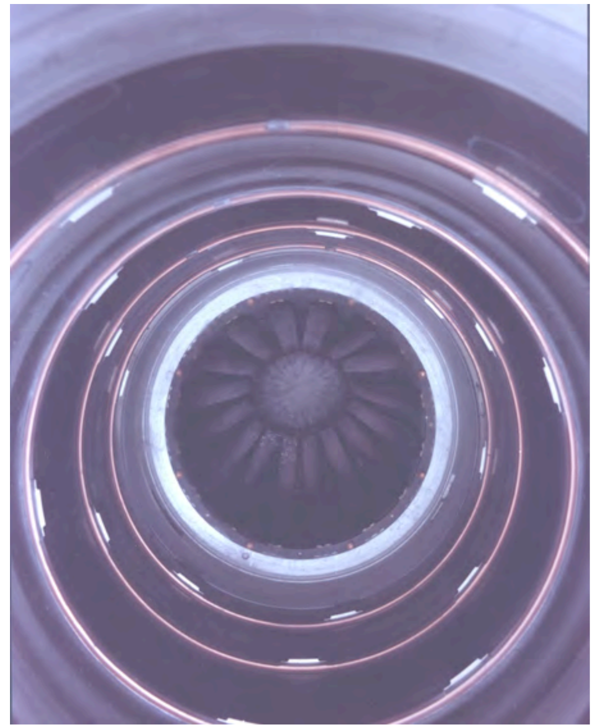

Quartz gyro housing with niobium pick-up loop and ribbon cable connection




dc SQUID mounted within a niobium package

Ultra-low Magnetic Field

- Magnetic fields are kept from gyroscopes and SQUIDs using a superconducting lead (Pb) bag
  - Mag flux = field x area.
  - Successive expansions of four folded superconducting bags give stable field levels at ~ 10^{-7} G.
- AC shielding at 10^{-12} [=120 dB!] from a combination of cryoperm, lead bag, local superconducting shields & symmetry.



On Orbit Performance Met Requirements

Trapped field:	**Gyro 1**	**3.0 MicroGauss**
	Gyro 2	**1.3 MicroGauss**
	Gyro 3	**0.8 MicroGauss**
	Gyro 4	**0.2 MicroGauss**

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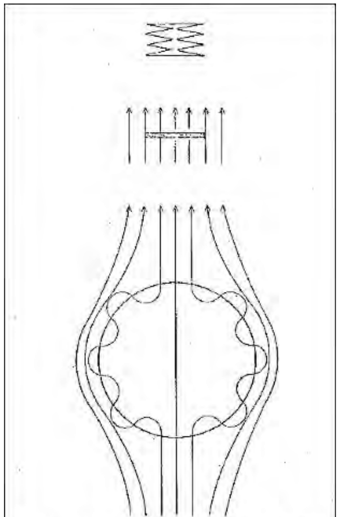
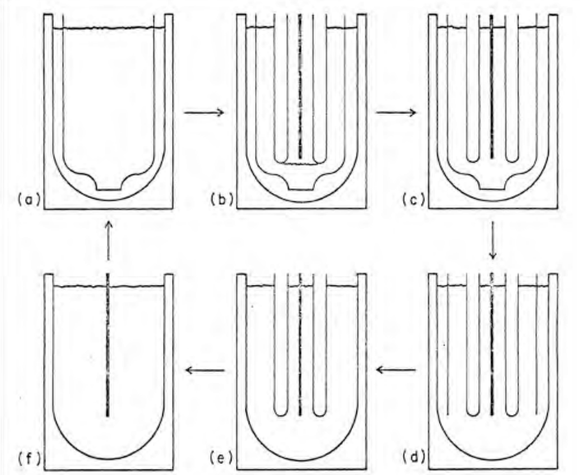
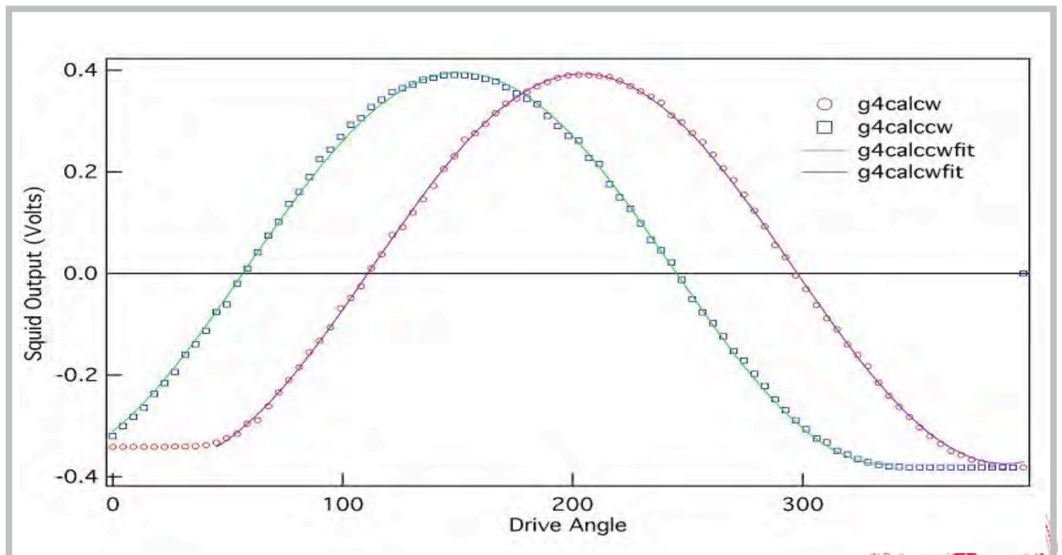
Ultra-low Magnetic Field



