Gravity Probe B

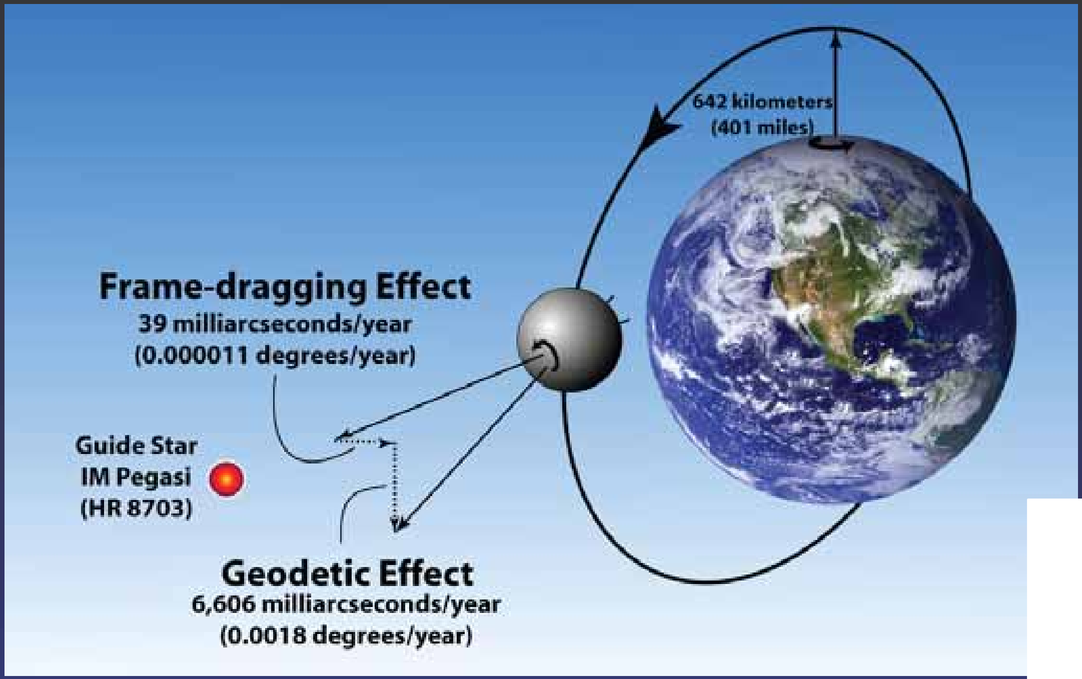
The Engineering of a Physics Experiment in Space & the Role of Students in it

