The Gravity Probe B Science Instrument

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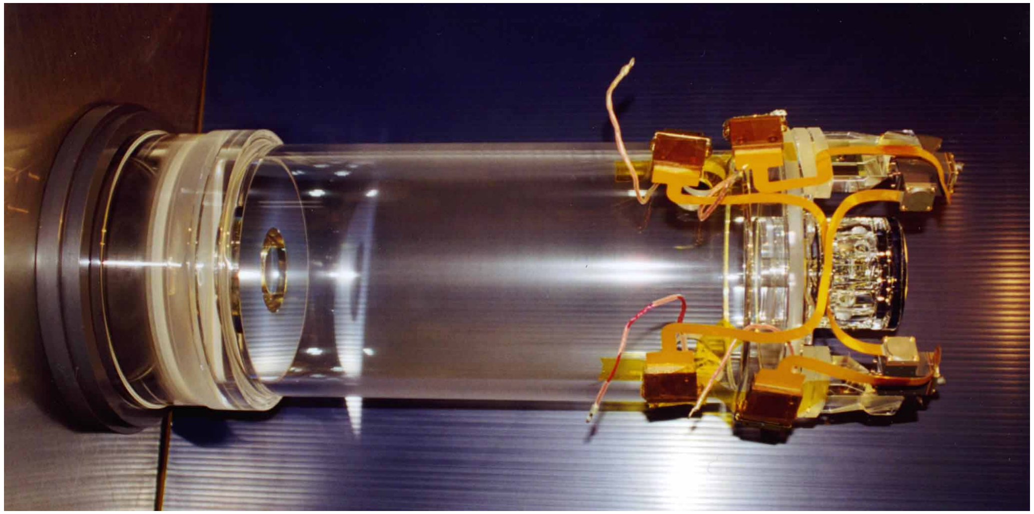

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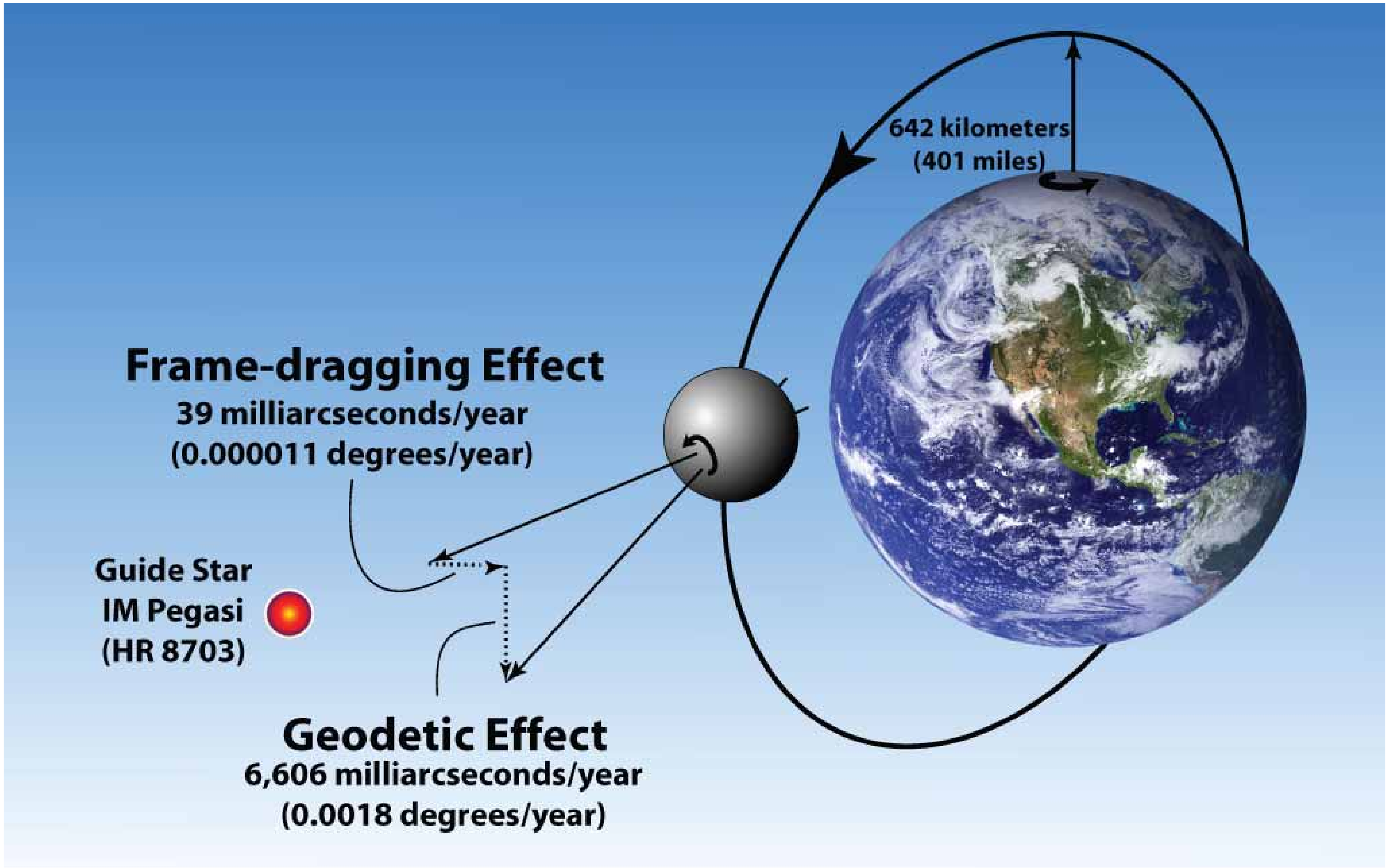
- Lockheed Martin
  - Vacuum probe and superfluid helium dewar
- Support from many other individuals at various institutions
- GP-B funded and supported by NASA