Expanding shield reduces field



Cyclic Bag Expansions



SQUID Control Electronics Features

- 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

- Preamp: Cascode FET, < 1 nV/ÖHz at 409 kHz flux mod. freq.
- Demodulator: Balanced FET switches
- Single pole integrator; 100 kHz bandwidth w/35 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

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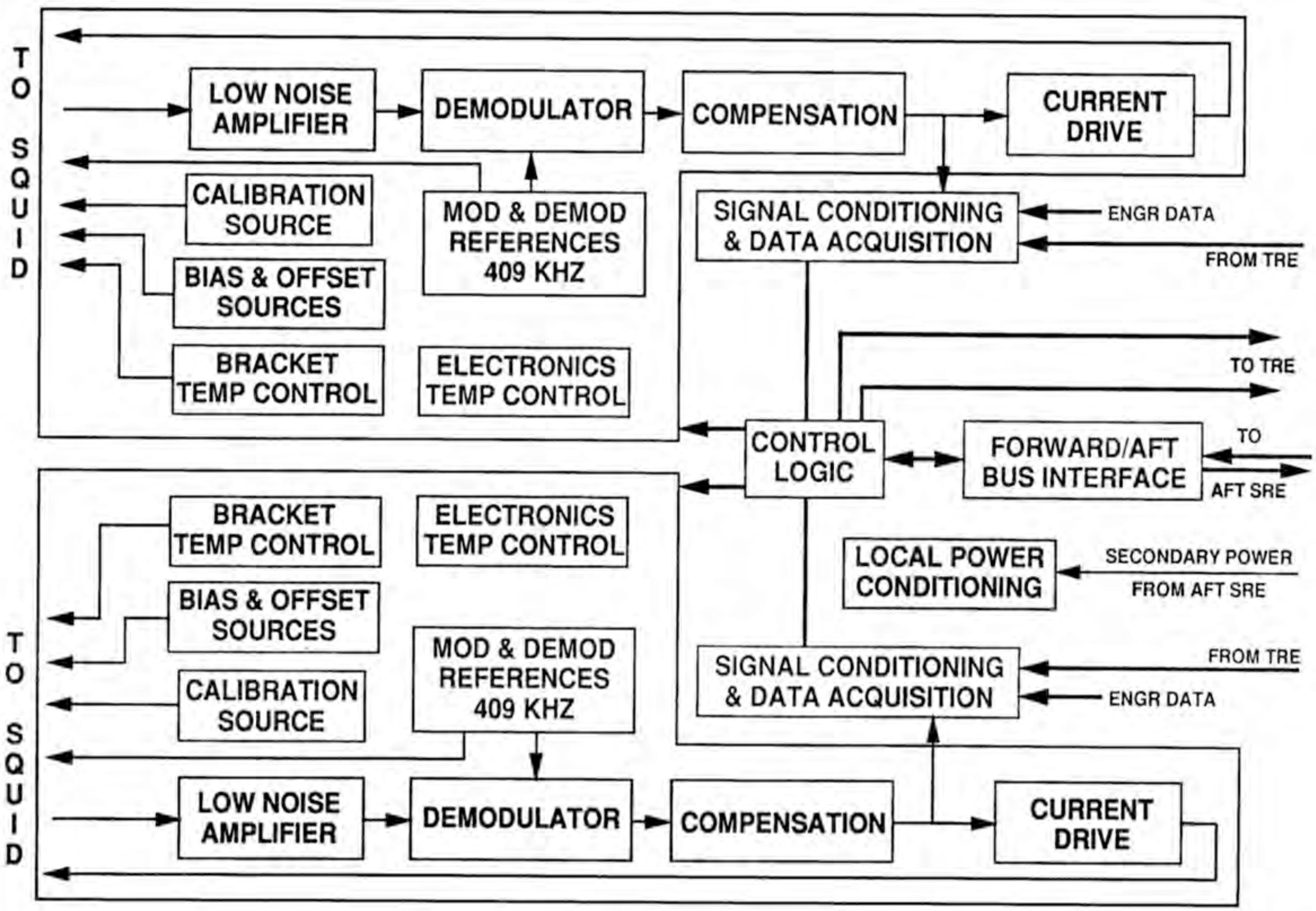
SQUID FLL & Temperature Control Electronics



