Gravity Probe B

The Engineering of a Physics Experiment in Space & the Role of Students in it

Aero-Astro 50th Anniversary

Francis Everitt
May 9, 2008
The Relativity Mission Concept

"If at first the idea is not absurd, then there is no hope for it."
-- A. Einstein

**Basic formula:**

Leonard Schiff

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

**Oblateness correction:**

* Dan Wilkins (Physics), John Breakwell (AA)
Launch: April 20, 2004 – 09:57:24
Seeing General Relativity Directly

Geodetic effect \[ \text{marc-s/yr} \]

- Einstein expectation \[ -6571 \pm 1^* \]
- 4-gyro result (1\(\sigma\)) \[ -6578 \pm 9 \]

Overall error estimate \( \leq 97 \text{ marc-s/yr} \) based on gyro-to-gyro disagreements & other not yet fully analyzed systematics

SQUID noise limit (4-gyro)
- 353 day continuous \[ \pm 0.12 \]
- segmented data \[ \pm 0.5 - 0.9 \]

\* \(-6606 + 7\) solar geodetic + 28 \(\pm 1\) guide star proper motion

\(1 \text{ marc-sec/yr} = 3.2 \times 10^{-11} \text{ deg/hr} \) – width of a human hair seen from 10 miles
1959 - 63 Early exchanges: Schiff, Fairbank (Physics) - Cannon (AA)

1963 + Physics-Aero/Astro proposal to NASA + Air Force supplement
Design formulated: FE (Physics), Dan DeBra, Dick Van Patten (AA)
Gyro development: John Lipa (Physics), John Nikirk (AA) + other technologies

1968 Transfer to HEPL, culminates 1980 in major NASA, NRC reviews
1984 STORE flight technology program, Lockheed Payload subcontract
Joint AA-HEPL app't Brad Parkinson; joint Physics-HEPL app'ts John Turneaure & John Lipa
late-1993 Flight program starts, Lockheed spacecraft subcontract

Student Participation to date:
83 doctorates, (29 Phys/Ap Phys; 53 AA, EE, ME; 1 Math)
15 Master’s degrees, 5 Engineer’s degrees
13 doctorates completed at other universities
~ 353 undergraduates from 11 departments
~ 51 high school summer students

Engineers as physicists & physicists as engineers
The GP-B Challenge

- Gyroscope (G) 10⁷ times better than best 'modeled' inertial navigation gyros
- Telescope (T) 10³ times better than best prior star trackers
- G – T <1 marc-s subtraction within pointing range
- Gyro Readout calibrated to parts in 10⁵

Basis for 10⁷ advance in gyro performance

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

Cryogenics
- magnetic readout & shielding
- thermal & mechanical stability
- ultra-high vacuum technology

Modeling
*ad hoc* [externally calibrated] vs *absolute*
Areas of Major Student Contributions

- The gyroscope: *suspending, spin-up & readout systems*
- Ultra-low magnetic field technology
- Dewar technology
- Telescope & artificial star
- Spacecraft attitude, translational & roll control
- Tracking & GPS
- Systems engineering & the “Niobium Bird”
- End-to-end error analysis – including TFM
- On-orbit operations
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
Challenge 1:  $< 10^{-11}$ deg/hr Classical Drift

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
Mass-Unbalance, Drag-Free: 2 Near Zeros

Drift-rate \( \Omega = \frac{T}{I\omega_s} \)
Torque \( T = M f \delta r \)
Moment of Inertia \( I = \frac{2Mr^2}{5} \)

**requirement** \( \Omega < \Omega_0 \approx 0.1 \text{ marc-s/yr} \) \((1.54 \times 10^{-17} \text{ rad/s})\)

\[ f \frac{\delta r}{r} < \frac{2}{5} v_s \Omega_0 \]

\[ v_s = \omega_sr = 950 \text{ cm/s} \ (80 \text{ Hz}) \]