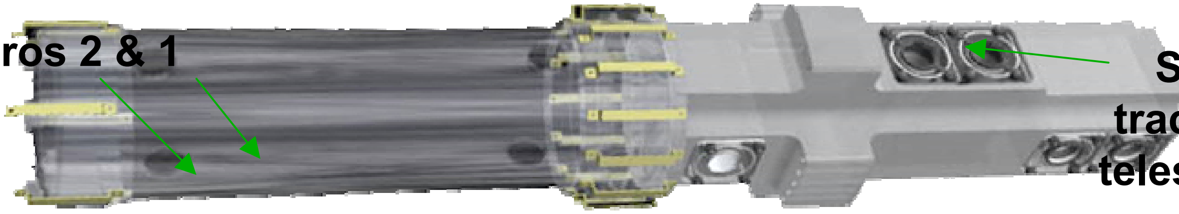
The Gravity Probe B Experiment



Instrument Concept

Operates at ~ 2.5 K

Guide star
IM Pegasi



Gyros 2 & 1

Star
tracking
telescope

Fused
quartz
block

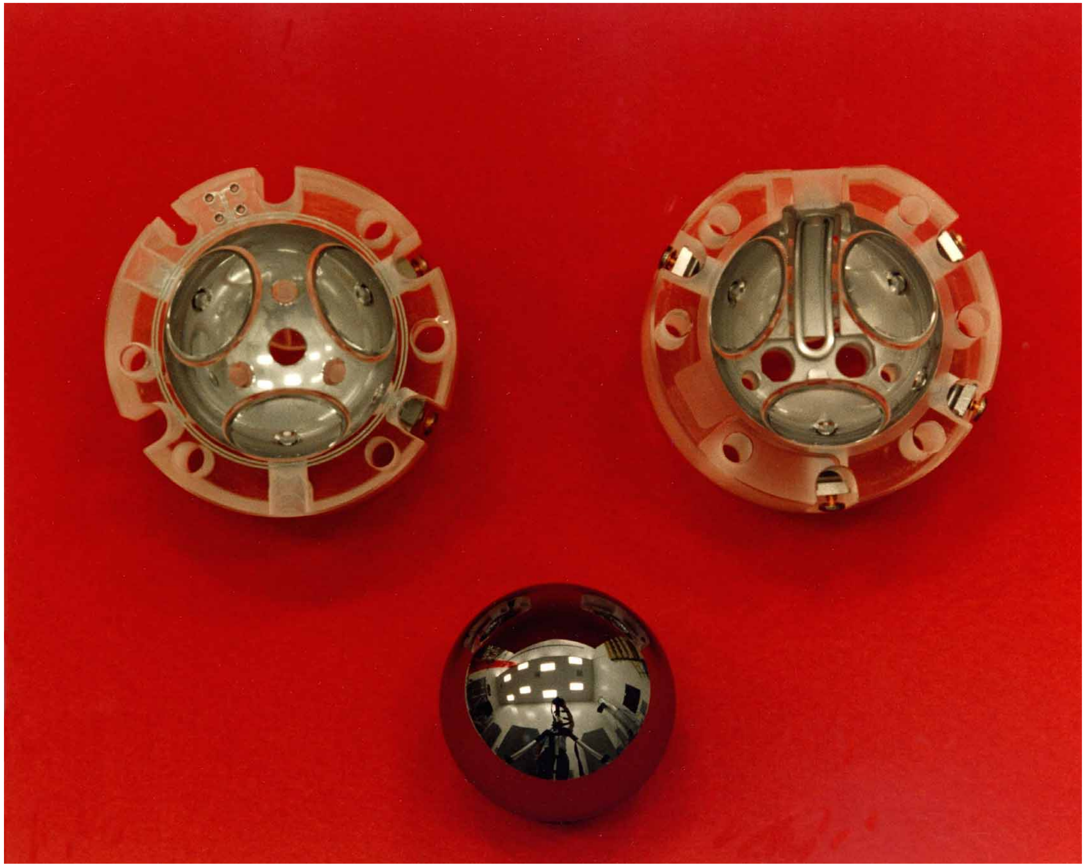
Gyros 4 & 3

Mounting
flange

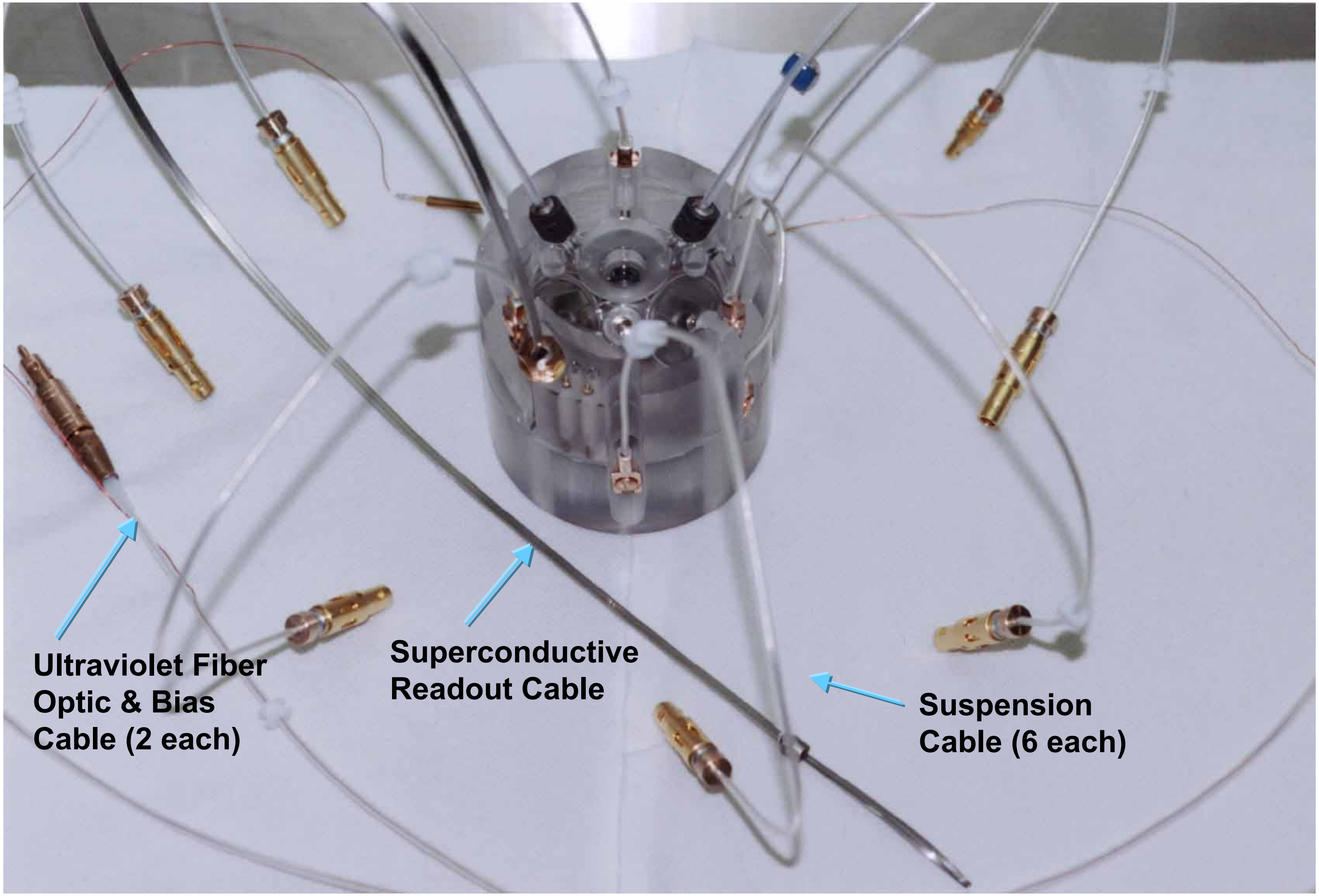
Rolls about line of sight to Guide Star
- Inertial pointing signal at roll frequency
- Averages body-fixed classical disturbance torques toward zero
- Reduces effect of body-fixed pointing biases

Fused-Quartz Gyroscope

- 38 mm diameter fused quartz rotor
  - Mass unbalance < 50 nm
  - Asphericity < 25 nm
- Fused quartz housing
  - 6 circular suspension electrodes
  - 4 turn superconducting pickup loop
  - He gas spinup channel
  - UV electric discharge system
    - Rotor charge < 15 pC
  - Other internal surfaces with grounded coating



Assembled Gyroscope



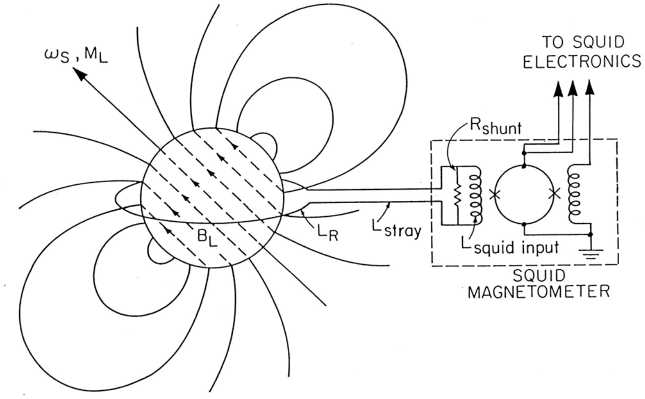
Ultraviolet Fiber Optic & Bias Cable (2 each)