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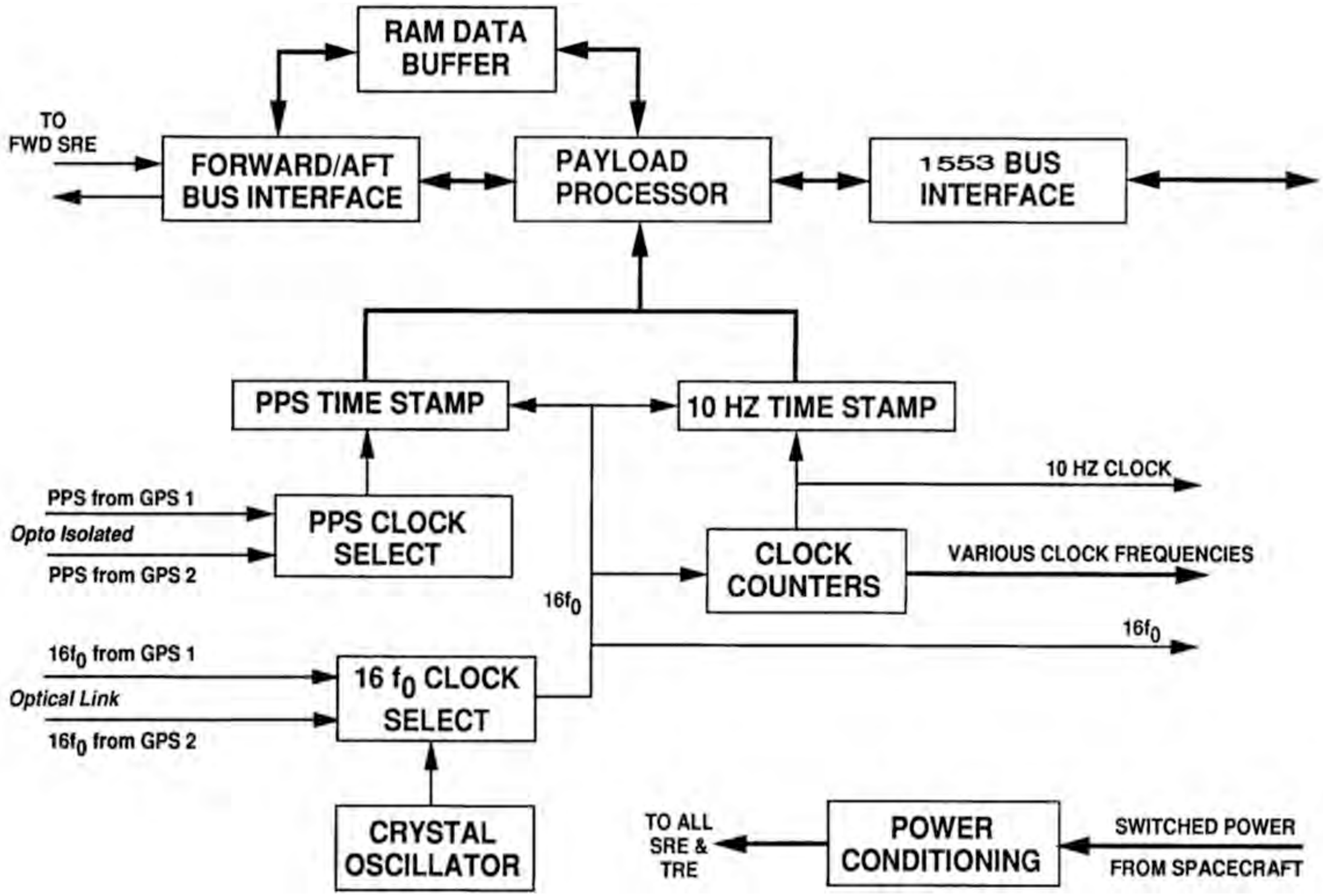