On Earth \( (f = g) \)
Standard satellite \( (f \approx 10^{-8} g) \)
GP-B drag-free \( (f \approx 10^{-11} g \text{ cross-axis average}) \)

\[ \frac{\delta r}{r} < 5.8 \times 10^{-18} \] (ridiculous)
\[ \frac{\delta r}{r} < 5.8 \times 10^{-10} \] (unlikely)
\[ \frac{\delta r}{r} < 5.8 \times 10^{-7} \] (attainable)

GP-B rotor \( \frac{\delta r}{r} \approx 3 \times 10^{-7} \)

drift-rate for the drag-free GP-B < 0.05 marc-s/yr

Neither Near Zero alone does it
Self-aligning laps
Uniform rotation-rate, pressure
6 combinations of directions, reversed 2 & 2 every 6 seconds
Continuous-feed lapping compound
Controlled pH
Interested, skilled operators!

MSFC
Wilhelm Angele
John Rasquin
Ed White

STANFORD
Thorwald van Hooydonk
Frane Marcelja
Victor Graham (visitor)

Advanced lapping machine
Dan DeBra & 5 undergraduates, including 1 from Aachen & 1 from Munich, Germany
Asphericity: 3rd Near Zero – The Measuring

Students 1988 - 1992

* Grace Chang (AA)
* Rebecca Eades (Math)
* Benjamin Lutch (undeclared)
* Dave Schleicher (Comp Sci)
* Dieter Schwarz (EE)
* Michael Bleckman (Hamburg)
* Christoph Willsch (Göttingen)

Roundness Measurement to ~ 1 nm
Mass Unbalance (& $\frac{\Delta I}{I}$): 1st Near Zero

* Michael Salomon (AA), * David Santiago (Physics)

Gyro # 1 @ 79.3858 Hz
36-hour polhode period

Paul Shestople, * Michael Dolphin (AA)

Gyro # 1 @ 79.3858 Hz

Mass Unbalance (nm)

<table>
<thead>
<tr>
<th>Gyro #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<td>Prelaunch estimate</td>
<td>18.8</td>
<td>14.5</td>
<td>16.8</td>
<td>13.5</td>
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<tr>
<td>On-orbit data</td>
<td>10.1</td>
<td>4.8</td>
<td>5.4</td>
<td>8.2</td>
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</tbody>
</table>

$\frac{\Delta I}{I} < 2 \times 10^{-6}$
Suspension System Development

1. Honeywell analog ground-based version (1967)
   John Nikirk, Dick Van Patten & John Gill (AA)
   *Chang-Huei Wu (AA) & Yueming Xiao
   *Bill Bencze (EE) & joint Stanford-LMSC team
   including:  Ph.D.’s: Rob Brumley (EE),
   Mike Eglinton (AA) & Yoshimi Ohshima (AA);
   Jennifer Bower (ME, later STEP Ph.D), &
   UGrad: Katie Brumley (UG), Leo DiCarlo
   (Physics) & Eddy Talvala (H.S., now EE Ph.D.)
Flight Suspension Characteristics

Operates over 8 orders of magnitude of g levels

**Flight Modes**
- Science Mission (SM) (Adaptive Authority Torque Minimizing)
- Spin-up & Alignment (Digital DC, SQUID Compatible)

**Ground Test**
- Ground Test (Digital DC, SQUID Compatible)

- Specific force:
  - 10^-7 m/s^2
  - 10^-6 m/s^2
  - 10^-5 m/s^2
  - 1 m/s^2
  - 10 m/s^2

- 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

- Range of motion within cavity (15,000 nm) for:
  - science (centered in cavity)
  - spin-up (offset to spin channel ~ 11,000 nm)
  - calibration (offset, 200 nm increments)
GP-B Gyro On-Orbit Initial Liftoff

Initial gyro levitation and de-levitation using analog backup system

Gyro2 Position Snapshot, VT=135835310.3

- Initial suspension
- Suspension release

Rotor Position (μm)

Time (sec)

½ a hair

Bill Bencze (EE)
David Hipkins (HEPL)
* Yoshimi Ohshima (AA)
Steve Larsen (LM)
Colin Perry (LM) +
many more, including 3 UGrad.
Drag-Free: 2nd Near Zero

