Gravity Probe B: Update
Previous Feb 2008

Institute of Navigation

Jan 2011

Gaylord Green
What is wrong with the Universe?

- Equivalence Principle – All objects fall at the same rate. The basis of Physics
  - Material does not matter
  - Size does not matter
  - Gravity applies a different force to each mass so that all mass falls at the same rate

- Newton – Gravity is a Force ~ \((G \times m_1 \times m_2)/r^2\)
  - Applies to the planets (Mercury orbit wrong)

- Einstein - Gravity is a field in space caused by mass.
  - Applies to the Universe (Missing 95% of the Universe)
  - Dark Matter ~ 30% of the universe
    - Galaxy rotation wrong so invent 6 x mass invisible
  - Dark Energy is ~ 65% of the universe
    - Candle brightness \((d)\) inconsistent with Doppler shift \((v)\)

Gravity Probe B Measures Einstein’s field prediction
**The Relativity Mission Concept**

- **Geodetic Effect**
  - Space-time curvature ("the missing inch")

- **Frame-dragging Effect**
  - Rotating matter drags space-time ("space-time as a viscous fluid")

\[ \Omega = \frac{3GM}{2c^2 R^3} (R \times v) + \frac{GI}{c^2 R^3} \left[ \frac{3R}{R^2} (\omega \cdot R) - \omega \right] \]

1 marc-sec/yr = \(3.2 \times 10^{-11}\) deg/hr – width of a human hair seen from 10 miles
Expected Gyroscope Behavior

Geodetic effect* (-6571 marcsec/yr)

Frame-dragging effect* (-75 marcsec/yr)

*Includes solar GR effects and guide star motion
Seeing General Relativity Directly

**Red:** Unprocessed flight data

**Blue:** After self-checking misalignment torque correction
The GP-B Gyroscope

- Electrical Suspension
- Gas Spin-up
- Magnetic Readout
- Cryogenic Operation

"Everything should be made as simple as possible, but not simpler."
-- A. Einstein
The London Moment Readout

Superconducting Magnetic Shield

London Moment (Magnetic Dipole)

- Pickup Loop
- Satellite Roll
- Input Coil
- DC SQUID
- SQUID Electronics

\[ \text{V}_{\text{Out}} \propto \theta \]

“SQUID” \( \rightarrow \) 1 marc-s in 5 hours

4 Requirements/Goals

- SQUID noise 190 marc-s/\( \sqrt{\text{Hz}} \)
- Centering stability < 50 nm
- DC trapped flux < \( 10^{-6} \) gauss
- AC shielding > \( \sim 10^{12} \)
Gyro Readout Performance On-Orbit

On-orbit Gyro Pointing Noise - May 23, 2004

Peak to peak ~ 24 arc-sec

<table>
<thead>
<tr>
<th>Gyro</th>
<th>Experiment Duration (days)</th>
<th>SQUID Readout Limit (marc-s/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>353</td>
<td>0.198</td>
</tr>
<tr>
<td>2</td>
<td>353</td>
<td>0.176</td>
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<tr>
<td>3</td>
<td>353</td>
<td>0.144</td>
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<tr>
<td>4</td>
<td>340</td>
<td>0.348</td>
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</table>
Flight Hardware

- Gyroscope
- Science Instrument Assembly
- Probe with Science
- Space Vehicle: Payload integrated with spacecraft
- Science Mission Payload: Dewar with probe & science instrument assembly
Payload Hardware

Gas Management Assembly (GMA)
- Provides Spin Up gas to Gyros

Dewar
- Holds 2200 liters of liquid Helium
- Superfluid at launch and on orbit

Probe
- Provides 1x10e-10 torr vacuum

Star

Telescope (inside)

Quartz Block Assembly (inside)
The Overall Space Vehicle

- 16 Helium gas thrusters, 0-10 mN ea, for fine 6 DOF control.
- Roll star sensors for roll phase control
- Mass trim to tune moments of inertia.
- Stanford-modified GPS receiver for precise orbit information.
- Magnetometers for coarse attitude determination.
- Tertiary sun sensors for very coarse attitude determination.
- Magnetic torque rods for coarse orientation control.
- Dual transponders for TDRSS and ground station communications.
- Redundant spacecraft processors, transponders.
- 70 A-Hr batteries, solar arrays operating perfectly.
A very different control system
- 16 proportional cold gas thrusters.
- Propellant: Helium boil-off @ 12 torr
- Isp = 130 sec; 6.5 mg/sec flow

ATC Performance:
- Inertial Pointing to <20 marc-s
- Translation to < 10^{-11} g average
- 6 DOF control

