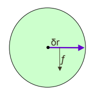
The Gravity Probe B
Gyroscopes and UV Charge Management

Saps Buchman, Bruce Clarke, Mac Keiser, Ping Zhou, Dale Gill, Frane Marcelja, and Robert Brumley

Why Space ?



External forces acting through center of force, different than CM

Mass Balance Requirements:

On Earth (f = 1 g)	(ridiculous)	$\frac{\delta r}{r} < 5.8 \times 10^{-18}$
Standard satellite ($f \sim 10^{-8}$ g)	(unlikely)	$\frac{\delta r}{r} < 5.8 \times 10^{-10}$
GP-B drag-free ($f \sim 10^{-12}$ g cross-track average)	(straightforward)	$\frac{\delta r}{r} < 5.8 \times 10^{-6}$

Requirement $\Omega < \Omega_0 \sim 0.1$ marc-s/yr (1.54×10^{-17} rad/s)

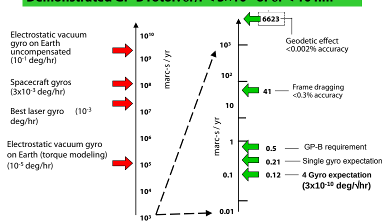
$\Rightarrow \frac{\delta r}{r} < \frac{2}{5}\frac{r\omega_s}{f}\Omega_0$

Drift-rate: $\Omega = \tau / I\omega_s$

Torque: $\tau = mf\,\delta r$

Moment of Inertia: $I = (2/5)mr^2$

Demonstrated GP-B rotor: δr/r < 3×10⁻⁷ or δr < 10 nm

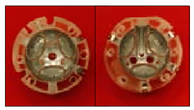


Space improves gyro accuracy by > 10,000,000

The Gyroscopes

- Electrostatic suspension
- Capacitance rotor position
- London moment read-out
- Helium spin-up
- UV charge management
- Cryogenic operations

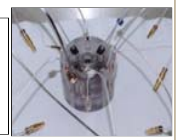
- Components:
  - Rotor
  - Housing
  - Read-out loop
  - Spin-up nozzle
  - UV fixtures
  - Suspension cables
  - Read-out cable



Read-out and Spin-up Housing Halves

Uncoated and Coated Rotor

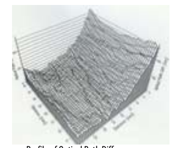
- Rotor
  - Fused silica: 1.9 cm radius
  - Nb film: 1.3 μm, 2% uniform
- Housing
  - Fused silica: 1.9 cm radius
  - Ti, Ti-Cu films
- Rotor to housing: 32.5 μm



Assembled Gyroscope

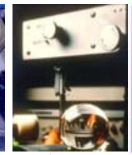
Rotor Fabrication

Quartz Holder for Homogeneity Measurement

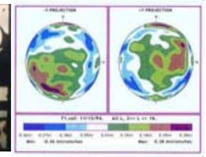


Profile of Optical Path Difference - nm

Polishing System

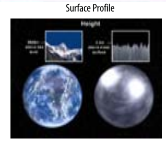


Roundness Measurement



Surface Profile

- Radius 1.9 cm
- Homogeneity < 2 ppm
- Sphericity < 1 ppm
- Mass unbalance < 1 ppm
- $\Delta I/I < 3 \times 10^{-6}$
- Nb Coating Uniformity <2%



Surface Profile Scaled to Earth Size

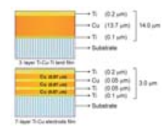
All Requirements Met

Housing Fabrication

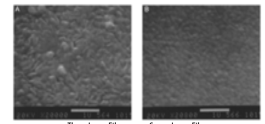
- Radius 1.9 cm
- Sphericity < 10 ppm
- 6 Electrodes in 3 Orthogonal Pairs
- 5 Turn Read-out Loop
- Channel and Ti Nozzle for Spin-up
- 7-layer Ti-Cu Electrode Coating
- 3-layer Ti-Cu-Ti Support and Spin-up Lands Coatings
- Ti Film For Bare Quartz

Fused-Quartz Gyroscope

Spin-up Read-out
Housing Halves

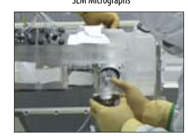


Lands and Electrodes Coatings



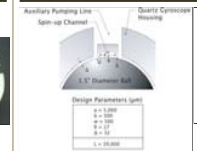
Three Layer Film Seven Layer Film
SEM Micrographs

Gyro to Spacer Assembly



Gyro insertion in Quartz Block

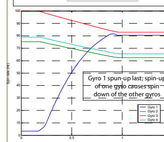
Spin-up and Alignment



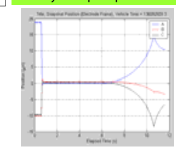
Differential Pumping Requirement
spin channel ~ 10 torr (sonic velocity)
electrode area < 10^{-3} torr

Torque Switching Requirement
$T_s/T_r < \Omega_0 t_s \sim 10^{-14}$
T_s, T_r - spin & residual cross-track torques
t_s - spin time; Ω_0 - drift requirement

