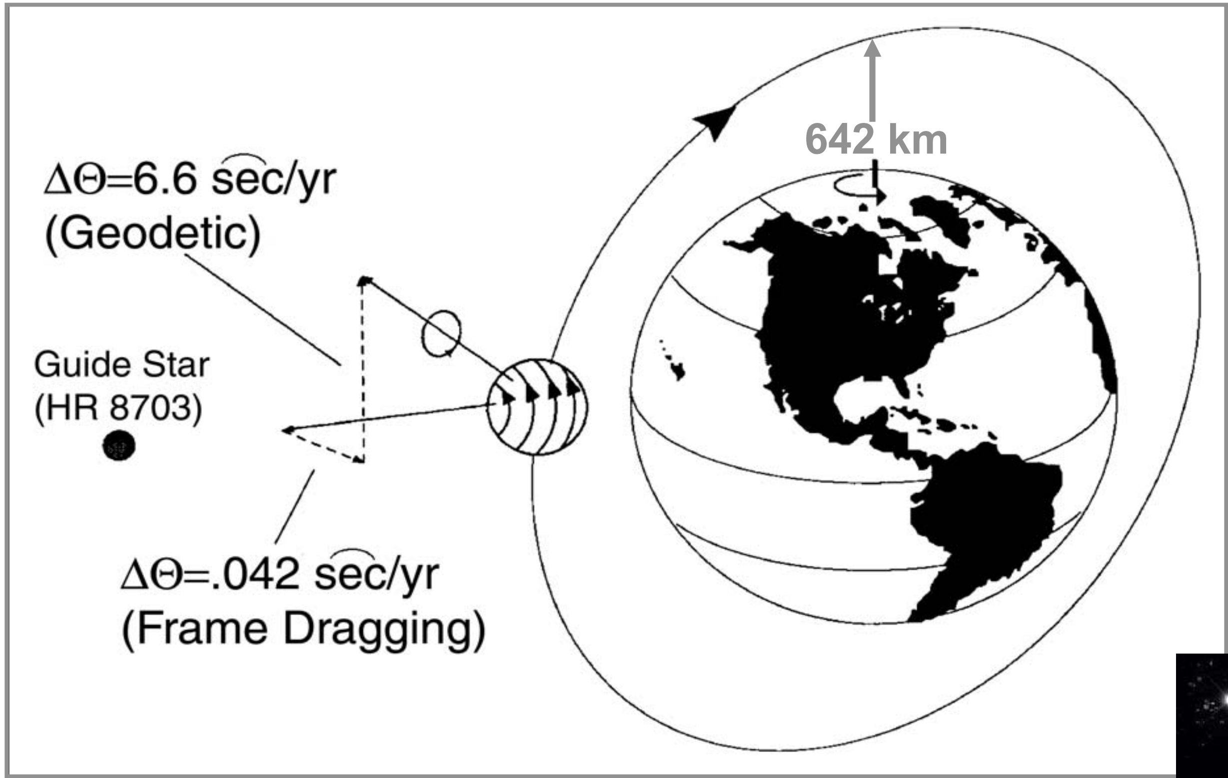
Gravity Probe B

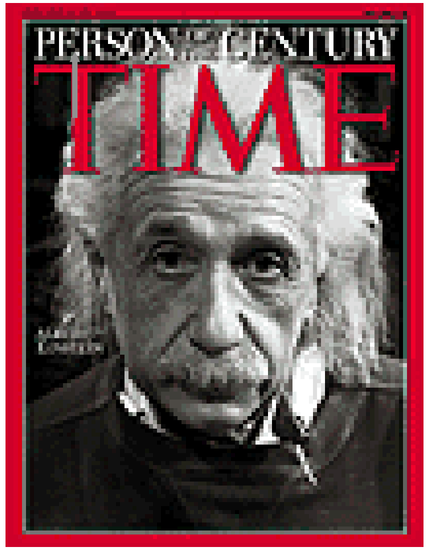
Status Update

Gaylord Green
Stanford University

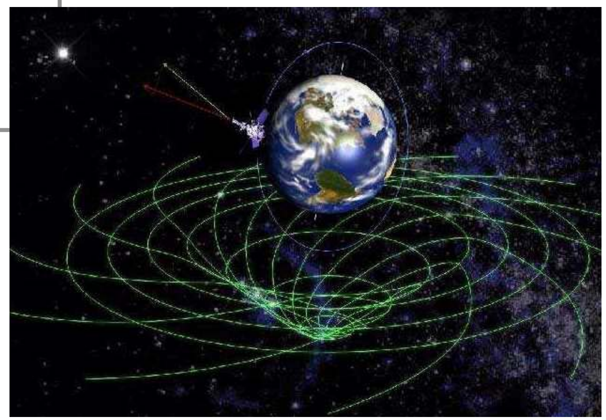
Launch: April 20, 2004 – 16:57:24 UTC

The Relativity Mission Concept

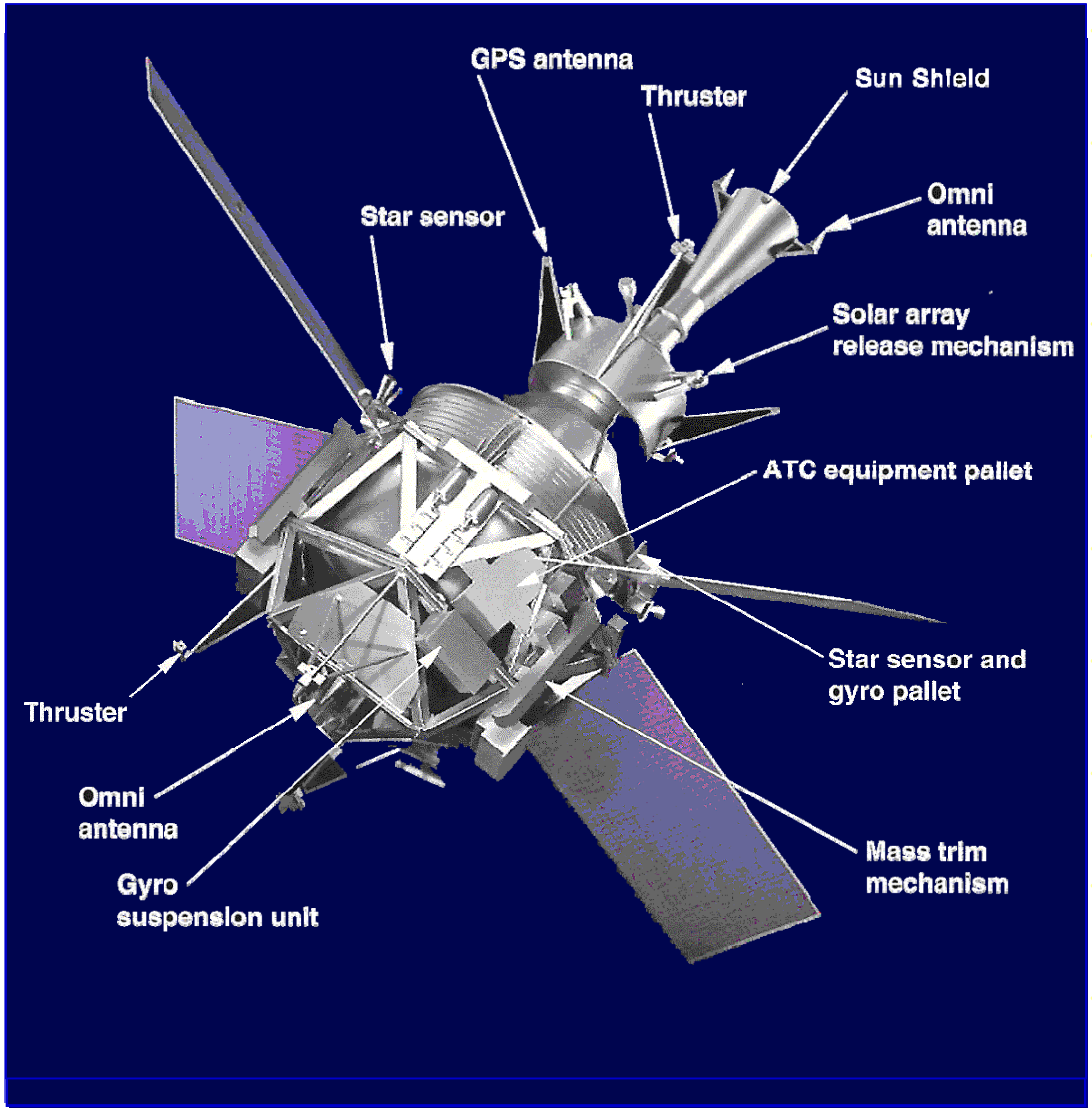




$$\overline{\Omega} = \left(\gamma+\frac{1}{2}\right)\frac{GM}{c^2R^3}\left(\overline{R}\times\overline{v}\right) + \left(\gamma+1+\frac{\alpha_1}{4}\right)\frac{GI}{2c^2R^3}\left[\frac{3\overline{R}}{R^2}\cdot\left(\overline{\omega}_e\cdot\overline{R}\right)-\overline{\omega}_e\right]$$



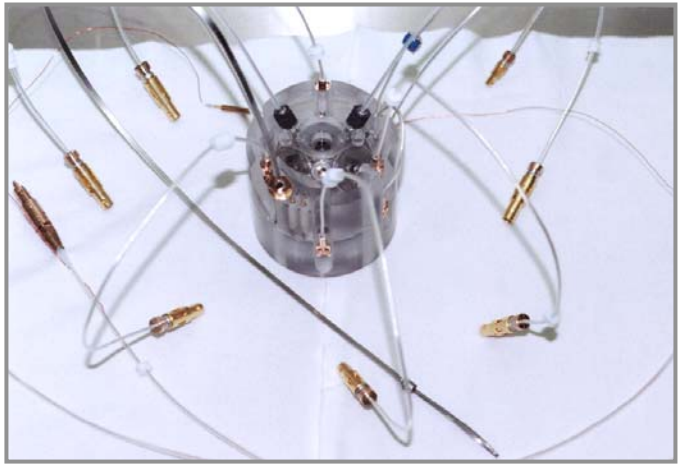