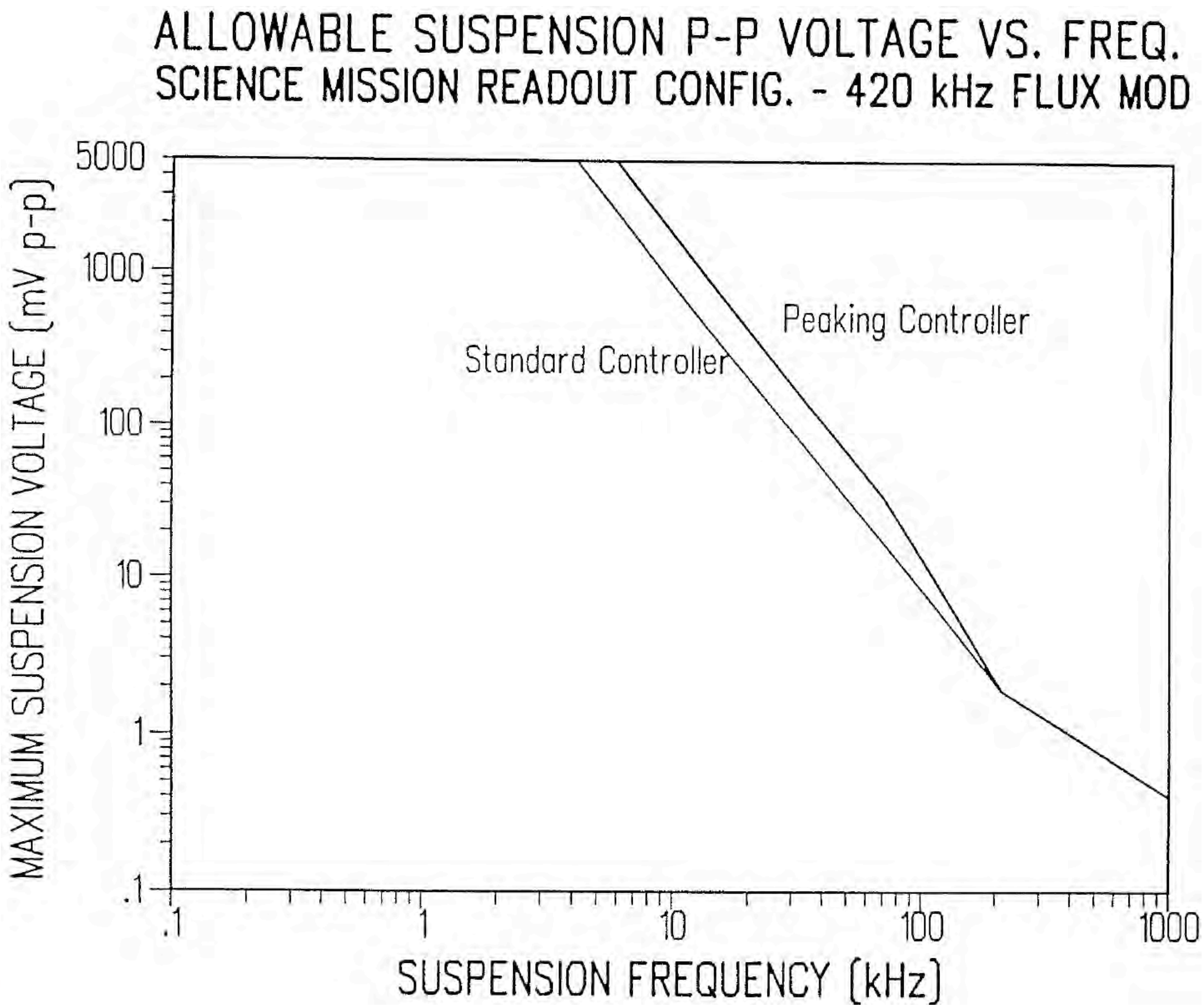
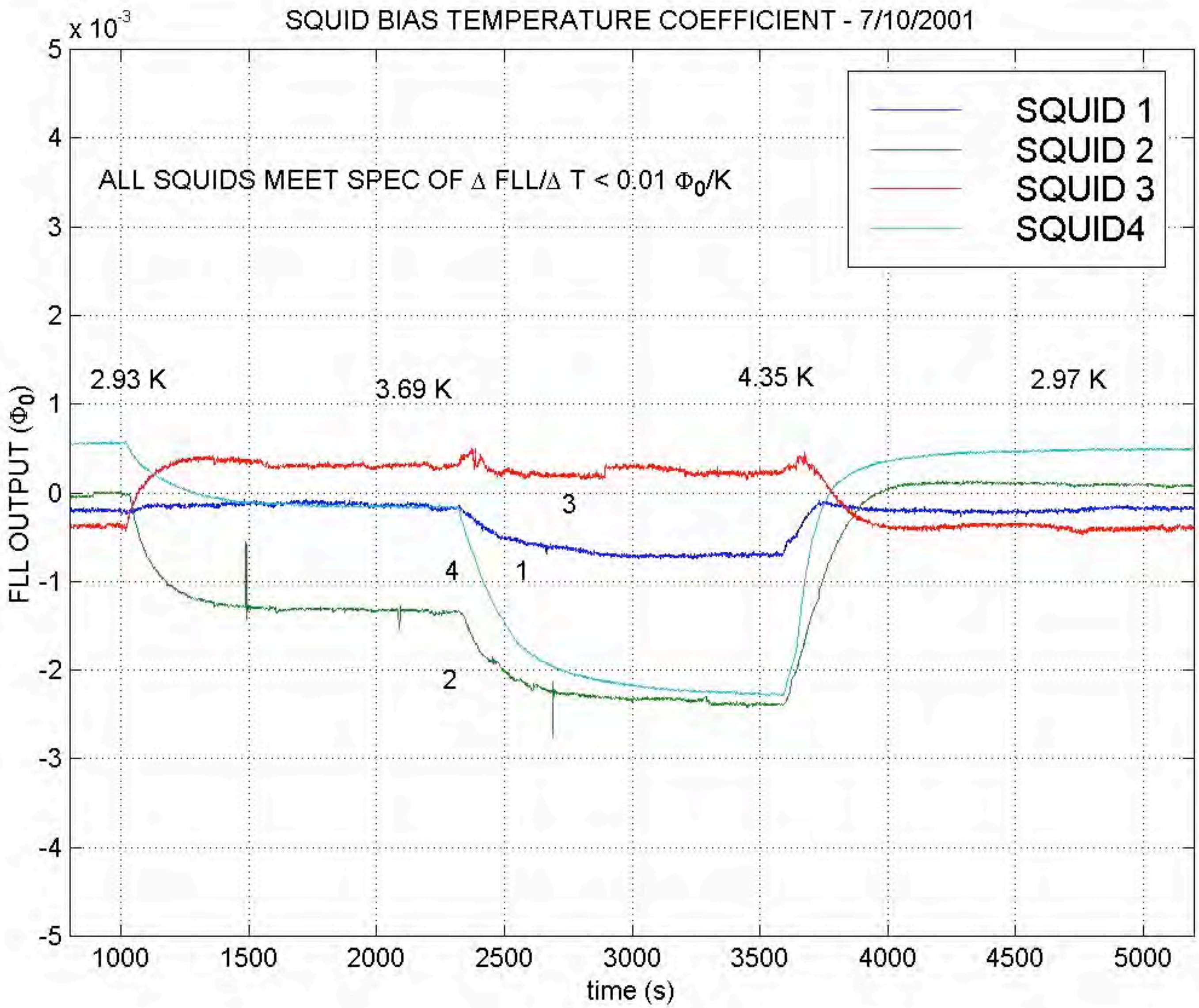
Timing System