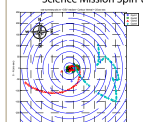
All 4 Gyroscopes spun to 60-80 Hz



Science Mission Spin-up



First Science Mission Levitation



Spin Alignment to 10 arcsec

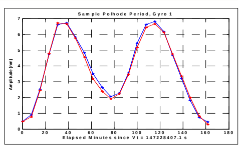
Gyro	Spin Speed (Hz)	df/dt (μHz/Hr)
1	79.4	0.57
2	61.8	0.52
3	82.1	1.30
4	64.8	0.28

Spin speed and spin-down meet requirements

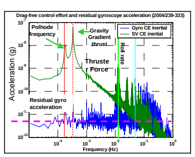
Performance in Space

Mass Unbalance (nm)

Gyro #	Pre-Flight Estimate	On-Orbit Data
1	18.8	6.9
2	14.5	4.4
3	16.8	3.3
4	13.5	6.0



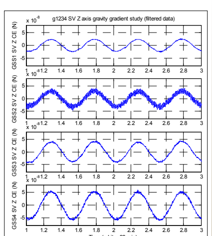
On-orbit measured mass unbalance much better than requirement



DC to 1Hz demonstrated accelerometer performance better than 10^{-11} g

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



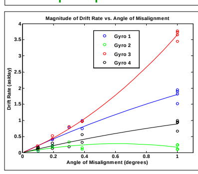
Gravity gradient variation at twice orbit
Gradient increases from gyro #1 to gyro #4

Gyroscopes performed well in space

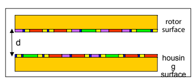
Patch Effect and Solutions

- Variation of electric potential over the surface
  - Can arise due to the polycrystalline structure
  - Can be affected by presence of contaminants
- Patch fields present on rotor and housing walls
- Cause forces and torques between surfaces

- Misalignment torques
  - Orthogonal to misalignment
  - Fully separable from Relativity
- Polhode damping
  - Period and phase determined to high precision
- Spin-down 1μHz/hr
  - Spin-speed determined to high precision

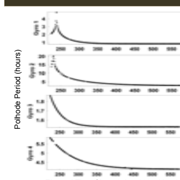


Calibration of drift rate vs. misalignment

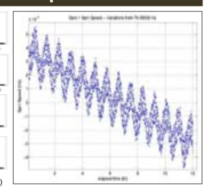


Schematic of surfaces with patches

Polhode and Spin-down



Polhode damping due to modulation of spin-speed at polhode period



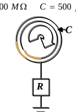
Spin-down (μHz) modulated by polhode
Spin-down rates 0.3-1.5 μHz/hr

$P_{SD} = I\omega\,\dot{\omega} = 10^{-11}\,W\;/(\mu Hz\;/\;hr)$

$P_{GP} = \frac{1}{2}\cdot\frac{V_P^2}{R}\left(\frac{R^2\omega^2C^2}{1+R^2\omega^2C^2}\right)$

$V_P\,(mV) = 72\cdot\dot{\omega}(\mu Hz\;/\;hr)$

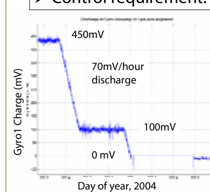
$R = 300\;M\Omega \quad C = 500\;pF \quad \omega = 500\;sec^{-1}$



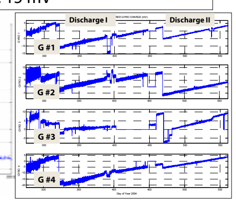
Patch induced dissipation model ~ 70mV dipole for 1 μHz/hr spin-down

UV Charge Management

- Rotor charge controlled via UV excited electrons
- Charge rates ~ 0.1 mV/day
- Continuous measurement at the 0.1 mV level
- Control requirement: 15 mV

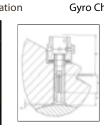


Discharge of Gyro1 after levitation

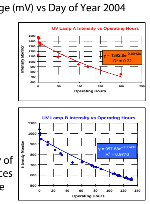


Gyro Charge (mV) vs Day of Year 2004

UV Lamp Assembly



UV Electrode



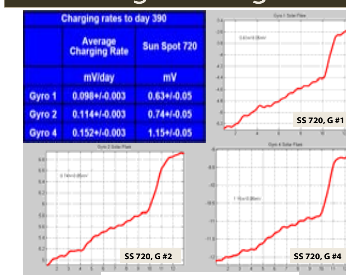
Intensity of UV sources vs. time

Charge controlled to < 5 mV

UV Charge Management

Charging rates to day 390

	Average Charging Rate	Sun Spot 720
	mV/day	mV
Gyro 1	0.098+/-0.003	0.63+/-0.05
Gyro 2	0.114+/-0.003	0.74+/-0.05
Gyro 4	0.152+/-0.003	1.15+/-0.05



Average and Sun Spot 720 charging rates

Conclusions: *Seven Near Zeros*
Gyro requirements: Met, N/A, Issue

1) Rotor homogeneity	< 10^{-6}	met
2) "Drag-free" (cross track)	< 10^{-11} g	met
3) Rotor asphericity	< 10 nm	met
4) Magnetic field	< 10^{-6} gauss	met
5) Pressure	< 10^{-12} torr	met
6) Electric charge	< 10^{8} electrons	met
7) Electric dipole moment	0.1 V-m	issue

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

This research supported by NASA on contract NAS8-39225