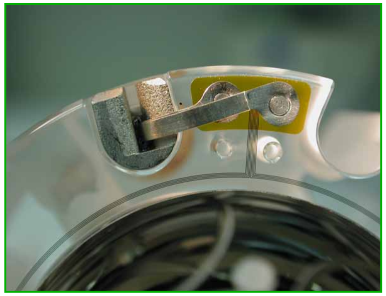
Superconductive Readout Cable

Suspension Cable (6 each)

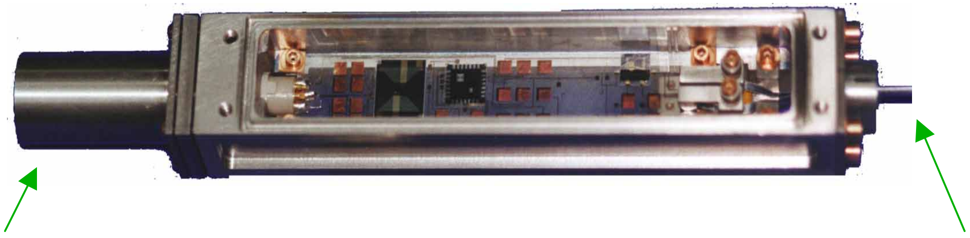
DC SQUID Readout

- London magnetic dipole moment aligned with spin
  - Property of spinning superconductor
  - 57 μG at 80 Hz
- Resolve 1 marc-sec in 10 hours
  - Noise < 190 marc-sec/√Hz
- Trapped magnetic flux contributes to readout scale factor
  - Varies at polhode period
  - Trapped flux < 9 μG
- Magnetic shielding system
  - Residual field < 9 μG
  - Attenuation of external fields < 2×10^{-12}





Detail of readout loop and connection to superconductive cable



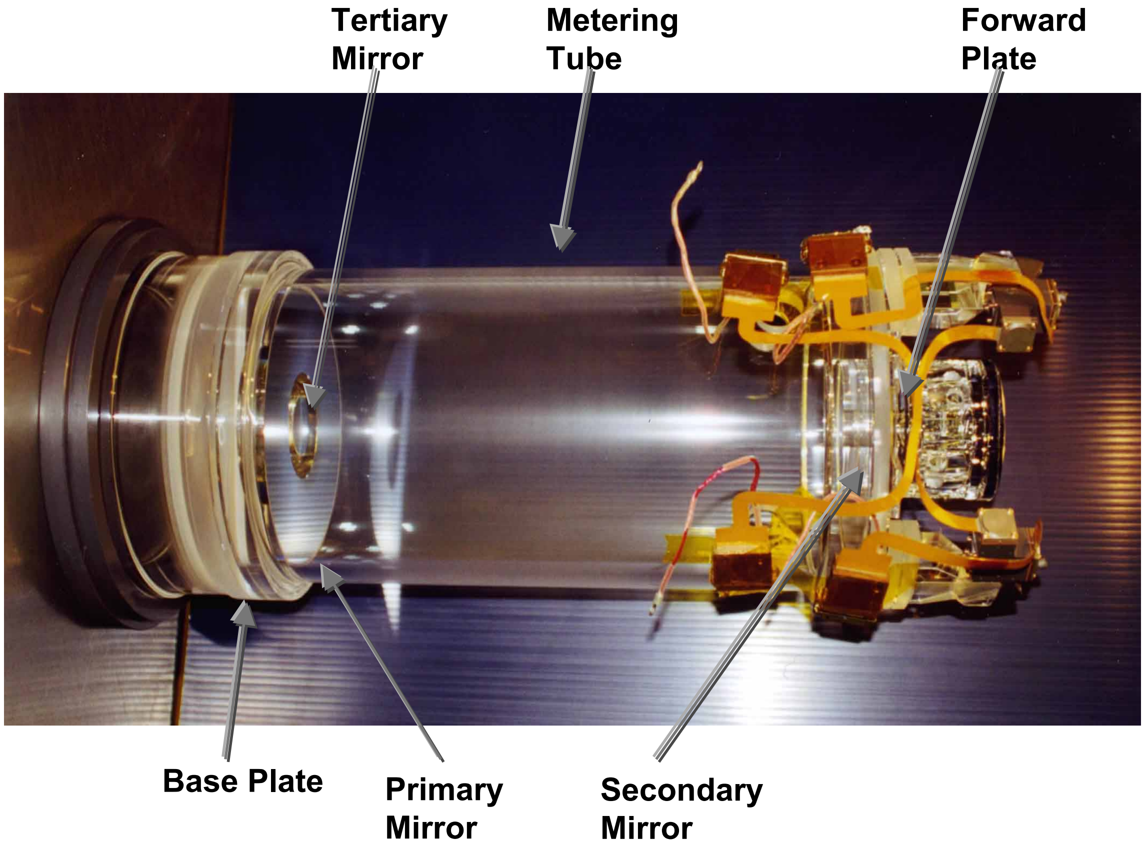
Output to SQUID readout electronics

DC SQUID Package

Input from pickup loop

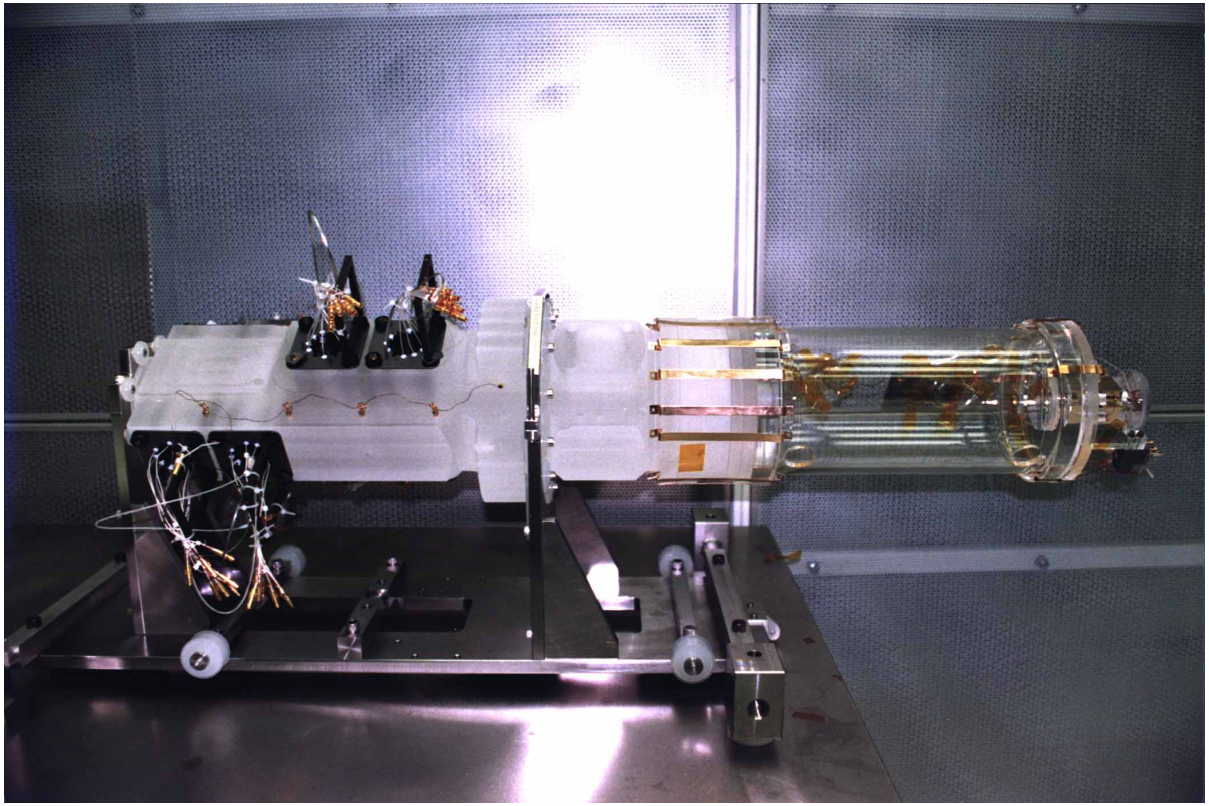
Star-Tracking Telescope

- All fused quartz construction
  - Physical length: ~ 35 cm
- Optical characteristics
  - Focal length: 3.9 m
  - Aperture: 14 cm
- Readout noise
  - < 34 marc-sec/√Hz
- Pointing accuracy
  - < 0.1 marc-sec