Aero-Astro 50th Anniversary

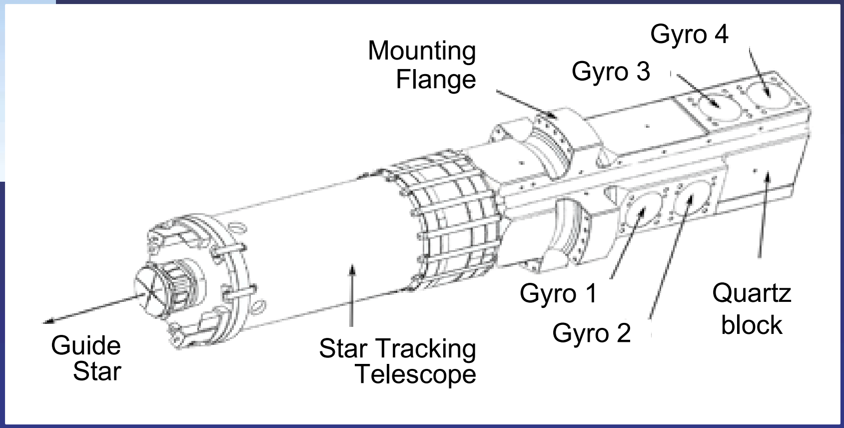
Francis Everitt

May 9, 2008

The Relativity Mission Concept



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



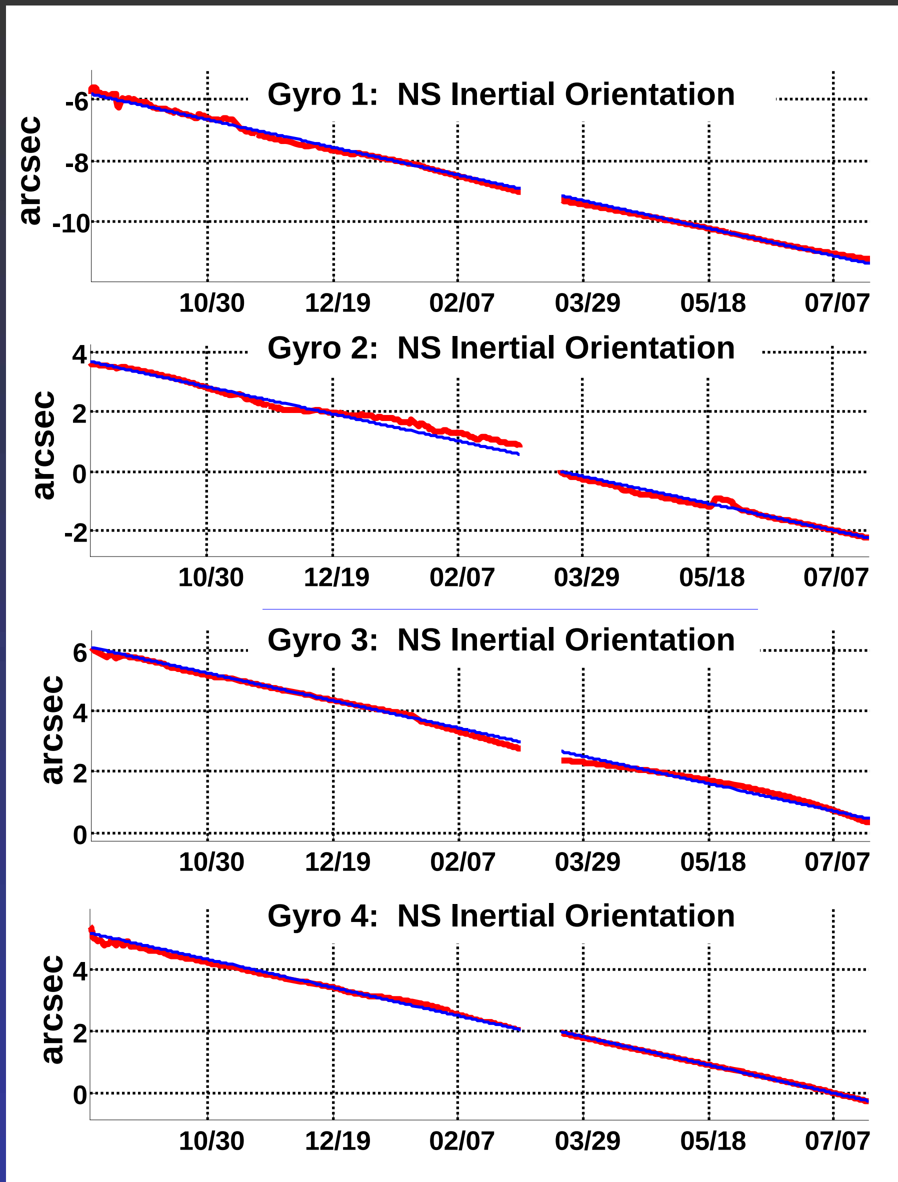
- Basic formula: *Leonard Schiff*

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

- Oblateness correction: ** Dan Wilkins (Physics), John Breakwell (AA)*

Launch: April 20, 2004 – 09:57:24

Seeing General Relativity Directly



Red: Raw flight data
Blue: With torque modeling (4 gyros co-processed)

Geodetic effect	marc-s/yr
Einstein expectation	- 6571 ± 1*
4-gyro result (1σ)	- 6578 ± 9
Overall error estimate ≤ 97 marc-s/yr based on gyro-to-gyro disagreements & other not yet fully analyzed systematics	
SQUID noise limit (4-gyro)	
- 353 day continuous	± 0.12
- segmented data	± 0.5 - 0.9