SRE – GSS Compatibility



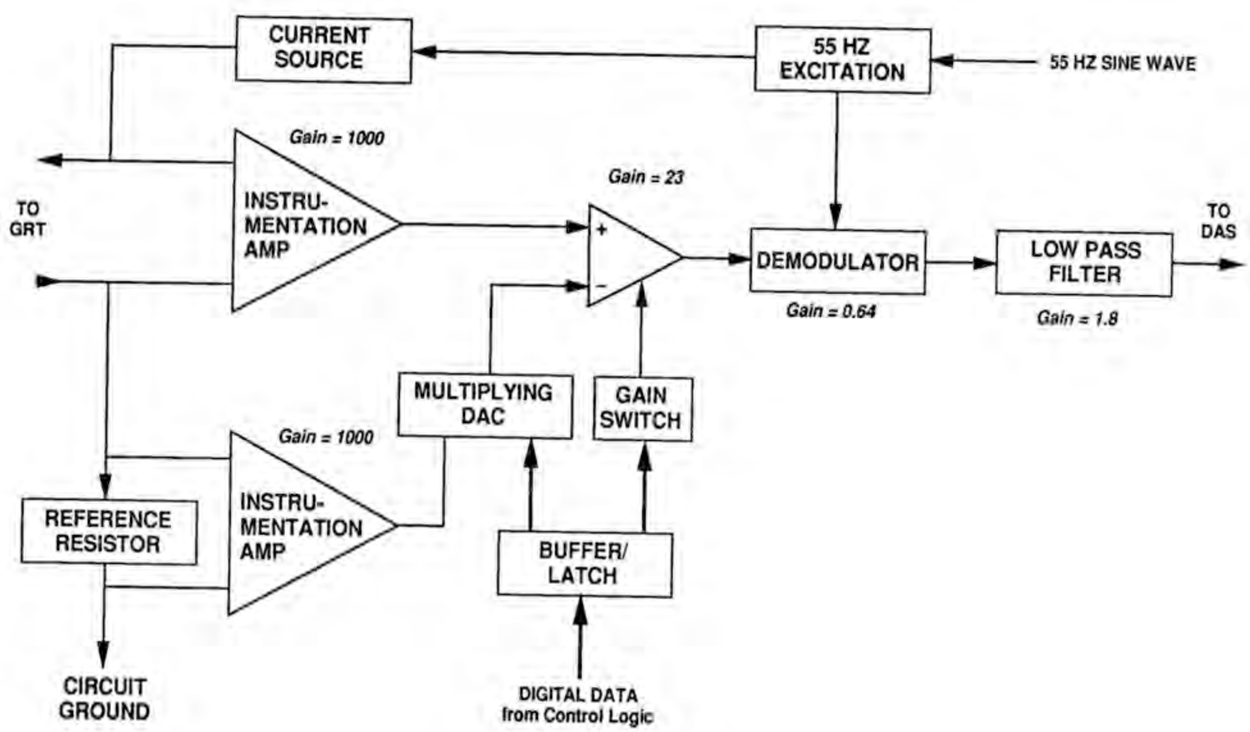
Temperature Control Requirement



Temperature Coef => Control Requirement <5μK at roll

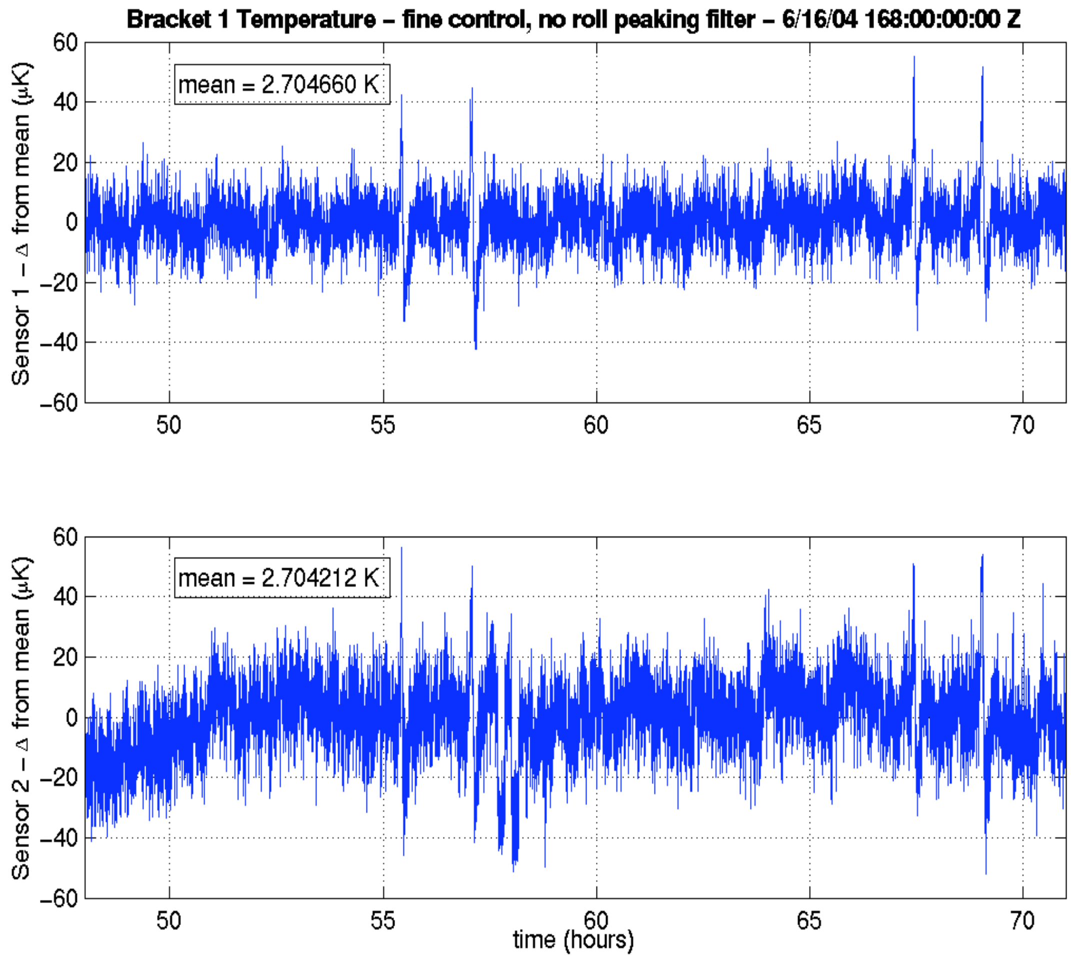
Temperature Control Electronics

- 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.