Science Instrument Assembly

Fused quartz block serves as metrology bench for the telescope and gyroscope readout



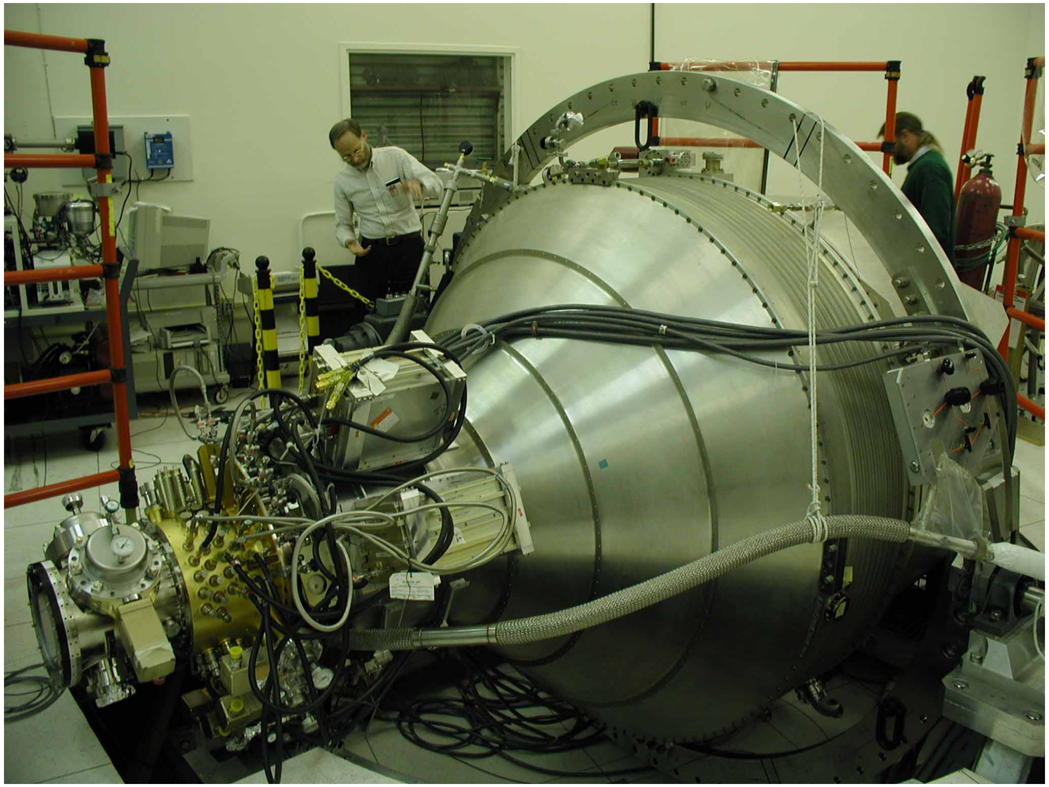
~ 1 m

Vacuum Probe

- Science instrument assembly located in aluminum vacuum can, which is at ~ 2.5 K
- Set of 4 windows for telescope to observe Guide Star
    - Vacuum close out
    - Reduce thermal radiation from top of probe which at the external ambient temperature of the dewar
- Incorporates low-temperature ultrahigh vacuum bakeout
    - $< 10^{-11}$ torr after bakeout
- > 200 cables to connect ambient electronics to low temperature instrument

Superfluid Helium Dewar

- Long lifetime helium dewar
  - ~ 2400 l of superfluid helium
  - > 16.5 months
- Incorporates superconducting lead bag
  - ~ 0.1 μG gyroscope region
  - Major contributor to attenuation of external fields



Space Vehicle

“Near Zero” Requirements

“Near zero” technologies were developed by GP-B

Little or no flight or laboratory heritage prior to GP-B

- Fused-quartz gyro rotor: 38 mm dia. sphere
  - Center of geometry – center of mass < 50 nm
  - Asphericity < 25 nm asphericity
- Gyro rotor electrical charge control
  - Gyro charge < 15 pC
- London moment gyro readout with DC SQUID
  - < 190 marc-sec/√Hz at roll frequency

“Near Zero” Requirements

- Magnetic shielding system
    - Ambient field at gyros < 9 μG
    - Attenuation of external fields $< 2\times10^{-12}$
- Trapped flux in gyroscope rotors
    - Dipole equivalent field < 9 μG
- Low-temperature star-tracking telescope
    - Pointing knowledge < 0.1 marc-sec
    - Pointing noise of < 34 marc-sec/√Hz
- Instrument vacuum probe
    - Vacuum $< 10^{-11}$ torr with low-temperature UHV bakeout

“Near Zero” Requirements

- Superfluid helium dewar
    - Hold time of > 16.5 mo.
    - Superconducting lead bag with 0.1 μG region for gyros
- Drag-free space vehicle
    - Average acceleration transverse to roll axis < 10^{-11} g
- Attitude control of space vehicle
    - Point toward Guide Star to < 20 marc-sec

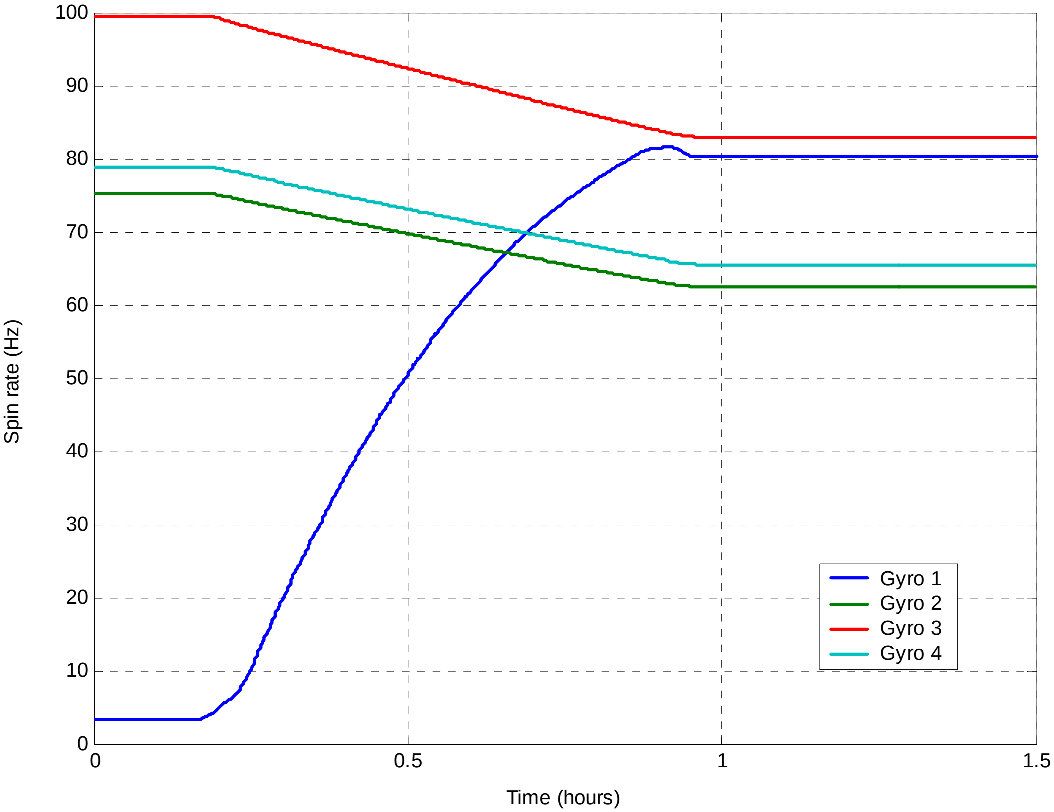
The performance of these technologies were verified by ground test or in some cases by simulation & analysis before flight