Specific impulse vs. mass flow rate

Prototype thruster cutaway view
Mass Trim to adjust CM and Axis of Inertia
Electrostatic Suspension System Functional Design

### Functional Design

**Flight Modes**
- **Science Mission (SM)** (Adaptive Authority Torque Minimizing)
  - SM Low Backup
  - SM High Backup

**Ground Test**
- Spin-up & Alignment (Digital DC, SQUID Compatible)
- Ground Test (Digital DC, SQUID Compatible)

**Primary Digital Control**
- Robust Analog Backup

**Specific force**
- $10^{-7}$m/s²
- $10^{-5}$m/s²
- $10^{-2}$m/s²
- 1 m/s²
- 10 m/s²

**Req'd voltage**
- 0.2V
- 2V
- 50V
- 300V
- 1000V

**Primary Disturbances**
- Grav. gradient
- ES torques
- Rotor charge
- Meteorites
- Spin-up gas
- Soft computer failures
- 1g field
GP-B Launch - 20 April 2004

Fairing Installation

Launch!

Release from booster.
Gravity Probe B’s GPS system
(a Commercial system modified by Stanford)

- GPS data sole data source for orbit determination
- Two fully redundant sets: receiver + four antennas
- Data (position, velocity, time) every 10 seconds
- More than 5000 points per day

<table>
<thead>
<tr>
<th>Position Accuracy</th>
<th>Velocity Accuracy</th>
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<tr>
<td>Requirement</td>
<td>25 m RMS</td>
</tr>
<tr>
<td>Actual</td>
<td>2.5 m RMS</td>
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</table>
Near Zeros & Their Technologies

Seven Near Zeros

1) Rotor inhomogeneities $< 10^{-6}$ 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
Pointing from Science Gyros (4 Orbits)
Rotor to case measurement measures spacecraft control system

NS & WE vs time

NS vs WE

Long-term mean uncertainty through mission < 10 marc-s
Seeing General Relativity Directly

Red: Unprocessed flight data

Blue: After self-checking misalignment torque correction
Result Issues 2008

- Within the Accuracy desired
  - Gyros did not always agree with each other
  - Segments did not always agree with each other

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First Glimpse June 2006
Second Glimpse December 2006
New Glimpses March 2007
Three Complications (likely due to Patch Effect)

1. Polhode damping $\rightarrow$ complicates $C_p$ determination

2. Misalignment Torques

Mean rate (arcsec/day) vs. mean misalignment (arcsec)

$\text{Drift rate magnitude (arcsec/day)}$

$k = 2.5 \text{ arc sec/day/degree}$
Three Complications (likely due to Patch Effect)

3. Roll-polhode Resonance Torque

- ‘Jumps’ occur when harmonic of changing polhode rate is coincident with roll rate

Gyro 2 per orbit orientation

Date (2005)
Two Champions of the Data Analysis

1. Spectral separation
   a) Rotor spin ~ 60 Hz - 80 Hz (changing with time)
   b) Spacecraft roll = 13 mHz (from on-board star trackers)
   c) Spacecraft orbit = 0.17 mHz (from on-board GPS)
   d) Rotor polhode ~ 0.1 mHz (changing with time)
   e) Earth’s orbit = 32 nHz (from JPL Earth ephemeris)

⇒ General Relativity acts at zero-frequency (inertial frame)

2. Trapped magnetic flux → Enables determination of a) & d)

1. + 2. + model of patch effect & gyro dynamics allow separation of relativistic & Newtonian effects
Gyro 1

Trapped Flux & Readout Scale Factor

\[ \Phi_B(t) = \Phi_B^{LM}(t) + \Phi_B^{TF}(t) \]

\[ = C_g^{LM} \beta + C_g^{TF} \beta \]

6 Sept 2004

polhode

\[ \hat{I}_1 \]

\[ \hat{I}_2 \]

\[ \hat{I}_3 \]
Trapped Flux & Readout Scale Factor

Gyro 1

\[ \Phi_B(t) = \Phi_{LM}^B(t) + \Phi_{TF}^B(t) \]
\[ = C_g^{LM} \beta + C_g^{TF} \beta \]
Trapped Flux & Readout Scale Factor

Gyro 1

\[ \Phi_B(t) = \Phi_{BM}^L(t) + \Phi_{BM}^T(t) = C_g^L \beta + C_g^T \beta \]
Trapped Flux & Readout Scale Factor

