Space, Cryogenics, GPS & Einstein: Preview of Gravity Probe B Results

Stanford's 4th Annual PNT Symposium
November 9, 2010

Francis Everitt
Orbiting Gyroscopes & Einstein

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

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

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

Geodetic Effect
- Space-time curvature ("the missing 3 cm")

Frame-dragging Effect
- Rotating matter drags space-time ("space-time as a viscous fluid")
GR in ‘Raw’ Data: Early Result

Geodetic effect | marc-s/yr
--- | ---
Einstein expectation | - 6571 ± 1*
4-gyro mean (2007) | - 6578 ± 97

* - 6606 + 7 solar geodetic + 28 ± 1 guide star proper motion

3 Built-in Checks
- light deflection centered on March 11
- aberration of starlight for scale factor
- 24.64877 day guide star orbital motion
**4 GP-B Triumphs**

- 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 \(\Rightarrow\) calibrated to parts in \(10^5\)

**Basis for \(10^7\) advance in gyro performance**

**Space**
- reduced support force, "drag-free"
- S/C roll about line of sight to star

**Cryogenics**
- magnetic readout & shielding
- thermal & mechanical stability
- ultra-high vacuum technology
• Electrical Suspension
• Gas Spin-up
• Magnetic Readout
• Cryogenic Operation
World’s Roundest Sphere

Roundness Measurement to ~ 1 nm

Students 1988 - 1992

* Grace Chang (A/A)
* Rebecca Eades (Math)
* Benjamin Lutch (undeclared)
* Dave Schleicher (Comp Sci)
* Dieter Schwarz (EE)
* Michael Bleckman (Hamburg)
* Christoph Willsch (Göttingen)
GP-B Cryogenic Payload

the Porous Plug: Controlling He in Space

Payload in ground testing at Stanford, August '02

First demonstration: Peter Selzer (SU Physics)
Engineered for space: Gene Urban, et al. (MSFC)
Bill Davis (Ball Aerospace), Sidney Yuan (Lockheed)

...IRAS, COBE, WMAP, Spitzer
Gravity Probe B Space Vehicle

- Redundant spacecraft processors, transponders.
- 16 He gas thrusters (0-10 mN) 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 & ground station communications.
- Stanford-modified GPS receiver for precise orbit information.
- Solar arrays + 70 A-hr batteries.
Precise orbit determination
- Orbit injection ~ 120m from pure polar
- Computation of predicted GR signal
- Gyro scale factor $C_g$ from orbital aberration signal

Evaluation of drag-free performance
- Backing out accelerometer bias to < 1mN
- The mysterious polhode-rate dependence

Time Transfer via PPS signal reconciling Vehicle Time with UTC
- 2μs rms @ 77.5s spacecraft roll period

Aeronomy (Mike Adams PhD – GP-B #100!)
- Position & velocity from GPS
- Acceleration & force $< 10^{-10}g/\sqrt{\text{Hz}}$ from GSS

Also Clark Cohen differential GPS attitude determination
3 Phases of In-flight Verification

A. Initial Orbit Checkout (IOC) - 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]

“Always be suspicious of the news you want to hear”
In-Orbit Science Operation

Spinup & Alignment
Complete Gyros 1, 2, 3

Aug
1 - Gyro 3 Analog Backup

Sept
2 - SRE Safemode

Oct
3 - bad GPS config

Nov
4 - roll notch filter

Dec
5 - Jan 20 Solar Flare

2004
Segment 2
Segment 3
Segment 5
Segment 6

2005

March
Segment 9
June
Segment 10
August
Calibration

Mar
6, 7, 8 - computer reboots

Apr
9 - roll notch filter

May
Aberration -- *Nature's calibrating signal for gyro scale factor* $C_g$

Orbital motion $\Rightarrow$ varying apparent position of star 
$\left( \frac{v_{\text{orbit}}}{c} + \text{special relativity correction} \right)$

S/V around Earth -- $5.1856$ arc-s @ $97.5$-min period
Earth around Sun -- $20.4958$ arc-s @ $1$-year period

$\Rightarrow$ Continuous accurate 
calibration of GP-B experiment
The 3 ‘Patch Effect’ Gremlins

A. Polhode-rate variation
   ☐ complicates $C_g$ calibration
   ☐ connects to gremlin C

B. Misalignment torques
   ☐ >100x bigger-than-expected gyro drifts
discovered on pointing to other stars

C. Roll-polhode resonance torques
   ☐ mysterious shifts over 1-3 days in
individual gyro orientations

All due to one cause (patch effect)
1. **Mechanical — Good & Essential**
   Rotor $\sim 5 \times 10^{-7}$
   Housing $\sim 4 \times 10^{-6}$