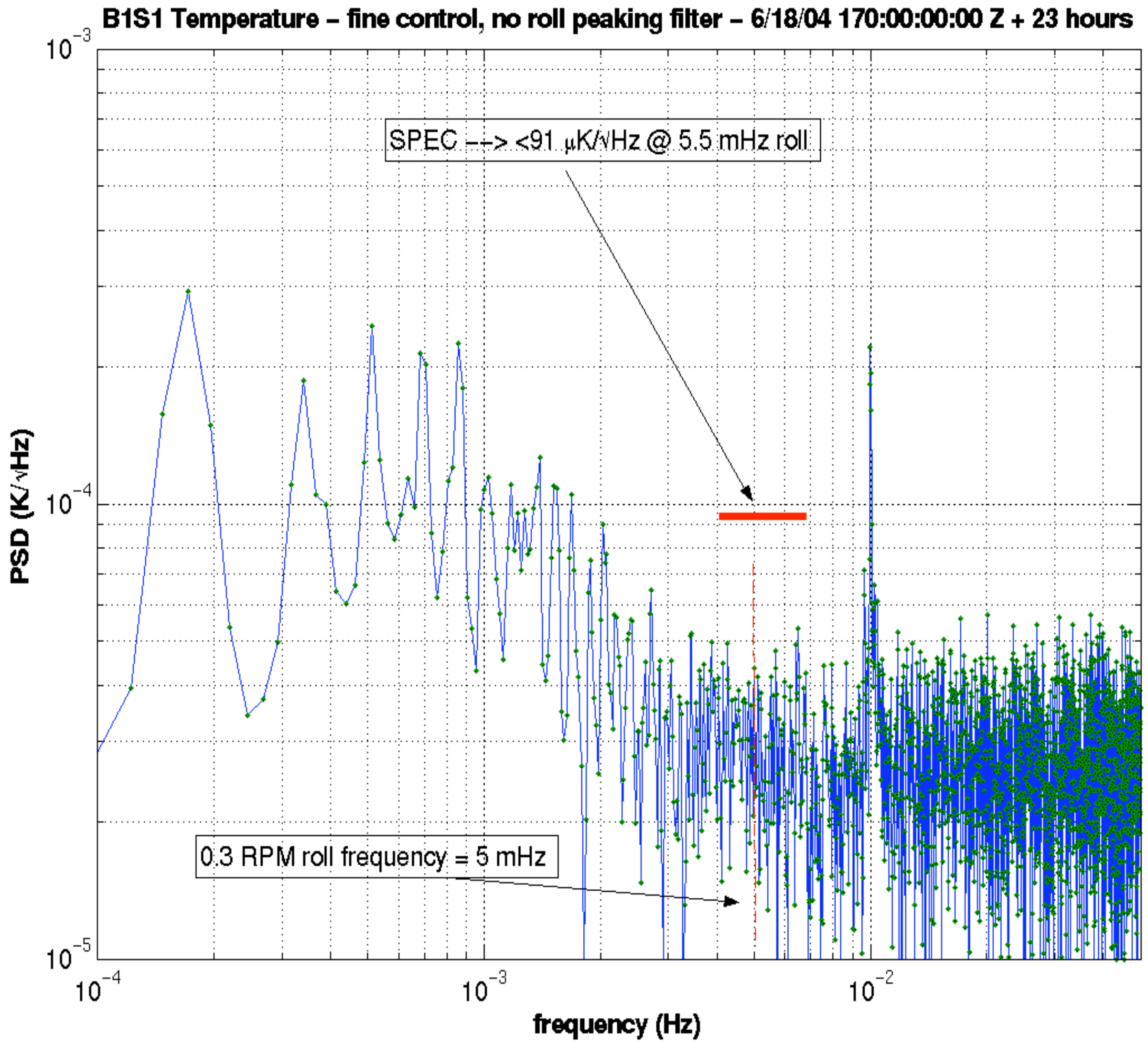


On-orbit SQUID Bracket Temperatures

(sensor 1 in feedback loop, sensor 2 observer)