**Science Gyro Position**
- Position (nm)
  - Vehicle X
  - Vehicle Y
  - Vehicle Z

**Science Gyro Control Effort**
- Force (nN)
  - Vehicle X
  - Vehicle Y
  - Vehicle Z

**Space Vehicle Thrust**
- Force (mN)
  - Vehicle X
  - Vehicle Y
  - Vehicle Z

**Gyro 1 - Space Vehicle and Gyro Ctrl Effort - Inertial space (2005/200, 14 days)**
- Control effort, m/sec²
  - X Gyro CE
  - X SV CE
  - 2xOrbit

**Cross-axis avg. 1.1 x 10⁻¹¹ g**

**Gravity gradient**

**Roll rate**

Gyro I: The Spin-up Problem(s)

1. Torque Switching Requirement

\[ \frac{T_r}{T_s} < \Omega_0 t_s \sim 10^{-14} \]

\( T_s, T_r \) - spin & residual cross-track torques
\( t_s \) - spin time; \( \Omega_0 \) - drift requirement

2. Differential Pumping Requirement

spin channel ~ 10 torr (sonic velocity)
electrode region < 10^{-3} torr

* Dan Bracken (Physics)
Don Baganoff (AA)
John Turneaure, * Mike Wooding,
* Todd Ramming (both Physics)

"Any fool can get the steam into the cylinders; it takes a clever man to get it out again afterwards." -- G. J. Churchward, ~ 1895
Full Speed Spin of Gyro 4 to 106 Hz

Spin Speed (Hz)

Time in hours

Spin gas manifold

... and then torquing it into alignment (W. Bencze thesis)
Ultra-low Pressure: 5th Near Zero

Low Temperature Bakeout (ground demonstration)

Gyro spindown periods on-orbit (years)

<table>
<thead>
<tr>
<th>Gyro</th>
<th>before bakeout</th>
<th>after bakeout</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>~ 50</td>
<td>15,800</td>
</tr>
<tr>
<td>#2</td>
<td>~ 40</td>
<td>13,400</td>
</tr>
<tr>
<td>#3</td>
<td>~ 40</td>
<td>7,000</td>
</tr>
<tr>
<td>#4</td>
<td>~ 40</td>
<td>25,700</td>
</tr>
</tbody>
</table>

pressure ~ $10^{-14}$ torr
(+ minute patch-effect dampings)

The Cryopump

John Lipa, John Turneaure (Physics) + students; adsorption isotherms for He at low temperature,* Eric Cornell, (undergraduate honors thesis)
**Gyro II: London Moment Readout**

- **SQUID noise**: 190 marc-s/$\sqrt{\text{Hz}}$
- **Centering stability**: < 50 nm
- **DC trapped flux**: < $10^{-6}$ gauss
- **AC shielding**: > ~ $10^{12}$

**4 Requirements/Goals**

- **SQUID noise**: 1 marc-s in 5 hours

**Key students:** G. Gutt (EE), M. Condron (Physics) + 7 SF State Masters’ degrees
Laboratory Demo (1/26/79)

View from above of L M vector of damped, precessing hollow Be rotor (10^{-5} torr pressure).

J. Lipa, J. Anderson, B. Cabrera, R. Clappier & F. van Kann

Five Major Developments to a Flight Instrument

- From ac to dc SQUIDs (100 x lower noise)
- 2 μK control of SQUID & SQUID electronics @ S/C roll
- Non-interfering gyro suspension system (no damping cylinder)
- 240 dB magnetic shielding
- Highest possible S/C roll-rate to beat SQUID 1/f noise

+Niobium Bird*: Hiro Uematsu (AA), Gordy Haupt (AA), Greg Gutt (EE) + ~ 6 undergraduates

*“Niobium Bird”
Gyro Readout Performance On-Orbit

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>
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<tr>
<td>1</td>
<td>353</td>
<td>0.198</td>
</tr>
<tr>
<td>2</td>
<td>353</td>
<td>0.176</td>
</tr>
<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>

Bruce Clarke, Barry Muhlfelder (HEPL), James Lockhart (SF State), Terry McGinnis (LMSC),
Ultra-Low Magnetic Field Technology