ON-ORBIT PERFORMANCE

He Gas Spinup

Final Spin Speeds	
Gyro #	Spin Speed (Hz)
1	79.3888
2	61.8189
3	82.0958
4	64.8520

Performed low-temperature UHV bakeout after the final gyro spinup

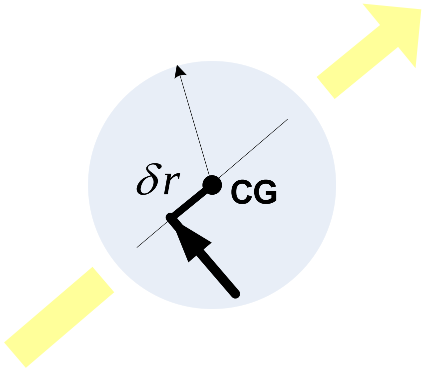


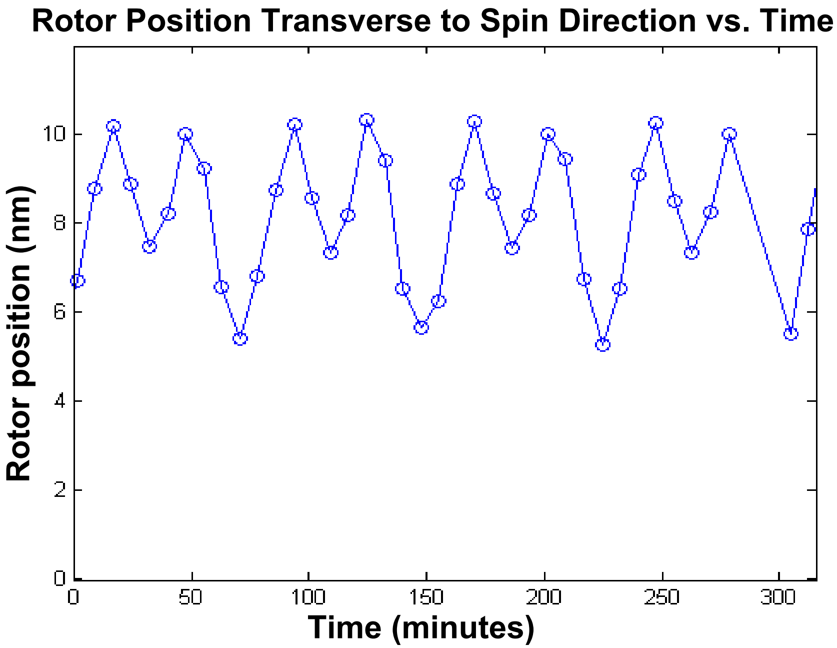
- Gyroscopes spun freely for the rest of the mission
- Residual He gas pressure < 10^{-13} torr

Gyroscope Mass Unbalance

Mass Unbalance (nm)		
Gyro #	Pre-Flight Estimate	On-Orbit Data
1	18.8	10.2
2	14.5	6.6
3	16.8	4.0
4	13.5	8.9

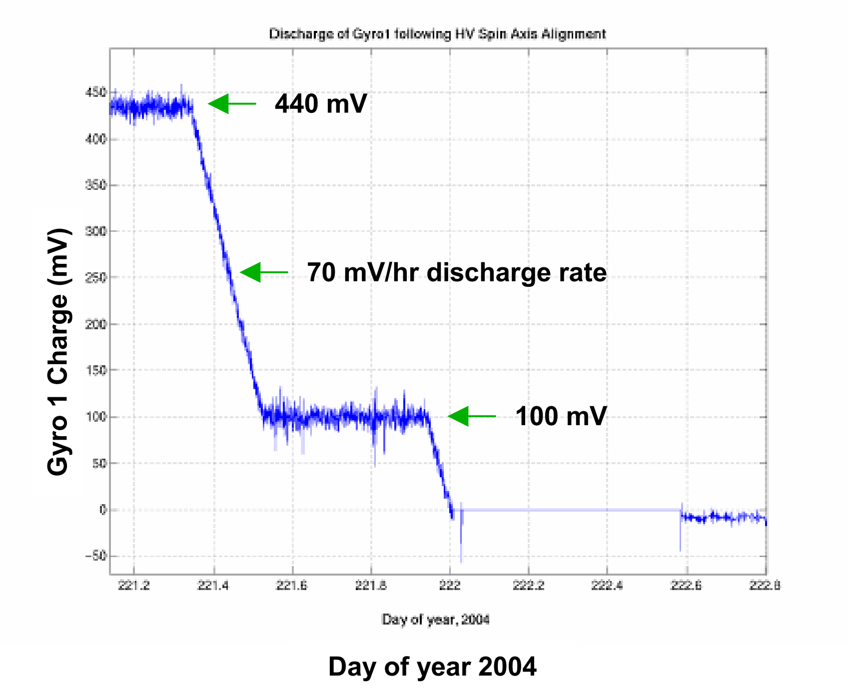
On-orbit measured mass unbalance much better than 50 nm requirement





Gyroscope Charge Control

- Charge control
  - Remove initial charge
  - Remove charging due to particle radiation
    - ~ 0.1 mV/day
- Charge measured with the gyro suspension system
- Gyro charge controlled by UV photo emitted electrons
- Charge control is bi-polar by applying voltage to a small electrode