The Overall Space Vehicle

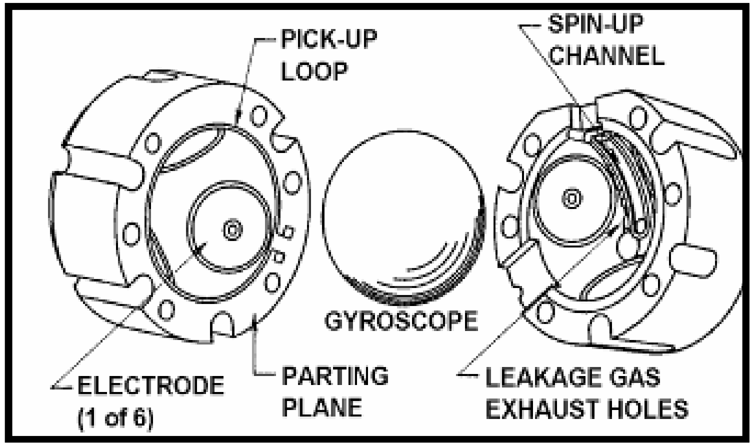


- Redundant spacecraft processors, transponders.
- 16 Helium gas thrusters, 0-10 mN ea, for fine 6 DOF control.
- Roll star sensors for fine pointing.
- Magnetometers for coarse attitude determination.
- Tertiary sun sensors for very coarse attitude determination.
- Magnetic torque rods for coarse orientation control.
- Mass trim to tune moments of inertia.
- Dual transponders for TDRSS and ground station communications.
- Stanford-modified GPS receiver for precise orbit information.
- 70 A-Hr batteries, solar arrays operating perfectly.