Expanding shield reduces field

Final flight lead bag (M. Taber)

Cyclic Bag Expansions
The GP-B Cryogenic Payload

Payload in ground testing at Stanford, August 2002

Notable doctoral dissertations:

* Peter Selzer (Physics) - porous plug for space
* John McCuan (Math) - helium tidal studies
* Chris Lages (AA) - He temp control in dewar
  + 3 UAH engineering dissertations on tide control
Boil-off, Altitude & Thrust - A Subtle Combination

- A very different control system
  - Continuous flow \(\rightarrow\) proportional thrusters
  - Reynolds' # \(\rho v l / \eta \sim 10!!\) -- flowing like honey

- Thrust calibration: * John Bull (AA) + * Jen Heng Chen (AA)

- Lockheed Martin thrusters: Jeff Vanden Beukel
  * Yusuf Jafry (AA) with LM team

He specific impulse vs. mass flow rate
## The GP-B Cryogenic Probe

### Magnetics: J. Mester, J. Lockhart & M. Sullivan

<table>
<thead>
<tr>
<th>Material</th>
<th>Supplier</th>
<th>Remanent (emu)</th>
<th>Susceptibility (emu/g)</th>
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<td><strong>Structural Metals</strong></td>
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<td>Al 6061</td>
<td>Alcoa, Reynolds</td>
<td>≤ 4.0x10^{-7}</td>
<td>7.0x10^{-7}</td>
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<td>Ti 99.6%, Grade 2</td>
<td>Goodfellows, TICO</td>
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<td>3.1x10^{-6}</td>
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<td>Copper 10100 99.99%</td>
<td>Teledyne Wah Chang</td>
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<td>Brush Wallman, NGK</td>
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<td>4x10^{-7}</td>
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<tr>
<td>binary BeCu</td>
<td>NGK Berico</td>
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<td>Sequoia Copper &amp; Brass</td>
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<td>Laird Plastics</td>
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</tr>
</tbody>
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**Probe & Dewar Development Team**

**Lockheed:** Richard Parmley - Lead, Gary Reynolds, Kevin Burns, Mark Molina & many other heroes

**Stanford:** Mike Taber, Dave Murray, Jim Maddocks + students

~30% of cost to meet magnetics requirement

-- R. Parmley
Warm Probe into Cold Dewar

1. Probe in mount

2. Ready for airlock

3. In airlock

4. Insertion into dewar

5. Insertion complete, removing airlock
Challenges 3 & 4: Matching & Calibration

Dither -- Slow 60 marc-s oscillations injected into pointing system

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

Orbital motion $v_{\text{orbit}}/c + \text{special relativity correction}$

- 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
GP-B & GPS: 3 Doctoral Dissertations

- Precision tracking & orientation (Clark Cohen, 1992)
- Orbit injection sensitivity (Penina Axelrad, 1990)
- Potential roll reference (Jeff Crerie, 1993)

...and as a bonus
Star Tracker I: Concept

Some dimensions:

- Physical length: 0.33 m
- Focal length: 3.81 m
- Aperture: 0.14 m

At focal plane:
- Image dia.: 50 μm
- 0.1 marc-s: 0.18 nm

Image Divider
Schematic

Don Davidson
Star Tracker II: Under Test

John Lipa, Jason Gwo, Suwen Wang (Physics, HEPL), Bob Farley (Lockheed), John Goebel (NASA Ames)

Telescope development
* Mo Badi (Ap Phys), * Dana Clark (ME),
* Chris Cumbermack (Pre-med!),
* Howard Shen (EE) + 6 others

Artificial Star #3: Dan DeBra (AA)
* Ted Acworth (AA) * Rob Bernier (AA)

Detector Package
Si Diode Detector
• Initial investigations
  Richard Vassar (AA 1971)
  Thierry Duhamel (AA 1974)

• Detailed preflight error tree (both torque & measurement errors)
  M. Keiser, A. Silbergleit, M. Heifetz, +
  *J. Kasdin (AA), *Y. Ohshima (AA),
  *I. Mandel (Physics ug), *D. Makarov (SF State ug) & others