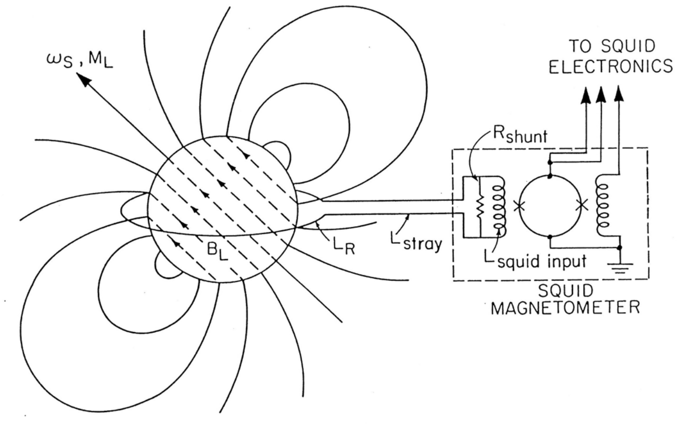
440 mV

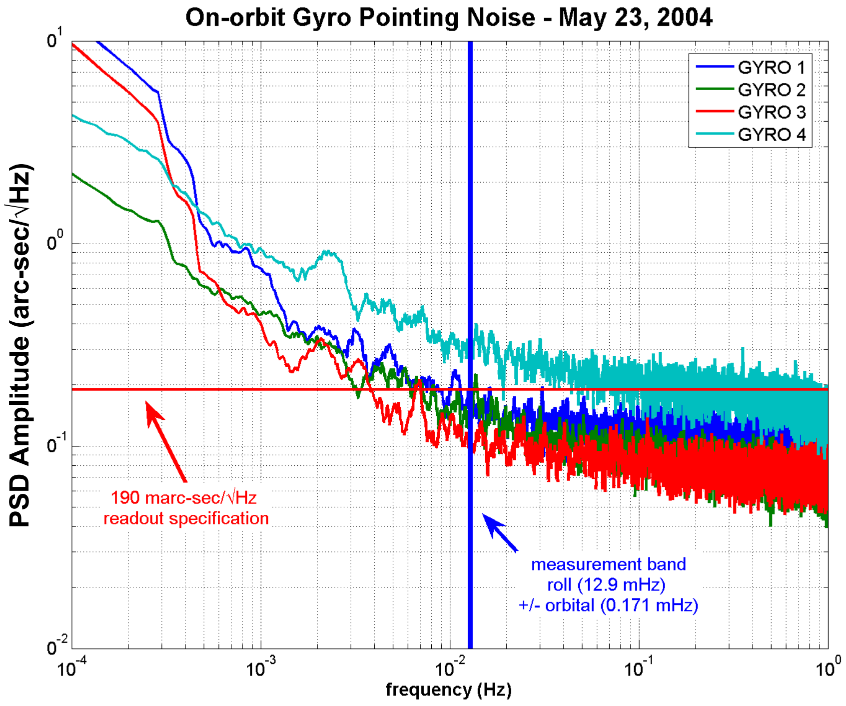
70 mV/hr discharge rate

100 mV

Gyro rotor charge controlled to < 5 pC

Gyroscope DC SQUID Readout




On-orbit Gyro Pointing Noise - May 23, 2004

190 marc-sec/√Hz
readout specification

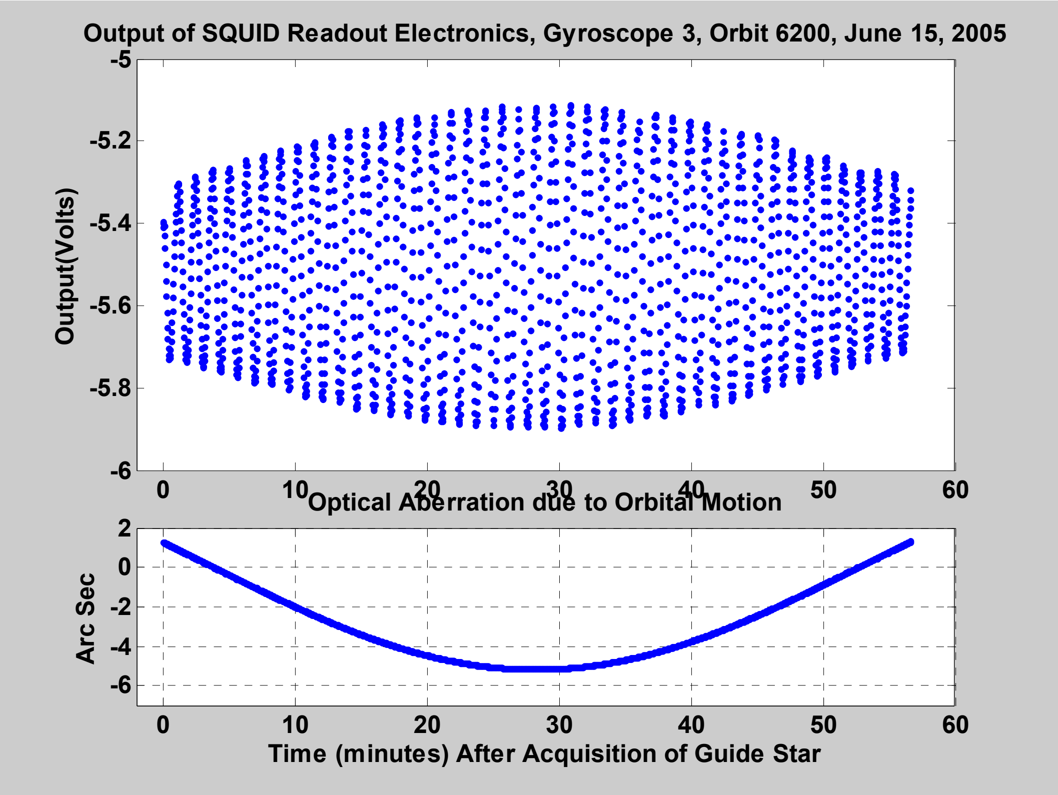
measurement band
roll (12.9 mHz)
+/- orbital (0.171 mHz)

- Readout noise for three gyroscopes less than requirement
- Readout noise for Gyro #4 is acceptable

Gyro Readout During ~½ Orbit

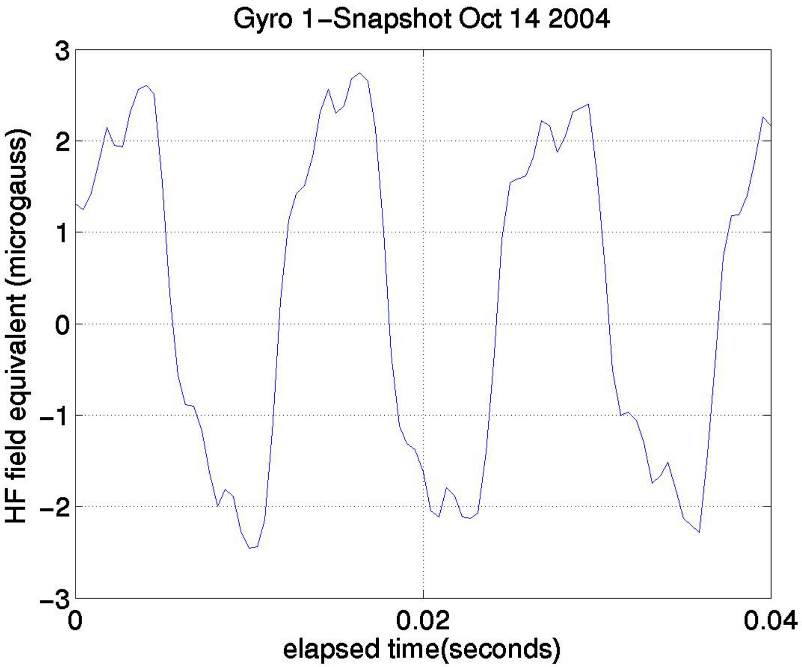
Gyro signal at roll frequency

- Constant part
  - Current average gyro orientation during ½ orbit
- Part modulated at orbit
  - Orbital aberration of Guide Star light
  - Used for scale-factor calibration based on very accurate orbital velocity using GPS