Gyro 1

\[ \Phi_B(t) = \Phi_{LM}^B(t) + \Phi_{TF}^B(t) \]

\[ \hat{I}_2 = C_g^{LM} \beta + C_g^{TF} \beta \]
Trapped Flux & Readout Scale Factor

\[ \Phi_B(t) = \Phi_{LM}^B(t) + \Phi_{TF}^B(t) \]
\[ = C_g^{LM} \beta + C_g^{TF} \beta \]
Trapped Flux & Readout Scale Factor

\[ \vec{\omega}_s \]

Gyro 1

\[ \Phi_B(t) = \Phi_B^{LM}(t) + \Phi_B^{TF}(t) \]

\[ = C_g^{LM} \beta + C_g^{TF} \beta \]
Science Data Segments & Spacecraft Anomalies

- **Spinup & Alignment Complete Gyros 1, 2, 3**
- **Gyro 4**

### 2004
- **Aug**: Segment 2
  - 1 - Gyro 3 Analog Backup
- **Sept**: Segment 3
  - 2 - SRE Safemode
- **Oct**: Segment 5
  - 3 - bad GPS config
  - 4 - roll notch filter
- **Nov**: Segment 6
  - 5 - Jan 20 Solar Flare

### 2005
- **Mar**: Segment 9
  - 6, 7,8 - computer reboots
- **Apr**: Segment 10
  - 9 - roll notch filter
- **Jun**: Calibration
Segment-to-Segment Consistency

Gyro 1

Gyro 2

Gyro 3

Gyro 4
Gyro-to-Gyro Consistency

- 95% probability ellipses
- combination: per gyro uncertainty + scatter
- Statistical & systematic errors included
The Combined Result

- **Statistical error from per gyro covariances + dispersion**
  - Statistic error from per gyro covariances + dispersion
  - Sensitivity analysis produced 720 relativity estimates
    - Eventually ~10,000 estimates
  - Systematic covariance added to statistical covariance

- **Statistical Uncertainty**
  - $\sigma_{NS} = \pm 32.0$ marcsec/yr
  - $\sigma_{EW} = \pm 6.8$ marcsec/yr

- **Systematic Uncertainty**
  - $\sigma_{NS} = \pm 5.0$ marcsec/yr
  - $\sigma_{EW} = \pm 4.6$ marcsec/yr

- **Parameters**
  - $r_{NS} = -6605.0 \pm 32.4$ marcsec/yr
  - $r_{EW} = -68.3 \pm 8.2$ marcsec/yr
GR Comparison

• GP-B result

\[ r_{NS} = -6605.0 \pm 32.4 \text{ marcsec/yr} \]
\[ r_{EW} = -68.3 \pm 8.2 \text{ marcsec/yr} \]

• GR Prediction

\[ r_{NS} = -6571 \pm 1 \text{ marcsec/yr} \]
\[ r_{EW} = -75 \pm 1 \text{ marcsec/yr} \]
The Review Committee

- The opinion of the SAC, a very robust confirmation of the general relativistic frame dragging effect (the primary science goal of the project), and can assign a very credible combined systematic and statistical error to the result.

- An important factor in making this progress possible was the support of KACST, both financial and technical.

- In the opinion of the SAC, the effort of the GPB team to bring the test of general relativity to a successful conclusion in the face of instrumental anomalies that threatened to make such a measurement impossible has been nothing less than heroic.

- GPB has measured a phenomenon - the precession of a gyroscope in the gravitational field of a rotating body - that no other experiment can claim to have measured.
Funding Sources

- NASA
  - Promoted Cancellation about 5 times
  - Last time a few months prior to launch
  - Science controlled by astronomers (more telescopes)
  - Perseverance of Francis Everitt assisted by Brad Parkinson made the program successful

- Richard Fairbanks (CEO Capital One)
  - Conference Room Named Gravity Probe B with Pictures

- KACST
  - King Abdullah City of Science and Technology
  - KACST is both the Saudi Arabian national science agency and its national laboratories.

- Vance Kaufman
  - Former CEO Lockheed Martin
  - Former PhD Student Gravity Probe B
Questions

Engineers thoughts on the problems of the universe
Rotation and Resonances

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)
The GP-B Challenge

- Gyroscope (G) $10^7$ times better than best 'modeled' inertial navigation gyros
- Telescope (T) $10^3$ times better than best prior star trackers
- G – T <1 marc-s subtraction within pointing range
- Gyro Readout calibrated to parts in $10^5$

Space
"Drag-free", separation of effects, elimination of "seeing" limitations

Cryogenics
Readout, mechanical stability, low magnetic field, UHV technology
Sub-milliarc-s Star Tracker