2. **Electrical — Bad & Very Unexpected**
   Large sideways forces from 'patch effect' voltages

3. **Magnetic — Seemingly Bad, Miraculously Good!**
   Trapped flux $\sim 0.4\% - 5\%$ of London Moment
Ideal vs. Actual $M_L$ Readout

**Detailed Trapped Flux Mapping (TFM)**

- London field at 80 Hz: 57.2 $\mu$G
  - Gyro 1: 3.0 $\mu$G
  - Gyro 2: 1.3 $\mu$G
  - Gyro 3: 0.8 $\mu$G
  - Gyro 4: 0.2 $\mu$G

3 Key Students
- John Conklin
- Michael Dolphin
- Michael Salomon

Page 16  Space, Cryogenics, GPS & Einstein: Preview of Gravity Probe B Results
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**Issue:** Must link data from many successive half orbits to calibrate $C_g$. Exact knowledge of polhode phase $\phi_p$ required.

**Resolution:** TFM determines $\phi_p$ to 1° throughout mission

1. Initial TFM treatment
   100σ to 6σ to 2σ

2. $\sim 10^{-4}$ calibration of polhode variation in $C_g$ due to trapped flux

3. Use of aberration signal to calibrate $\sim 10^{-3} C_g$ variation over mission
- GR signal in fixed inertial direction
- Torque direction varies due to annual aberration
- Uncorrupted relativity signal parallel to misalignment

Replot data against misalignment phase
- Amplitude gives combined relativity signals
- Phase separates the two effects
Resonance Torque

- **Spin axis path predicted from rotor & housing potentials**
  - Roll averaging fails when $\omega_r = n\omega_p$
  - Orientations follow Cornu spiral
  - Magnitude & direction depend on patch distribution, roll & polhode phases at resonance

- **Example:** Gyro 2, Resonance 277 – Oct 25, ’04
Adding in the Resonance Torque

\[ \frac{ds_{NS}}{dt} = T_{NS} + k(\phi_p, \gamma_p) \mu_{EW} + \sum_m A_m(\gamma_p) \cos \Delta \phi_m - B_m(\gamma_p) \sin \Delta \phi_m \]

\[ \frac{ds_{EW}}{dt} = T_{EW} - k(\phi_p, \gamma_p) \mu_{NS} + \sum_m A_m(\gamma_p) \sin \Delta \phi_m + B_m(\gamma_p) \cos \Delta \phi_m \]

\[ \Delta \phi_m = \phi_{roll} - m \phi_p \]

From once-per-orbit averaging to 2-sec processing
2-sec Filter Development

24 month effort:
- reworking 4 years experience w/ 2 floor model
- parallel processing for 14x increase in speed

KACST Team Members

Badr Aisuwaidan
(residuals analysis, truth modeling)

Majid Almeshari
(efficient parallel processing)

Homoud Aljabreen
(non-linearity, thermal sensitivities)

Ahmad Aljadaan
(results viewer, submission process)

Rashed Al Yousef
(dSPACE spacecraft simulator)

Mufih Al Rufaydah
(telescope research)
Comparison with General Relativity

\[
\begin{array}{ccc}
\text{GR Prediction} & \text{GP-B Result} \\
\hline
r_{NS} & -6571 \pm 1 & -6605.0 \pm 32.4 \\
r_{EW} & -75 \pm 1 & -68.3 \pm 8.2 \\
\end{array}
\]
Frame-dragging & Mach’s Principle

- H. Thirring 1918
- Gyroscope @ center of hollow rotating sphere
- Extension to closed universe

- Einstein’s *The Meaning of Relativity* (1953, pp. 100-107)
  - "...these effects, which are to be expected in accordance with Mach’s ideas, are actually present according to our theory, although their magnitude is so small that confirmation of them by laboratory experiments is not to be thought of."

- The 12-step argument in Misner-Thorne-Wheeler (1973)
  - "...Einstein’s theory identifies gravitation as the mechanism by which matter there influences inertia here."

- Frame-dragging & dark energy?
86 Doctorates (29 Physics; 56 A/A, ME, EE; 1 Math.)
15 Master's Degrees, 5 Engineer's Degrees
14 Doctorates at Other Universities (University of Alabama - Huntsville, Purdue, Harvard, MIT, University of Wisconsin, University of Aberdeen – Scotland)

~ 353 Undergraduates from 11 Departments
~ 55 High School Summer Students