Gyro Rotor Trapped Magnetic Flux

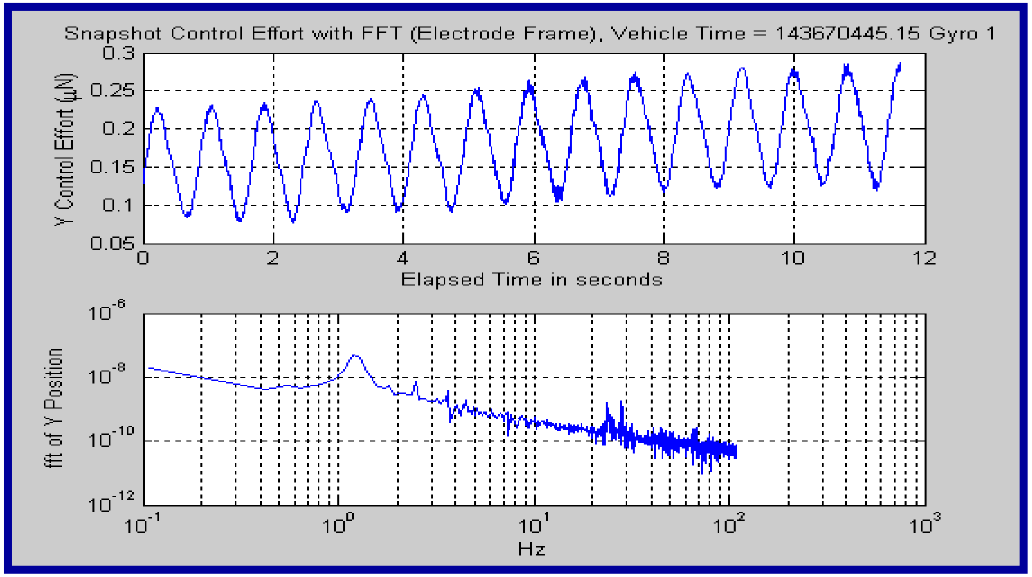
- Dipole equivalent trapped magnetic flux
  - Gyro 1: 3.0 μG
  - Gyro 2: 1.3 μG
  - Gyro 3: 0.8 μG
  - Gyro 4: 0.2 μG
- Gyroscope readout scale factor depends on a combination of the London magnetic moment and the trapped flux
  - Trapped flux contribution will vary at polhode frequency



Trapped magnetic flux well below requirement of 9 μG

Issue – The Patch Effect

- First observations
  - Rotor force modulated at polhode of rotor spinning at 1.3 Hz
    - 30% modulation of ~2×10^{-7} N
  - Z force modulation at polhode of rotor
    - ~2×10^{-8} N
- Consequences
  - Spindown torque
  - Polhode damping
  - Misalignment torque



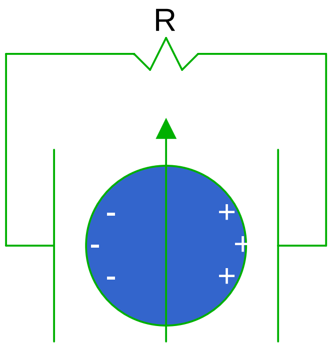
Observations explained by a patch effect of ~100 mV on rotor

Gyroscope Spindown

Gyro	df/dt (μHz/hr)	τ (yr)
1	0.57	15,900
2	0.52	13,600
3	1.30	7,200
4	0.28	26,400

Spindown due to patch effect was unexpected however the magnitude meets our requirement for the spindown torque

Simple spindown model due to patch effect

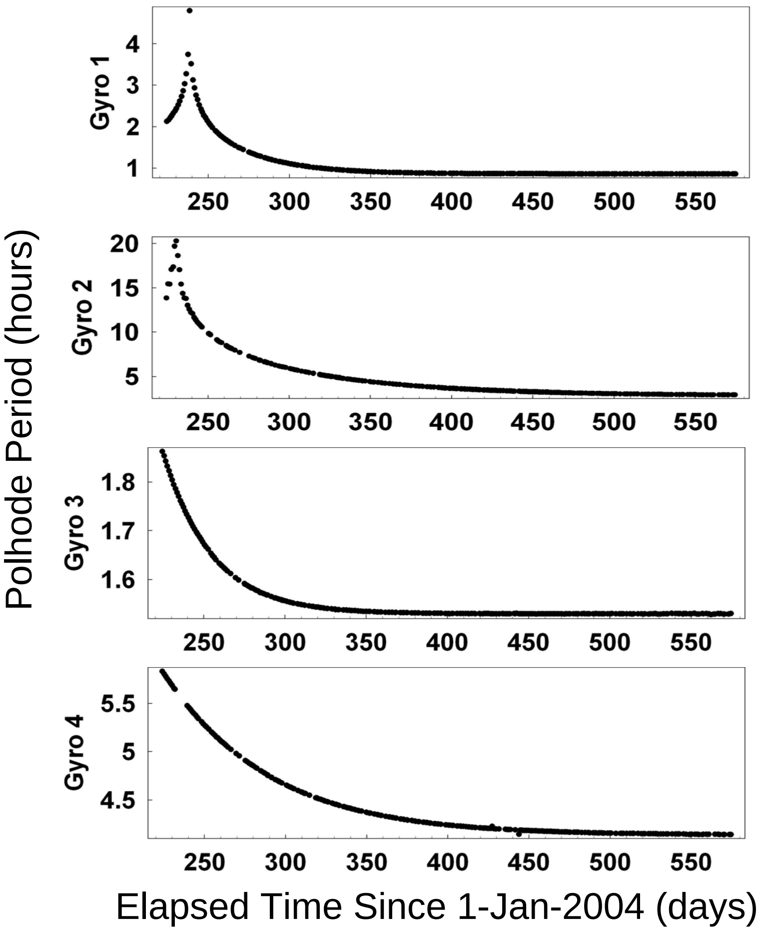


Patch effect potential of 40 - 80 mV accounts for spindown rates

Gyroscope Polhode Damping

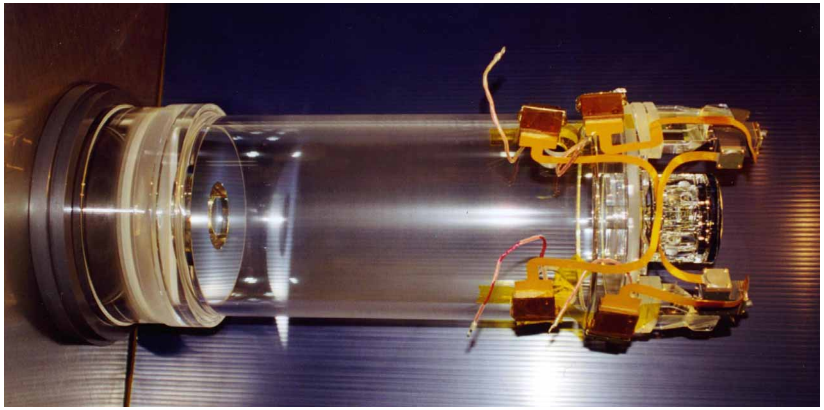
- Accurate polhode periods found using snapshot data at 2200 samples/s
- Dissipation times
  - Gyro 1: 31.87 days
  - Gyro 2: 74.62 days
  - Gyro 3: 30.73 days
  - Gyro 4: 61.19 days
- Polhode period used to model the trapped flux portion of the scale factor