Detector
Package

Dual Si Diode
Detector

GP-B Telescope
Image Divider Schematic

X-Axis

Y-Axis

Beam Splitter
Roof Prism
Si Photo Diodes

Guide Star
Light Beam

BASE
SUPPORT TUBE
PHOTODIODE READOUT MODULE
BEAM SPLITTER ASSEMBLY
CORRECTOR PLATE
QUARTZ BLOCK INTERFACE
PRIMARY
TERTIARY
SECONDARY

NASA
STANFORD UNIVERSITY
Dither -- Slow 60 marc-s oscillations injected into pointing system

Aberration (Bradley 1729) -- Nature's calibrating signal for gyro readout

Orbital motion → varying apparent position of star
\( v_{\text{orbit}}/c + \text{special relativity correction} \)
Earth around Sun -- 20.4958 arc-s @ 1-year period
S/V around Earth -- 5.1856 arc-s @ 97.5-min period

Continuous accurate calibration of GP-B experiment
The GP-B Cryogenic Payload

Payload in ground testing at Stanford, August 2002
Boil off gas from Dewar vented continuously through 16 Proportional Thrusters provides spacecraft attitude and translational control.

Drag-Free: 2\textsuperscript{nd} Near Zero

Boil off gas from Dewar vented continuously through 16 Proportional Thrusters provides spacecraft attitude and translational control.

Drag-free off Drag-free on

Gravity gradient

Roll rate

Cross-axis avg. 1.1 x 10\textsuperscript{-11} g
3rd Near Zero - GP-B Gyroscope

CERTIFICATE

The most spherical manmade objects are the fused quartz gyroscopic rotors onboard the Gravity Probe B spacecraft operated by NASA and Stanford University. Their average departure from mathematically perfect sphericity is only $1.8 \times 10^{-7}$ of their diameter.

Keeper of the records
GUINNESS WORLD RECORDS LTD

 gyro, housing, and electrodes
In-flight Verification, 3 Phases

A. Initial Orbit Checkout - 128 days
   - re-verification of all ground calibrations [scale factors, tempco’s etc.]
   - disturbance measurements on gyros at low spin speed

B. Science Phase - 353 days
   - exploiting the built-in checks [Nature’s helpful variations]

C. Post-experiment tests - 46 days
   - refined calibrations through deliberate enhancement of disturbances, etc. [...learning the lesson from Cavendish]

Detailed calibration & data consistency checks eliminated many potential error sources & confirmed many pre-launch predictions, but…

Observation (Phase B) – Segmented data (solar flare events, etc.)

Discovery 1 (Phase A, B) – Polhode-rate variations affect $C_g$ determinations

Discovery 2 (Phase B, C) – Larger-than-expected misalignment torques
Discovery 1: Polhoding & $C_g$

- **Issue:** $C_g$ better than $10^{-4}$ linking data from 6 or more orbits

- **The actual 'London moment' readout:**
  - $M_L$ + dipole component of trapped flux along spin axis $M_T \sim 1\% M_L$
  - Total trapped flux fixed in rotor but $M_T$ modulated by polhoding
  - Orbit-to-orbit fit complicated by varying polhode rate

![Polhode Period (hours) vs Elapsed Time (days) since January 1, 2004](image)

- **Current:** Fit 4 to 6 polhode harmonics to get mean $M_T$
- **Refinement:** Utilize Trapped Flux Mapping data
Discovery 2: Misalignment Torques

- Torque & misalignment angle \( \Phi, \Psi \rightarrow \) 0.1 to 1.0 arc-s/yr drift rates
- Probable cause – Electrostatic ‘patch effect’ on rotor and housing
- Relativity
  - Fixed direction in inertial frame
- Misalignment Torque/Drift
  - Torque \( \approx \) to \( \psi \)
  - Drift \( \perp \) misalignment vector
Character of ‘Resonance Torque’ Effect

- Predicted interaction of rotor & housing potentials
  - Averaging over roll & polhode periods no longer good approximation
  - Orientations follow full or partial loxodromic curve
  - Shape of path independent of potential distribution; magnitude & direction of offset depend on distribution
  - Offset depends on roll phase at time of resonance

- Example: Gyro 2, Resonance 277

October 25, 2004

Note: Not all resonances follow loxodromic curve so exactly: conditions may be changing over 1-2 day duration of resonance
Kalman Filter Method Example