GP-B Gyroscopes

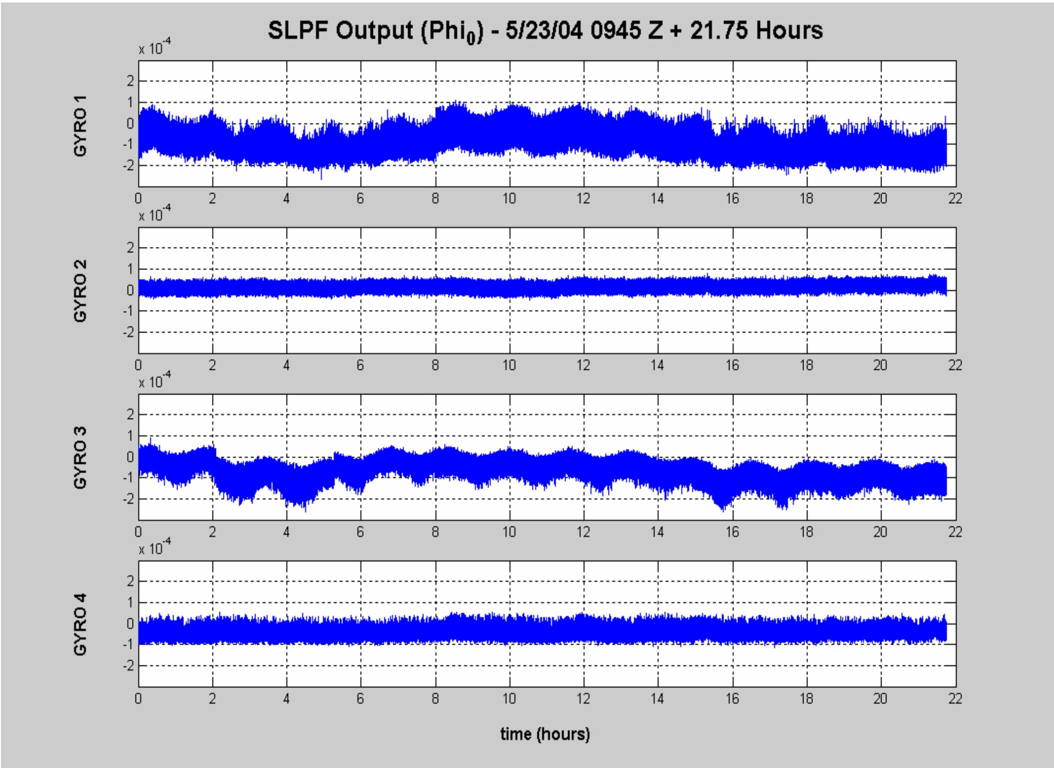
• Fused quartz rotor	$\Delta R/R<10^{-6}$
• Quartz housing	$\Delta R/R<10^{-5}$
• Electrostatic suspension	10^{-9}g - 1 g
• Capacitative positioning	<0.3nm at roll
• He gas spin-up	60-80Hz
• UV charge control	<5 pC
• Low temp. bake-out	$<10^{-11}$ torr
• Spindown	< 20,000 year
• Spin to roll alignment	<1arcsec
• Superconducting read-out	$<0.2\text{arcsec}/\sqrt{\text{Hz}}$