Damping explained by modulation of spin-speed damping at polhode period

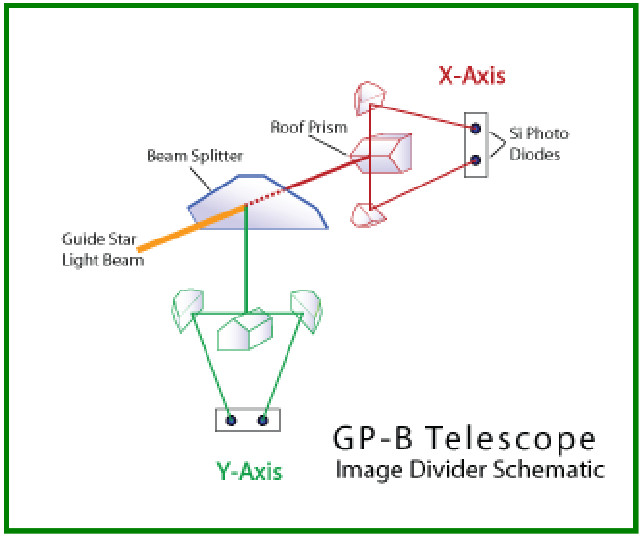


Star-Tracking Telescope

- Characteristics
  - Focal length: 3.9 m
  - Aperture: 14 cm
- Roof edge at focal point to divide image
- Normalized telescope signal
  - Formed from photo detector currents i^+ and i^-
  - nts = $(w^+ i^+ - w^- i^-)/(w^+ i^+ + w^- i^-)$
- Readout scale factor matching
  - Dither direction to guide star 2 orthogonal directions
  - Dither amplitude: ~ 60 marc-sec



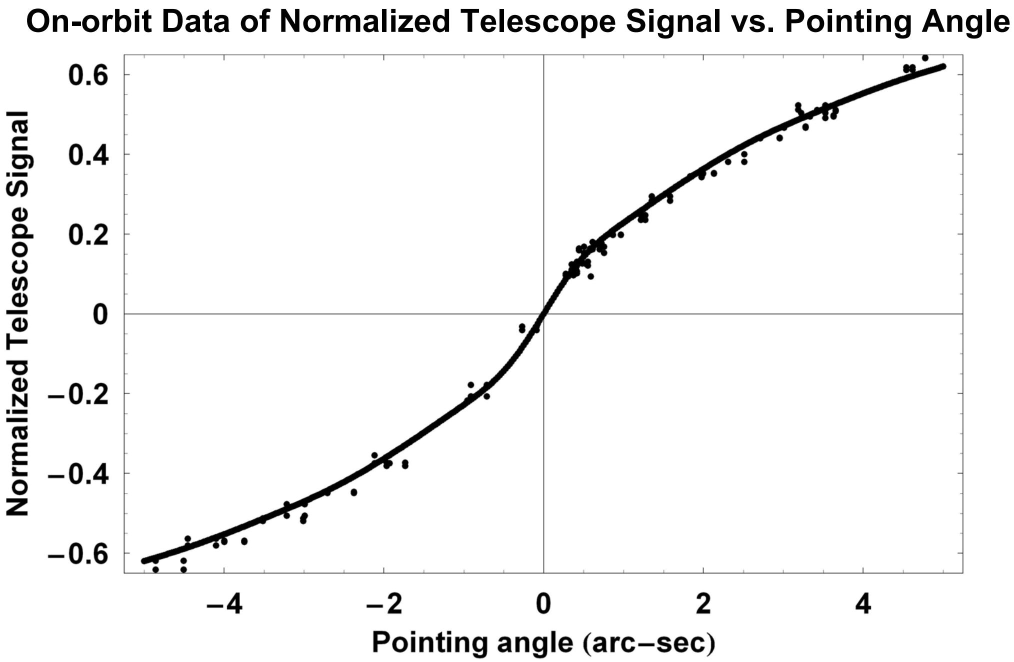
30 marc-sec/√Hz pointing noise



Dual Photo Detectors (72 K)

Telescope Model

- Telescope model
  - Focal length: 3.9 m
  - Aperture: 14 cm
  - Defocus: +5.0 mm
  - $\text{Zernike}_{4,0}$ corr: -.415 μm
- θ(arc-sec) = 3.04 nts (1 + 5.62 nts^2)



Theoretical model of telescope with a defocus term and an axially symmetric aberration term match on-orbit data

Telescope Nonlinearity

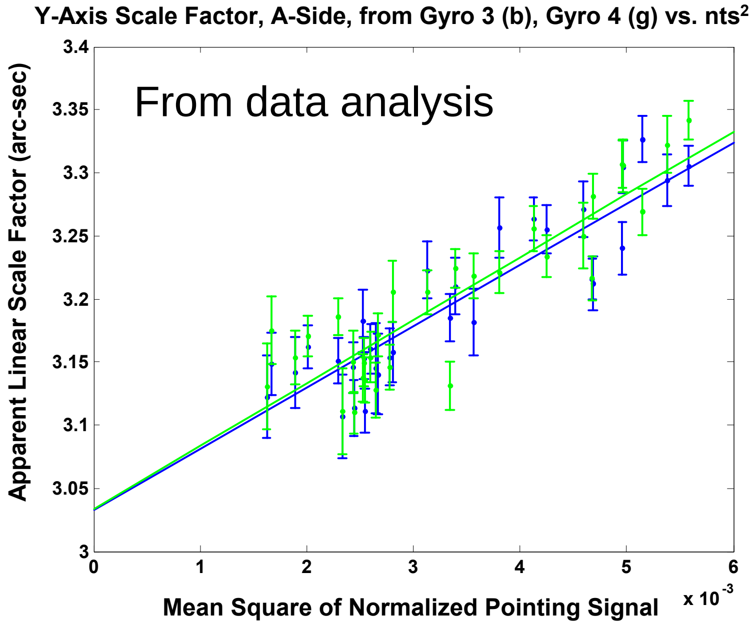
- Apparent linear scale factor from data analysis vs. mean nts^2 has a slope of 49.1 arc-sec
- Searched for value of nonlinearity using on-orbit pointing data to match the 49.1 arc-sec slope
- θ(arc-sec) =

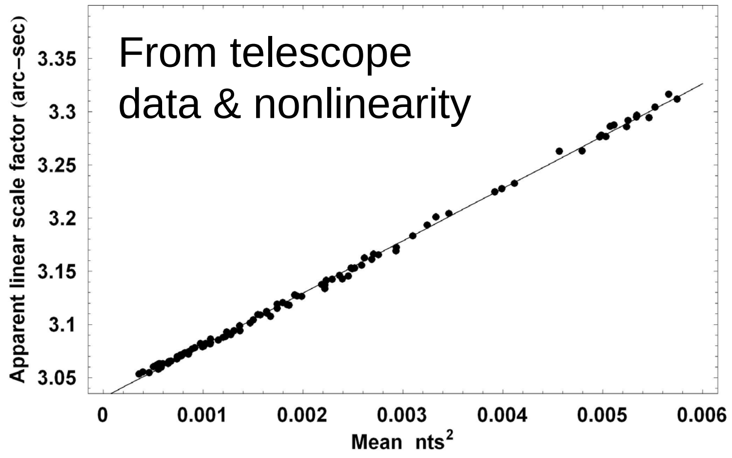
  $$3.04\ \text{nts}\ (1 + 5.39\ \text{nts}^2)$$
- Nonlinearity estimate is very close to result found from telescope model

Pointing accuracy with cubic correction

- 1.7 marc-sec at pointing of 400 marc-sec
- ~ 0.1 marc-sec in inertial space for typical rms pointing*

*Assumes accurate scale-factor matching





Conclusion

- Even though many technologies were initially unavailable and lacked flight or laboratory heritage, the challenging performance requirements of the GP-B Science Instrument were met
- Built-in instrument capability and calibrations allowed the identification of unexpected behavior
  - Example: misalignment patch-effect torque was identified.
    - A method was developed to separate it from the GR precessions in the data analysis

The dominant NS precession of the gyroscope is the geodetic effect