85 Days with Solar Flare Segmentation
[December 10, 2004 – March 5, 2005]

R\textsubscript{NS} estimate : -6597 ± 20 marc-s/yr

2nd floor analysis from December 2006
Initial Geodetic Effect Results

\[
\begin{array}{c|c|c|c|c}
\text{'Geometric'} & \text{Full Year} & \text{glimpse 1} & \text{glimpse 2} & \text{glimpse 3} & \text{glimpse 4} \\
& \text{158 days} & \text{85 days} & \text{82 days} & \text{41 days}
\end{array}
\]

-6571 ± 1

\[\text{Net expected}\]

\[\text{Separate gyro, ~ 5-day batches}\]

-6638 ± 97

Residual gyro-to-gyro inconsistencies due to incomplete modeling ~ 100 marc-s/yr

\[\text{Combined gyro processing, continuous filtering}\]

-6584 ± 52

-6597 ± 20

-6595 ± 10

-6604 ± 7

\[\text{SQUID noise limit}\]

\[\text{Progress in modeling with algebraic approach evident}\]

\[\text{1\sigma statistical error only}\]

-6571 ± 1

\[\text{Net expected}\]

* Earth -6606, solar geodetic +7, proper motion +28 ± 1  → net expected -6571 ± 1
Glimpses of Frame-Dragging

First Glimpse June 2006
Second Glimpse December 2006
New Glimpses March 2007

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Trapped Flux Affects Readout

solar magnetic field... like the trapped flux


http://www.windows.ucar.edu/tour/link=/sun/images/sunspot_magnetism_big_jpg_image.html
Effect of Single Fluxon
Output of Multiple Fluxons

Multiple (32) fluxons. Reality: hundreds of fluxons.
Polhoding, Trapped Flux & $C_g$

- $C_g$ approaching $10^{-5}$ linking data from many orbits
- The actual 'London moment' readout:
  
  **London field at 80 Hz:** 57.2 µG
  - Gyro 1: 3.0 µG
  - Gyro 2: 1.3 µG
  - Gyro 3: 0.8 µG
  - Gyro 4: 0.2 µG

- Two methods of determining $C_g$ history
  - Orbit-to-orbit fit of LF SQUID signal incorporating up to 17 polhode harmonics
  - Direct computation from Trapped Flux Mapping results
Scale Factor Determination & TFM

Fluxon Distribution

Polhode, spin parameters

Scale factor variations
Trapped Flux Mapping Progress

- Polhode phase to 0.5° - 2.6° throughout year with potential further improvement
  - Vital in Low Frequency SQUID signal analysis

- With improved spin speed/spin down rate results, TFM High Frequency determination of $C_g$
  - High Frequency & Low Frequency determinations in good agreement
  - HF determination free of polhode/orbital resonance disturbances

- Use of HF $C_g$ profile in LF SQUID signal analysis
  - Reduces high dimension non-linear estimation problem to lower dimension linear problem
  - Trade studies indicate end result will be 2x reduction in overall error
Assessment of Measurement to Date

- Modeling of scale factor & torques improved substantially
- Filtering technique more robust; can estimate many more parameters
- **CAVEATS**
  - Excessive sensitivity to modeling of torque coefficients
    - occasional worrying outliers
  - Inconsistencies between 4 gyros are real
    - long-term modeling with detailed torque coefficient history in work
  - Combined gyro processing eliminates some error sources
Spinoffs from GP-B
Five Major Categories and a few examples

- Precision Machining, Assembly, and Bonding
  - Gyros, housings, Coatings, catalyzed optical contacting
- Cryogenics
  - Porous plug, Space Dewar, payload probe, instruments
- Ultra – low magnetic field and shielding
  - $10^{-6}$ Gauss, $10^{13}$ isolation
- Drag Free and Pointing Technologies
- New Spacecraft Technologies
  - Micro thrusters (changing a disturbance into a control mechanism)
  - Satellite Dynamical Balancing in Space (CG and Inertia Axes)
  - GPS Attitude measurements
  - GPS Blind Landing System
What is next at Stanford - STEP

- Relativity is incompatible with the Standard Model
- Gravity is not consistent with the 3 other forces

Gravity

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<td>Standard Model</td>
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Strong
Weak
Electromagnetic

Dark Energy

CERN
Hadron

Higgs

STEP
Microscope

Equivalence
Satellite Test of the Equivalence Principle (STEP)

Improve the current test of Equivalence to $10^{-18}$ from $10^{-13}$

**Positive Result**

- Equivalence is the basis of Relativity - New theory required
- Required for most string theory predictions
- Evidence of a fifth force

**Negative Result**

- Requires a theory which does not violate Equivalence
- Places bounds on all future theories
- Hard to conceive of a fifth force which is independent of materials
STEP - A $10^{-18}$ Experiment

Sun Synchronous Drag Free $10^{-14}$