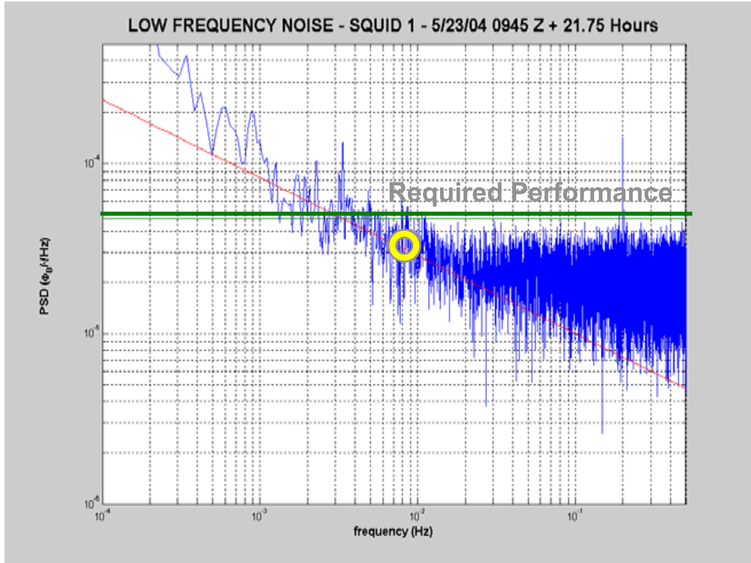


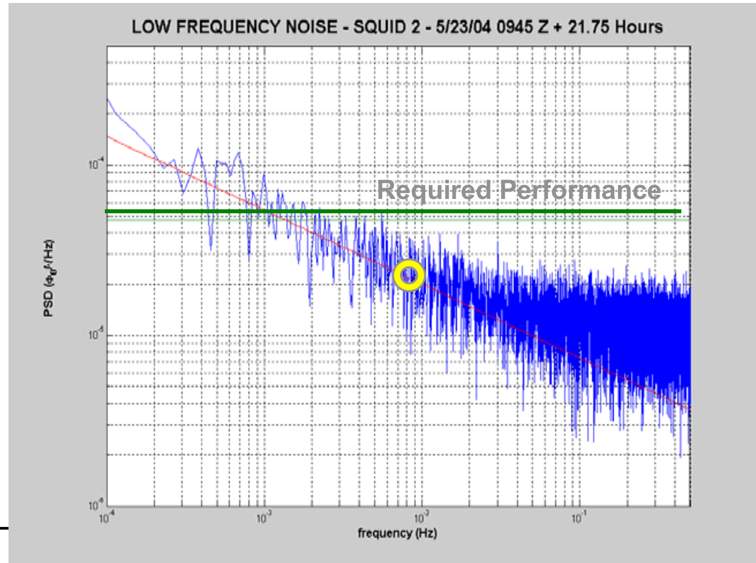


Gyro Readout Performance

Output of SQUID low-pass filter for caged gyros

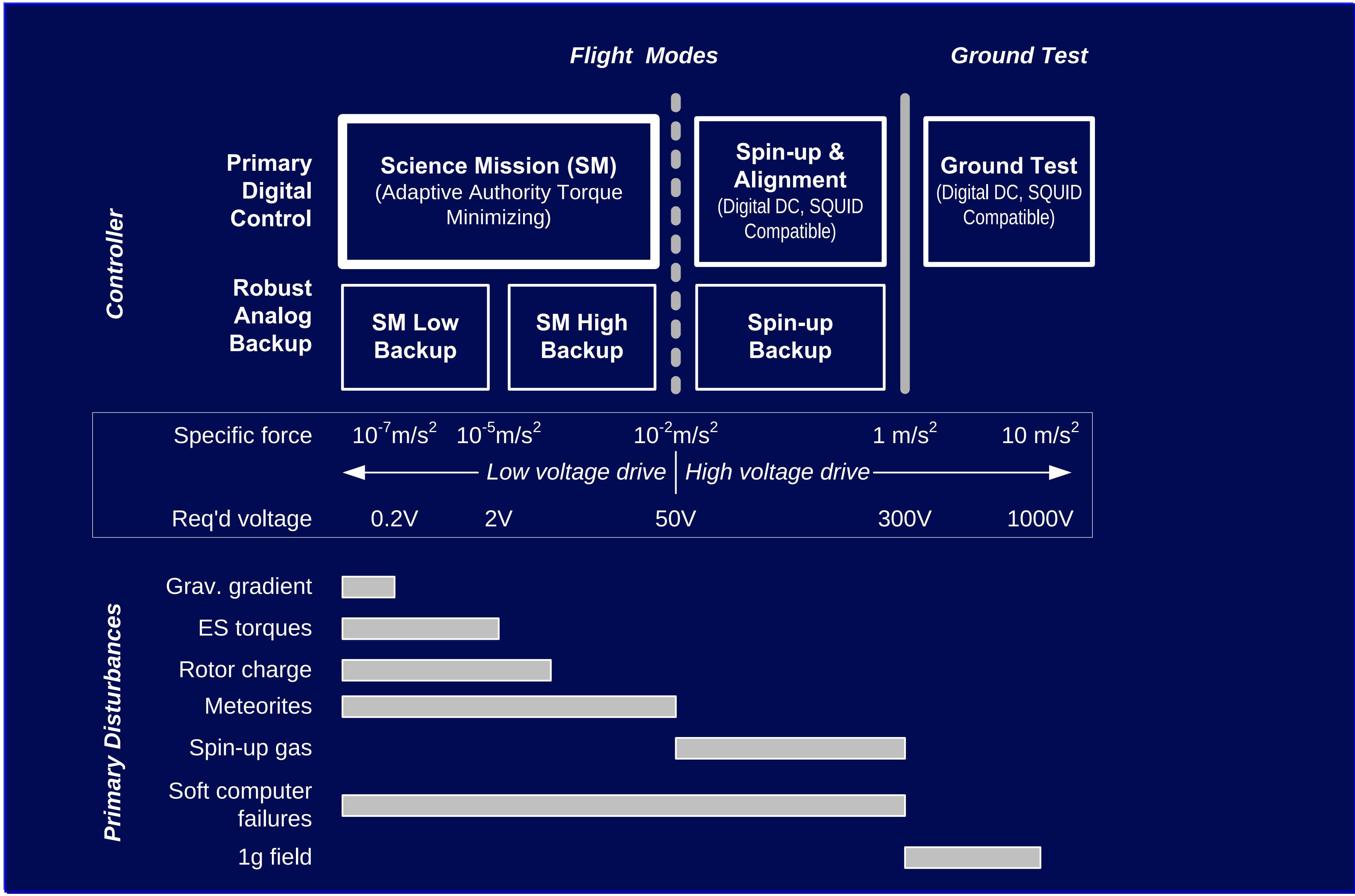






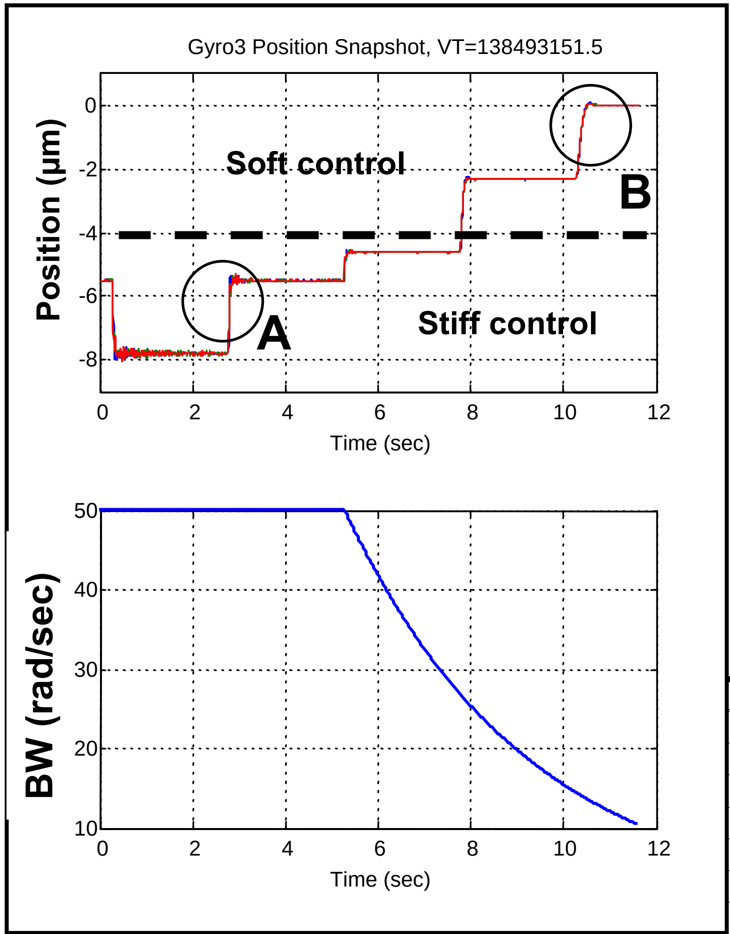
Gyro readout noise < 190 marc-s/Hz$^{1/2}$