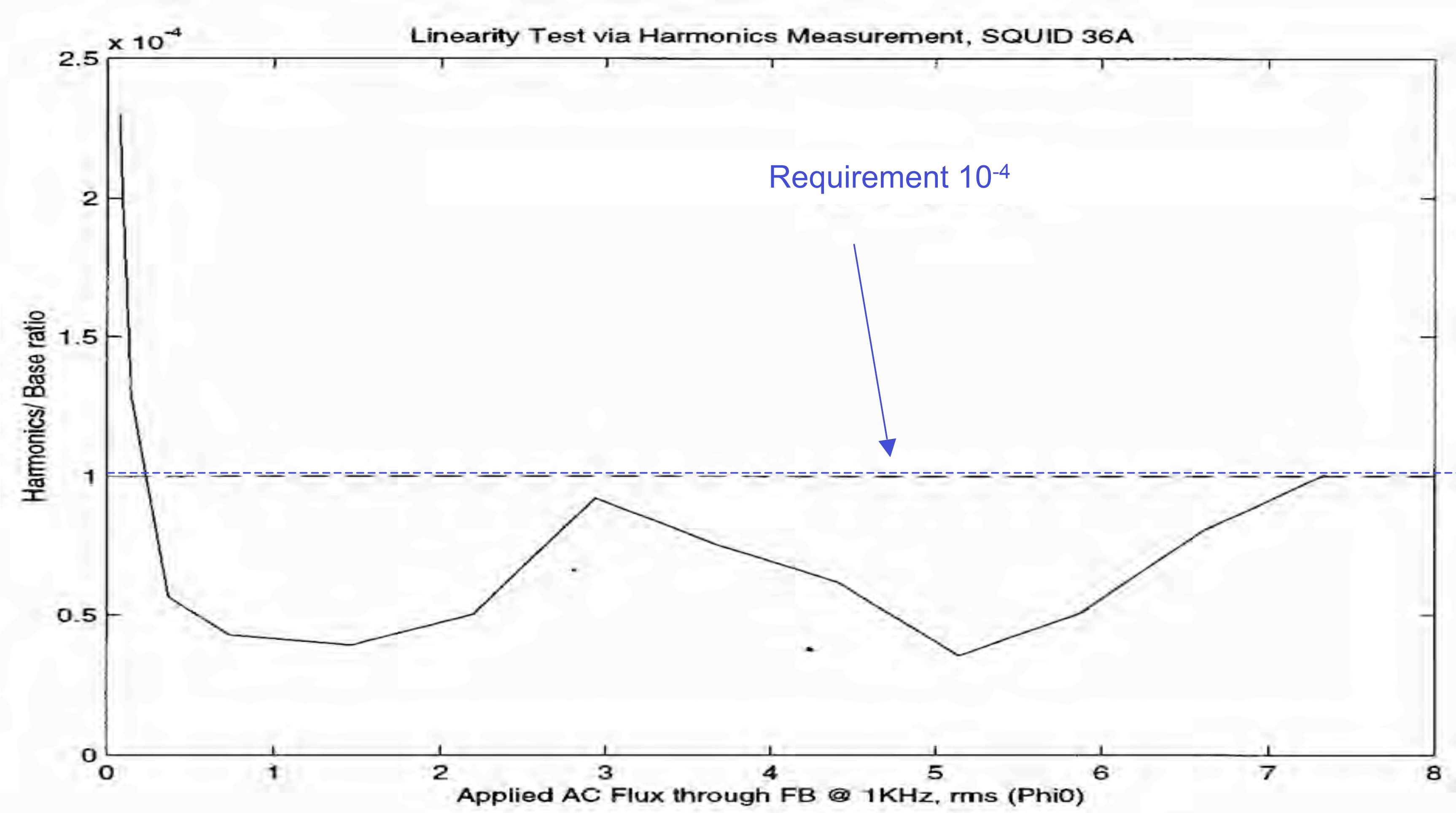


Power Spectral Density of SQUID Temperature



SQUID Bracket Temperature Control < 2 μK in 3 mHz BW about Roll

SRE Ground Test Results: Linearity



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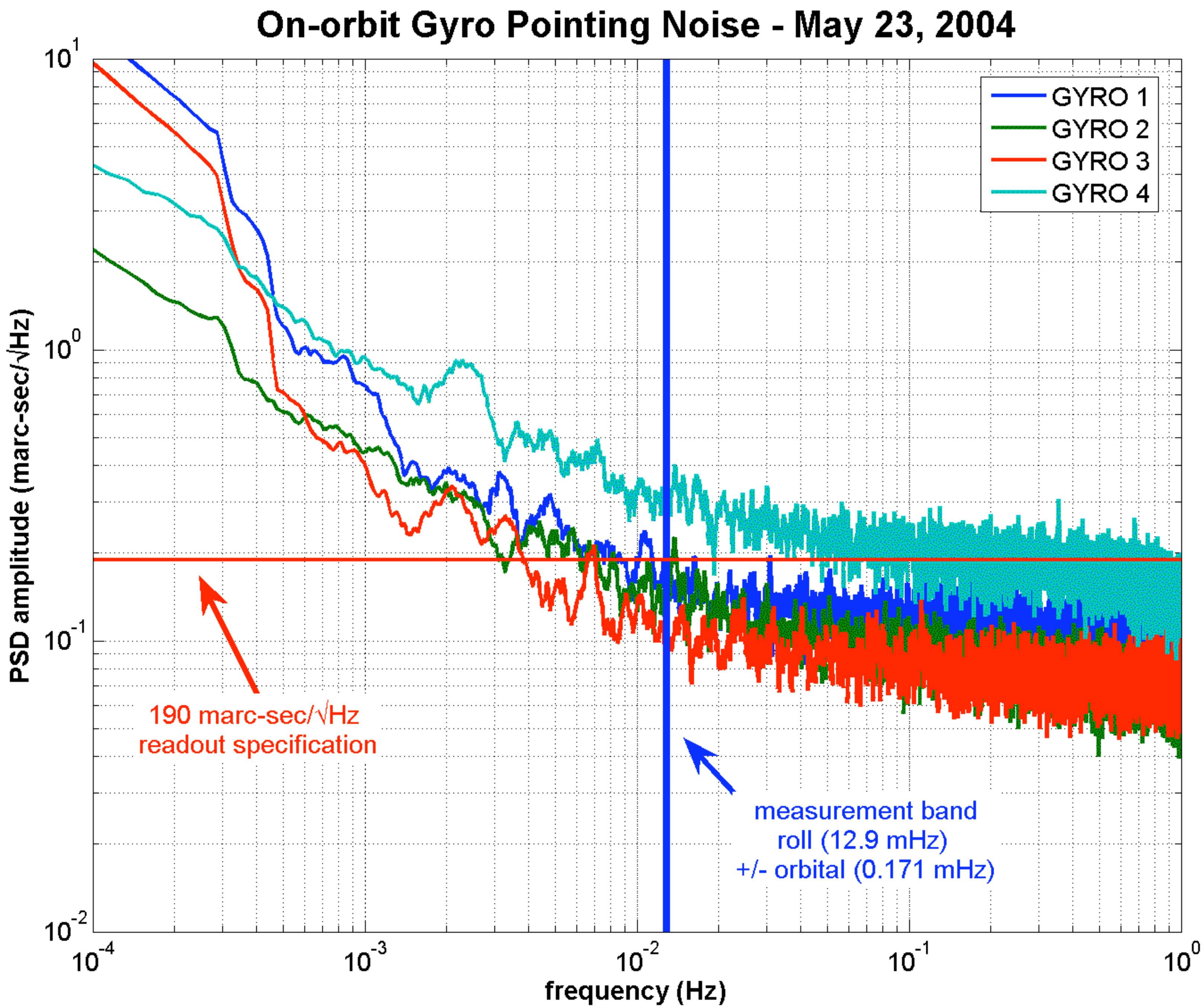
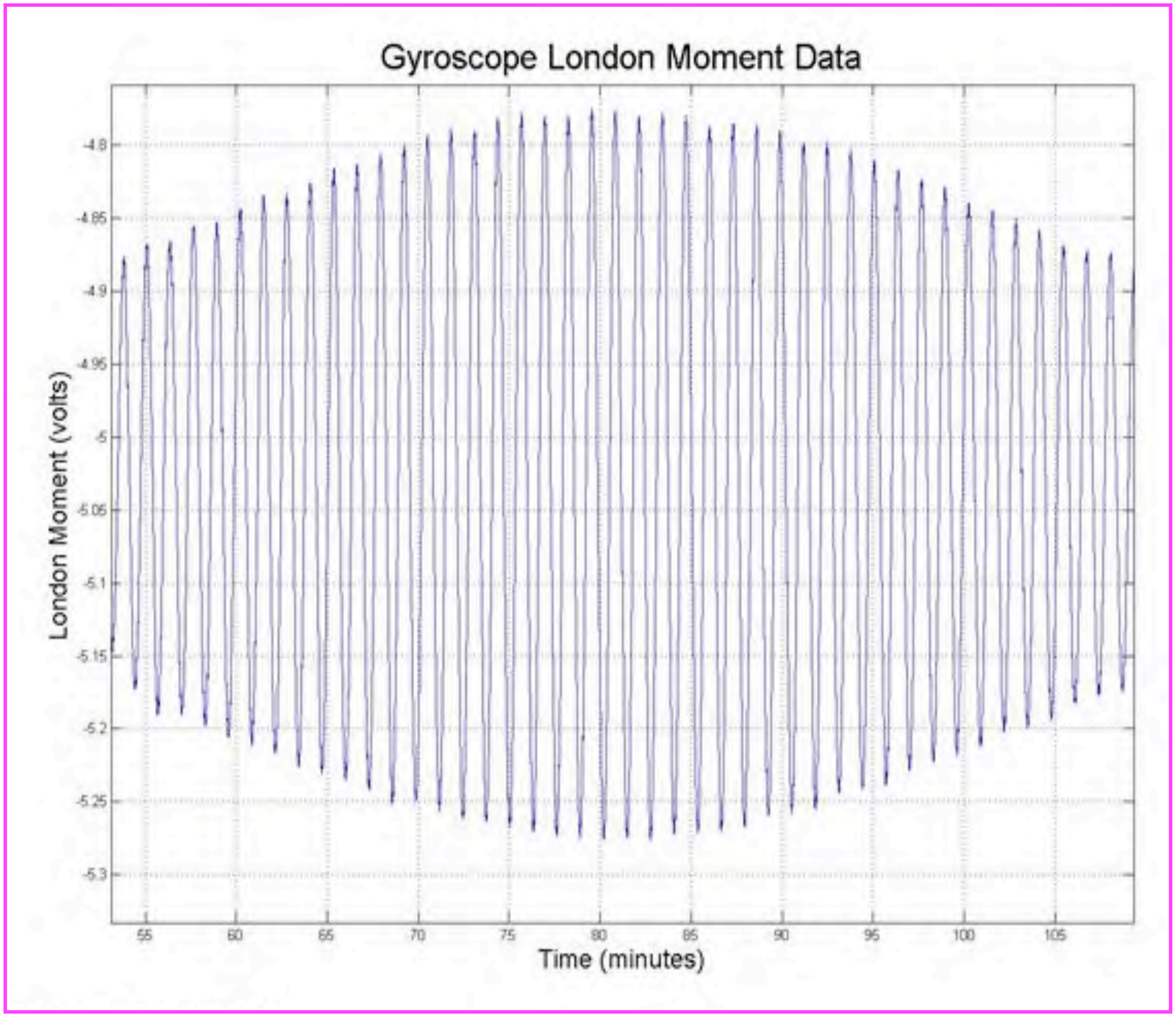

On-orbit Gyro Pointing Noise - May 23, 2004
GYRO 1
GYRO 2
GYRO 3
GYRO 4
PSD amplitude (marc-sec/√Hz)
frequency (Hz)
10^1
10^0
10^-1
10^-2
10^-4
10^-3
10^-2
10^-1
10^0
190 marc-sec/√Hz
readout specification
measurement band
roll (12.9 mHz)
+/- orbital (0.171 mHz)

SRE Flight Data



Peak to peak ~ 24 arc-sec

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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/$\sqrt{}$ 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.

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