The Gravity Probe B
Science Instrument

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  – Vacuum probe and superfluid helium dewar

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The Gravity Probe B Experiment

Frame-dragging Effect
39 milliarcseconds/year
(0.000011 degrees/year)

Guide Star
IM Pegasi (HR 8703)

Geodetic Effect
6,606 milliarcseconds/year
(0.0018 degrees/year)
Instrument Concept

- Gyros 2 & 1
- Gyros 4 & 3
- Mounting flange
- Fused quartz block
- Star tracking telescope
- Guide star IM Pegasi

Operates at ~ 2.5 K

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 < 2x10^{-12}

Detail of readout loop and connection to superconductive cable
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
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

Guide Star
IM Pegasi
(HR 8703)
“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 < 2×10⁻¹²

• 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-ORBUT PERFORCMANCE

He Gas Spinup

<table>
<thead>
<tr>
<th>Final Spin Speeds</th>
<th>Gyro #</th>
<th>Spin Speed (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>79.3888</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>61.8189</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>82.0958</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>64.8520</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Mass Unbalance (nm)</th>
<th>Gyro #</th>
<th>Pre-Flight Estimate</th>
<th>On-Orbit Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>18.8</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>14.5</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>16.8</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>13.5</td>
<td>8.9</td>
</tr>
</tbody>
</table>

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
    - $\sim 0.1 \text{ mV/day}$
- 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

Gyro rotor charge controlled to $< 5 \text{ pC}$

![Charge Control Graph]

Day of year 2004
• Readout noise for three gyroscopes less than requirement
• Readout noise for Gyro #4 is acceptable

On-orbit Gyro Pointing Noise - May 23, 2004

PSD Amplitude (arc-sec/√Hz)

190 nano-sec/√Hz readout specification
measurement band
roll (12.9 mHz)
+/- orbital (0.171 mHz)
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 \( \approx 2 \times 10^{-7} \) N
  – Z force modulation at polhode of rotor
    • \( \approx 2 \times 10^{-8} \) N

• Consequences
  – Spindown torque
  – Polhode damping
  – Misalignment torque

Observations explained by a patch effect of \( \approx 100 \) mV on rotor
Gyroscope Spindown

<table>
<thead>
<tr>
<th>Gyro</th>
<th>df/dt (μHz/hr)</th>
<th>τ (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.57</td>
<td>15,900</td>
</tr>
<tr>
<td>2</td>
<td>0.52</td>
<td>13,600</td>
</tr>
<tr>
<td>3</td>
<td>1.30</td>
<td>7,200</td>
</tr>
<tr>
<td>4</td>
<td>0.28</td>
<td>26,400</td>
</tr>
</tbody>
</table>

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 $i^-$
  - $nts = \frac{(w^+ i^+ - w^- i^-)}{(w^+ i^+ + w^- i^-)}$
- Readout scale factor matching
  - Dither direction to guide star
    2 orthogonal directions
  - Dither amplitude: ~ 60 marc-sec

30 marc-sec/$\sqrt{\text{Hz}}$ pointing noise
Telescope Model

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

On-orbit Data of Normalized Telescope Signal vs. Pointing Angle

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
- \(\theta (\text{arc-sec}) = 3.04 \text{ nts} (1 + 5.39 \text{ nts}^2)\)
- 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