• Preflight data analysis tools
  - Signal generators
  - Preprocessing algorithms
  - 2-step estimators
  - End-to-end tests
  Heifetz, Keiser, Silbergleit, Solomonik, +
  *Mandel, *A. Neinenmann, *A. Krechetov,
  *J. Berberian & *D. Santiago (all Physics)
On-Orbit: GP-B Mission Operations

Anomaly Room

Marcie Smith (NASA Ames)
Kim Nevitt (NASA MSFC)
Rob Nevitt (NavAstro)
Brett Stroozas (NavAstro)
Lewis Wooten (NASA MSFC)
Ric Campo (Lockheed Martin)
Jerry Aguinado (LM) + many more, including ~ 25 graduate & undergraduate students
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 Harrison & Cavendish]

Surprise A – Polhode-rate variations affect $C_g$ determinations
Surprise B – Larger than expected misalignment torques

Two mutually reinforcing gremlins
Two Mutually Reinforcing Gremlins

- Polhode-rate variations affect \( C_g \) determinations

Polhode Period (hours) vs Elapsed Time (days) since January 1, 2004

- Larger than expected misalignment torques

Mean Rate (marc-s/day) vs Mean Misalignment Gyro 3 (arc-s)

Both originate in much larger than expected ‘patch effect’ asymmetries on rotor & housing
Polhoding, Trapped Flux & $C_g$

- $C_g$ approaching $10^{-5}$ linking data from many orbits
- The actual 'London moment' readout:

<table>
<thead>
<tr>
<th>Gyro</th>
<th>Trapped fields</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>3.0 $\mu$G</td>
</tr>
<tr>
<td>2</td>
<td>1.3 $\mu$G</td>
</tr>
<tr>
<td>3</td>
<td>0.8 $\mu$G</td>
</tr>
<tr>
<td>4</td>
<td>0.2 $\mu$G</td>
</tr>
</tbody>
</table>

London field at 80 Hz: 57.2 $\mu$G

- 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 (TFM) results
Trapped Flux Mapping: 3 Key AA Dissertations

- **Gyro Motion:**
  - Spin speed to ~ 10 nHz (x 1000 improvement)
  - Spin down rate to ~ 1pHz/s (x 100 improvement)
  - Polhode phase to ~ 2° (x 100 improvement)

- **Trapped Flux Distribution**

M. Dolphin
J. Conklin
M. Salomon

Polhode, spin parameters

Magnetic potential map

Fluxon map
Explicit Torque Models & Continuous Estimation & Filtering

- Consistent Floor 1/Floor 2 processing
- Gyro orientation profiles based on 5-day moving window
- Common relativity, roll-phase offset & vehicle pointing inputs for 4 gyros
- Continuous Guide-Star Valid / Guide-Star Invalid pointing history
85-day result

\[ R_{NS} = -6632 \pm 43 \text{ marc-s/yr} \]

\[ R_{WE} = -82 \pm 13 \text{ marc-s/yr} \]
Locking down the Final Results

Trapped flux mapping – first key.  Nov ‘08
  • Full separation of $C_G$ and torque effects.

Systematic removal of systematic errors – second key  May ‘09
  • Identify and physically model sources.
  • Cross-check against alternate monitors and ground hardware.

Finalize post-flight error tree – last key  Sep ’09
  • Cross checks from bottom-up/top-down analysis.
  • SAO-measured guide star proper motion “double-blind” test.

Detailed SAC peer-review & final publication  Mar ‘10

Completion of Mission

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<thead>
<tr>
<th></th>
<th>Geodetic</th>
<th>Frame-dragging</th>
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</thead>
<tbody>
<tr>
<td>Advanced, fine-grain</td>
<td>~2 (0.05%)</td>
<td>~2 (3-6%)</td>
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<tr>
<td>processing on full data set</td>
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<td>Complete systematic</td>
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<tr>
<td>error bounding</td>
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Geodetic Frame-dragging (marcsec/yr, % uncertainty)