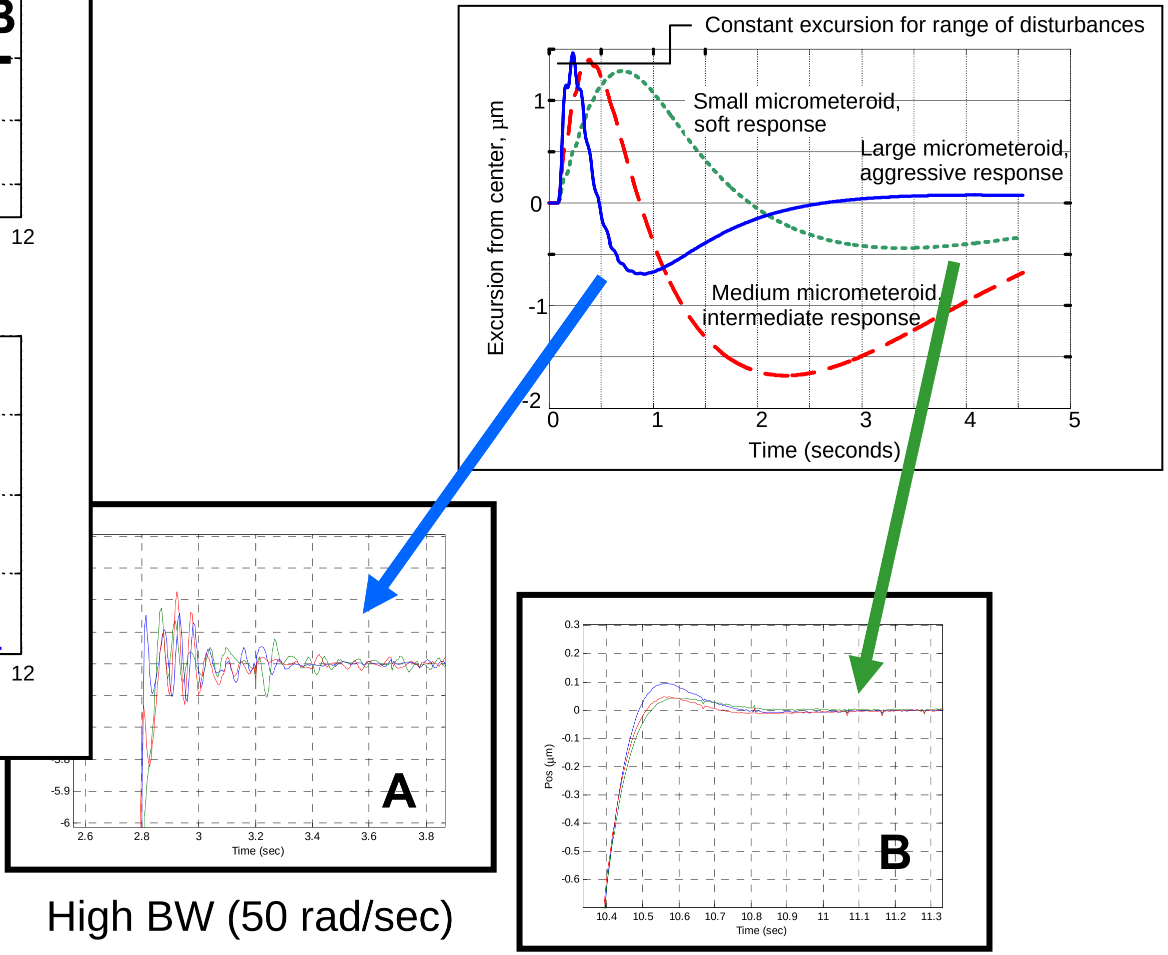
Gyro Suspension System Modes



Variable Authority Gyro Suspension

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





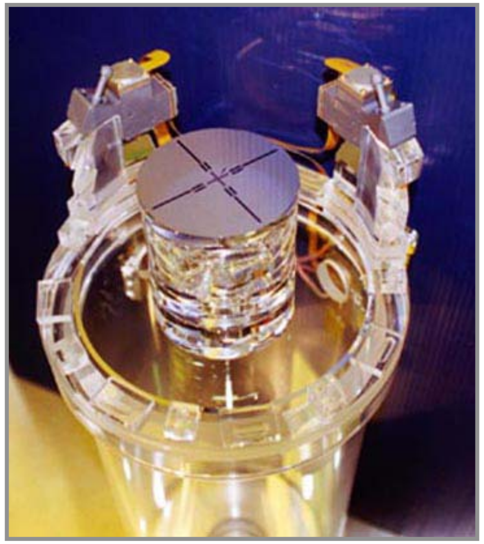
High BW (50 rad/sec)

Low BW (3 rad/sec)

GP-B Telescope

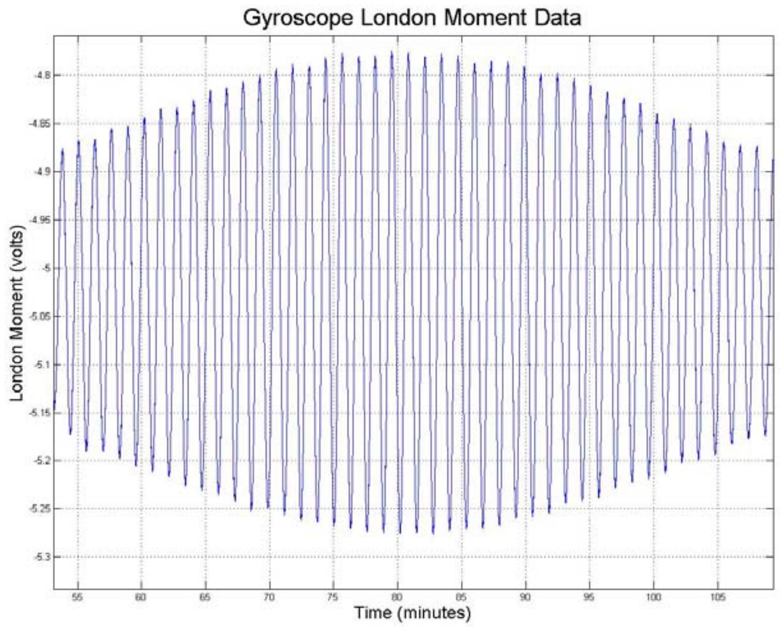
- Folded Schmidt Cassegranian
- 150” focal length, 5.6” aperture
- All quartz construction
- Potassium hydroxide bonding
- Image splitting with roof prisms for quadrant read-out information
- Low temperature read-out using photodiodes and silicon preamplifiers at 70K
- 4 telescope windows with 60% transmission in visible and IR and rf rejection

Detector



Telescope with image divider

Science Data - One Guide Star Valid



Level 1 Data Jun 13,2005 22:23:00 through Jun 14,2005 00:20:00

Data processing:

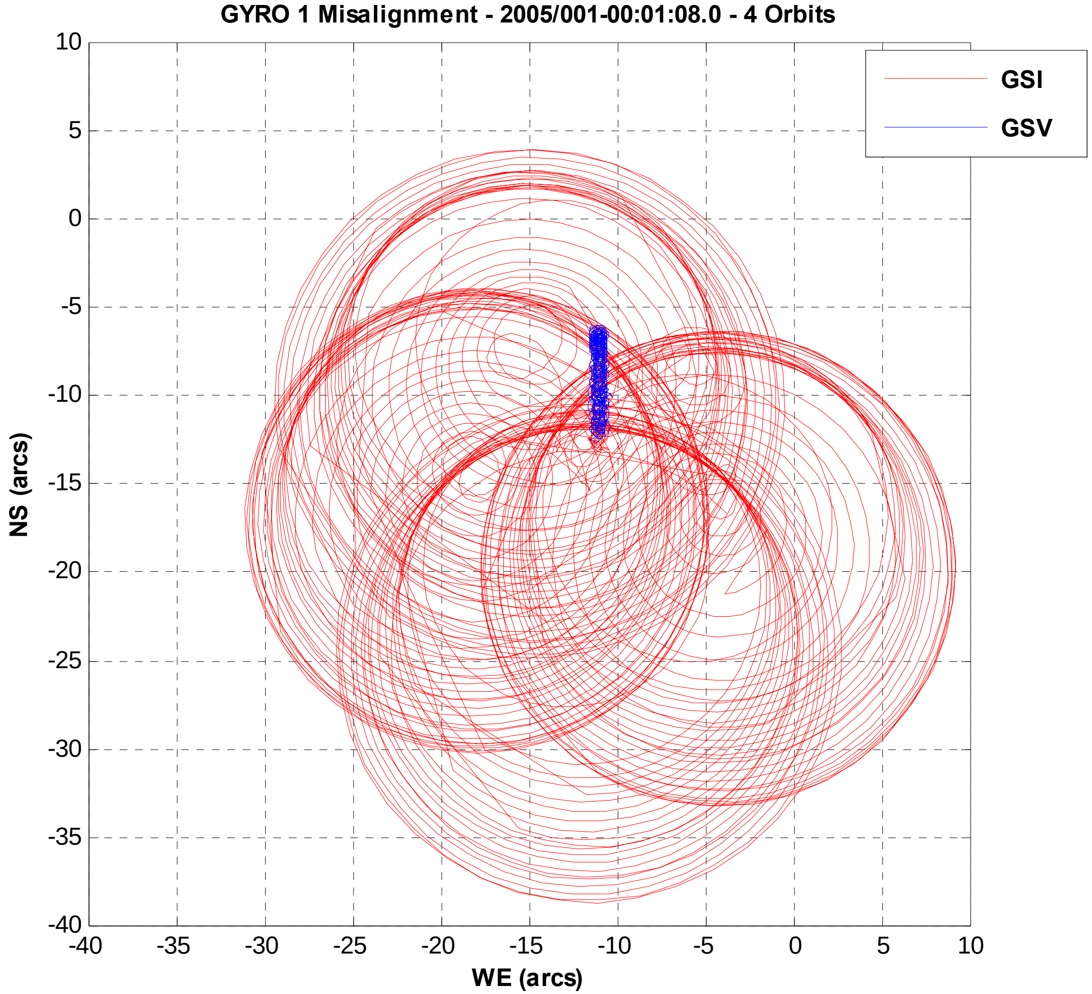
- Remove known (calibrate-able) signals from SQUID signal to get at gyro precession

Remove effects of:

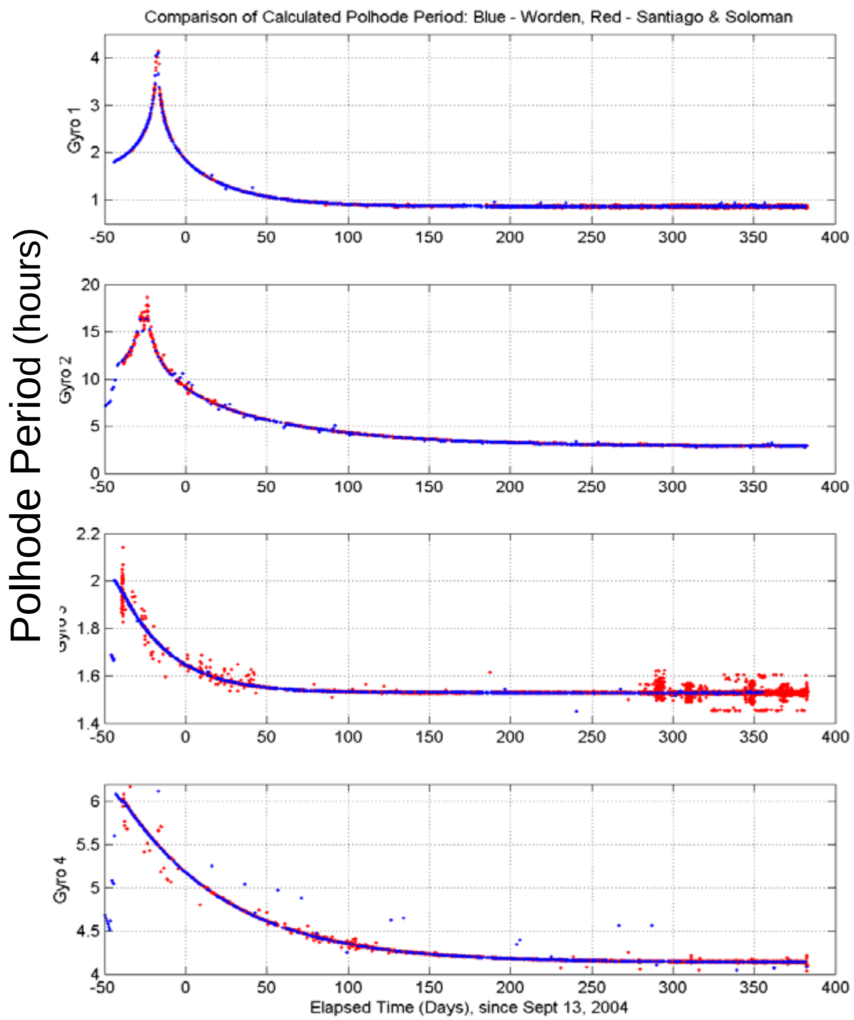
- Motional aberration of starlight
- Parallax
- Pointing errors & roll phase errors
- Telescope/SQUID scale factors
- Pointing dither
- SQUID calibration signal
- Scale factor variation with gyro polhode (trapped flux)
- Other systematic effects

GSV & GSI Pointing III, S/V Coning

- Gyro misalignment in NS/WE coordinates – 4 orbits



Polhode Damping & Spindown



Polhode period histories for each gyro

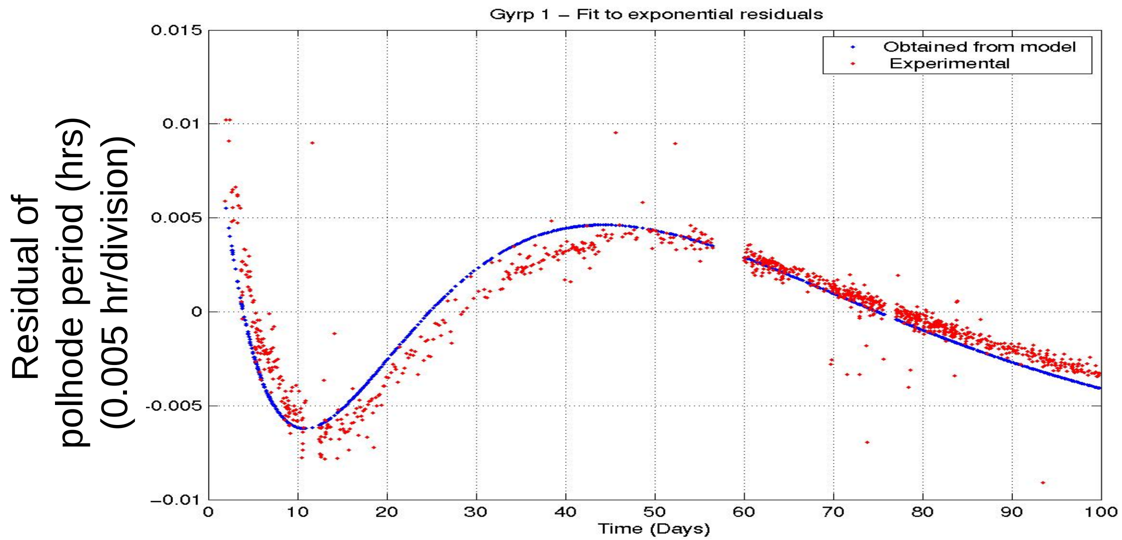
- From two sources:

Red: on-board HF FFT + daily ground processing during mission (polhode modulation of spin harmonics amplitudes)

Blue: ~ 2 million snapshots analyzed after mission

Polhode Damping & Spindown

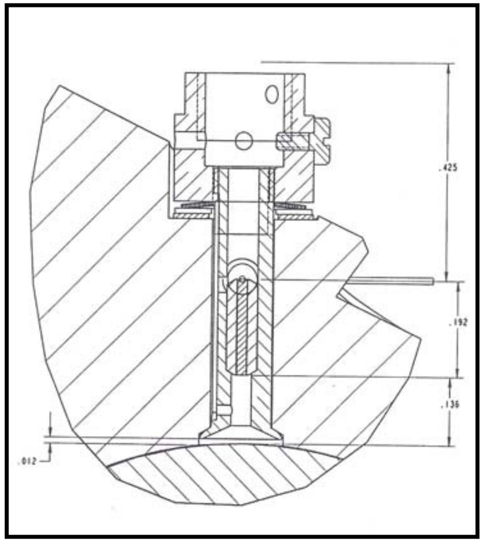
- Polhode-period curves during science very close to exponential
- *Q^2* shown to be responsible for non-exponential behavior
- Two distinct fitting methods give identical *Q^2* – impressive agreement



- Model curve ⟹ one measured (initial) value $T_p^{mes}(0)$ + one fitting parameter (Q^2) + energy dissipation equation
- Difference between experimental & theoretical points < measurement error 1 - 2 mhr

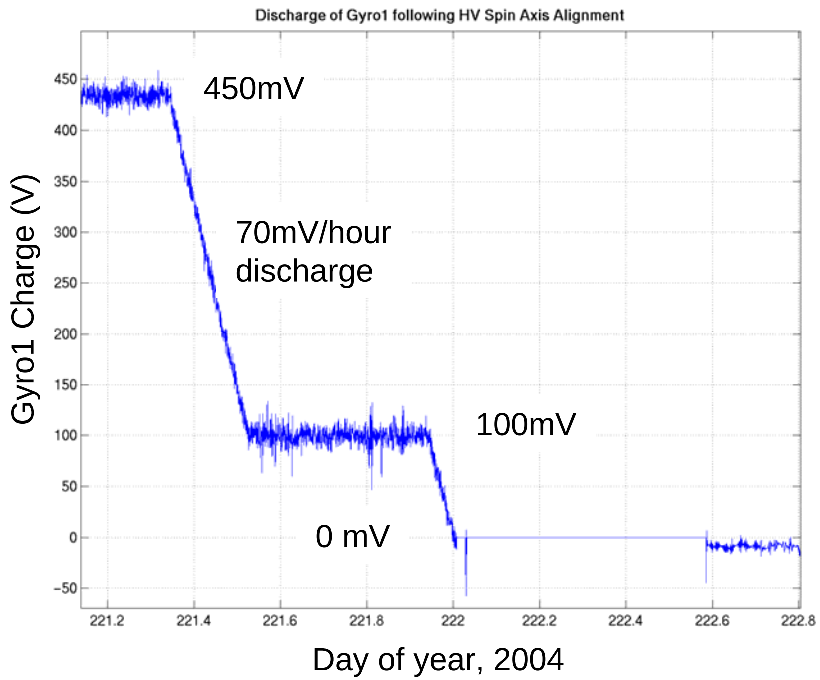
Rotor Electric Charge

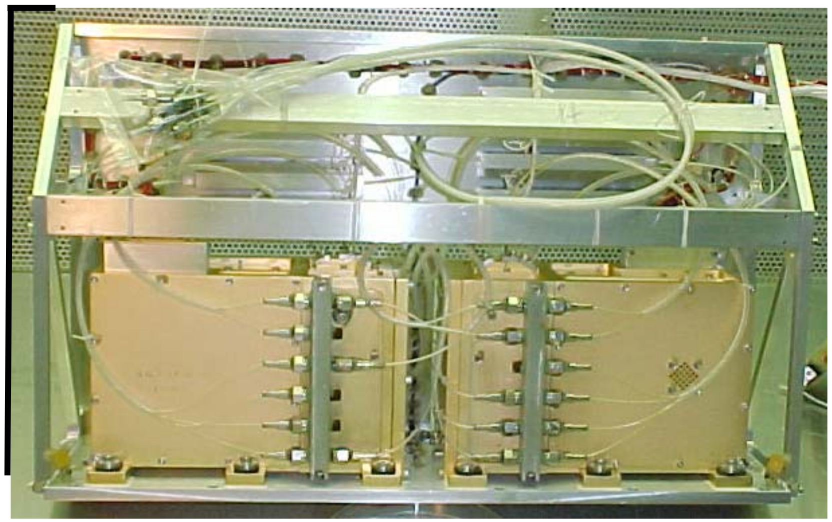
- Rotor charge controlled via UV excited electron exchange with dedicated electrode.
- Charge rates ~ 0.1 mV/day



Ti Steering Electrode

Discharge of Gyro1

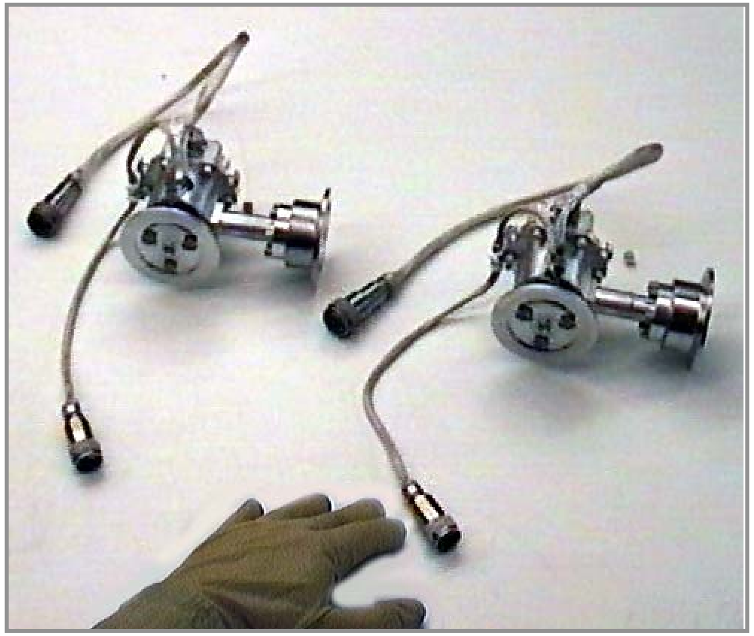


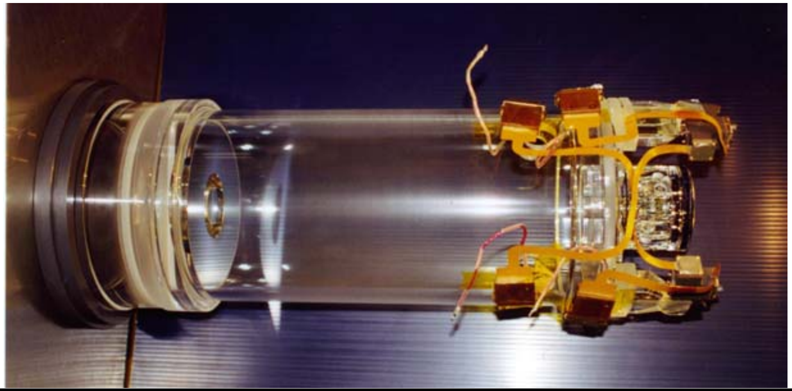


UV Lamp Assembly

Technologies Demonstrated

- **Telescope pointing and mechanical stability**
  - **~ 34 marc-s/√Hz**
- **Ultra-low magnetic fields**
  - **$4x10^{-7}$ gauss**
  - **AC shielding at 10^{-12}**
- **Ultra-high vacuum**
  - **10^{-11} torr**
- **Proportional thrusters for drag-free orbit**
  - **Thrust: 0 – 10 mN& Mdot: 6-7 mg·s^{-1}**
  - **10^{-11} g residual**
  - **Thermal control (Micro K)**
- **Gyro suspension system**
  - **10^9 dynamic range**
  - **< 0.5 nm RMS positioning**
- **Gyro**
  - **Mass unbalance: 10 nm**
  - **Spherical to 10 nm**





3 Stages of In-flight Verification

A. Initial orbit checkout (121 days)
   - **Re-verification of all ground calibrations.**
   - **Scale factors, thermal sensitivities, etc.**
   - **Disturbance measurements on gyros at low spin speed.**

B. Science Phase (~ 11 months)
   - **Exploiting the built-in checks (i.e. Nature's helpful variations).**

C. Post-experiment tests (~ 1 month starting Aug 2005)
   - **Refined calibrations through careful and deliberate enhancement of disturbances, etc.**

Mission Operations Center (MOC) at Stanford University

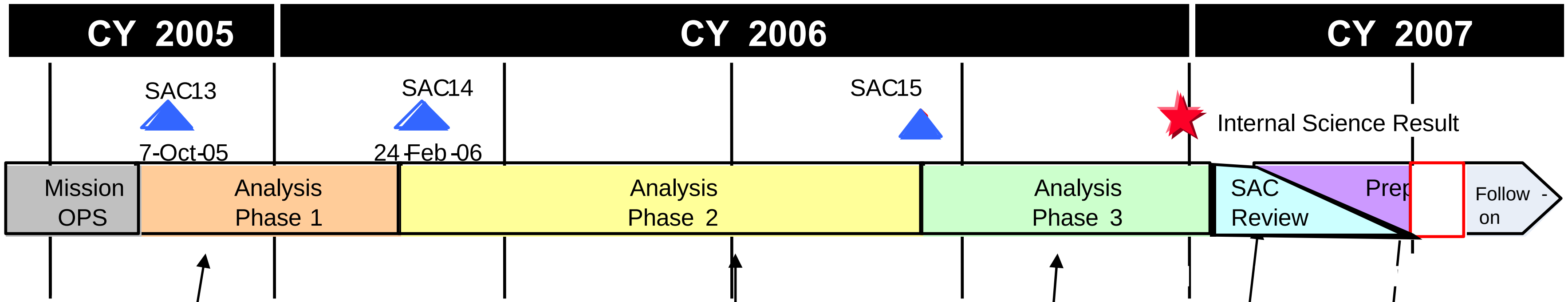
Science Data Statistics

More than 99% (1.13 Terabytes) of science data stored & available for analysis

Gyro	Total Days	Computer Reboots	Vehicle Mispointing	ECU Noise	Other	**Net Days**
1	353	8	6	5-18	4	**317-330**
2	323	8	6	4	9	**296**
3	323	8	6	6-24	9	**275-293**
4	338	8	6	3	4	**317**

- Computer Reboots: *affects all gyroscopes; reboots define segments*
- Vehicle Mispointing: *SAA telescope interference & long guide star acquisition*
- ECU Noise: *Science data interference ⇒ removed by frequency separation*
- Other: *Calibrations, missing data, etc.*

GP-B Data Analysis Schedule



Phase 1 – "Local" data Analysis

- ✓ Short-term daily orientations.
- ✓ Data grading.
- ✓ Instrument calibrations.
- ✓ Core analysis tool development.
- ✓ Simple truth modeling.

Phase 2 - ID Systematic effects

- ✓ Orientation by logical "batch" – 75 orbits
- ✓ ID time-dependent scale factors.
- Modeling
- ✓ Add systematics into data analysis
- ✓ Add'l grading, truth modeling.

Phase 3 – 4 gyros over a year

- Combine all gyros with using best data, models – internal science results.
- Fully vet systematic error sources.

Peer Review

- Critical review by SAC, other invitees.
- Combine guide star motion data.
- Refine data analysis.

Announce and Publish Results

- Prepare scientific and engineering papers and data release to scientific community.
- Prepare public presentation of results.

Results will be published April 2007 at the April APS meeting (Jacksonville, Florida, USA

Visit the GP-B web site for more information

http://einstein.stanford.edu

Center for Position, Navigation and Time
GPS
Atom Interferometer Inertial Sensors