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

1 marc-sec/yr = 3.2 × 10^{-11} deg/hr – width of a human hair seen from 10 miles

Growth of a Partnership

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

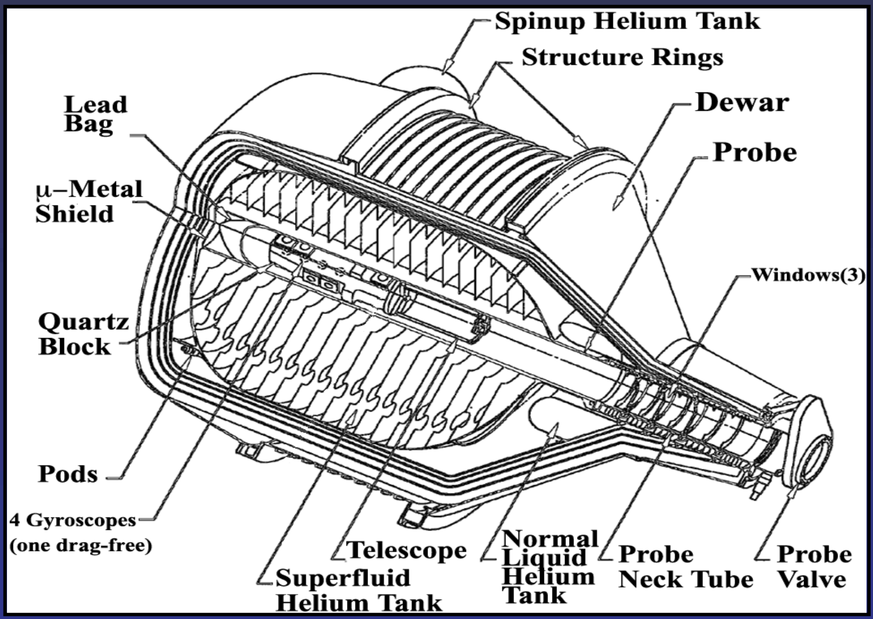
Student Participation to date:

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) — 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



Basis for 10^7 advance in gyro performance

Space

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

Cryogenics

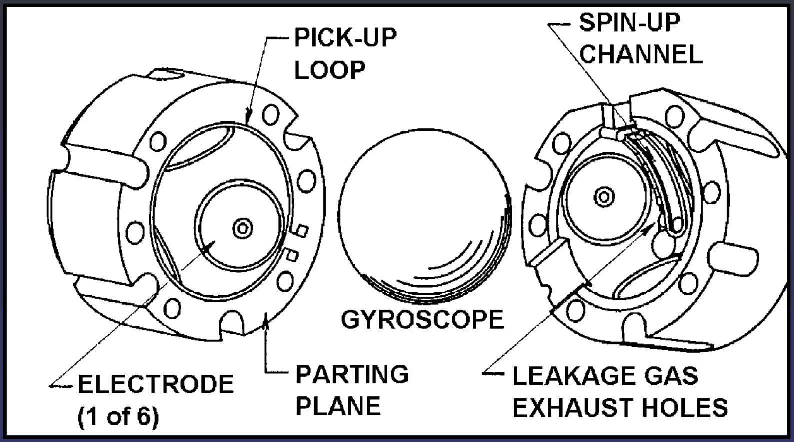
- magnetic readout & shielding
- thermal & mechanical stability
- ultra-high vacuum technology

Modeling — *ad hoc* [externally calibrated] vs *absolute*

Areas of Major Student Contributions

- The gyroscope: *suspension, 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**

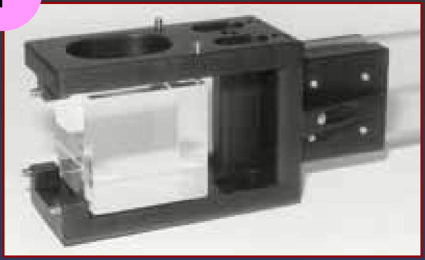
"Everything should be made as simple as possible, but not simpler."
-- A. Einstein

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**

1



2

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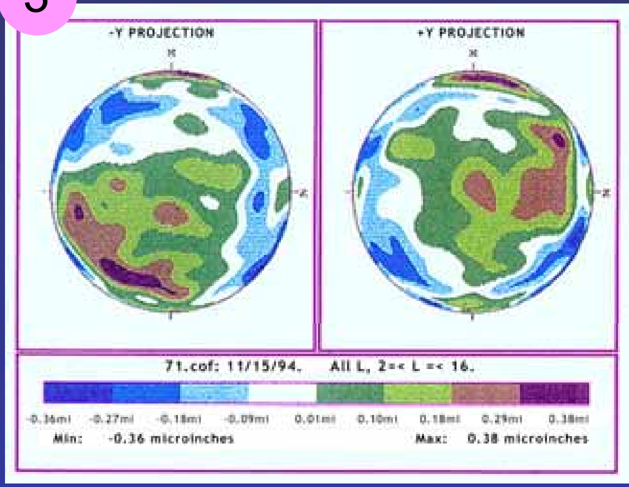
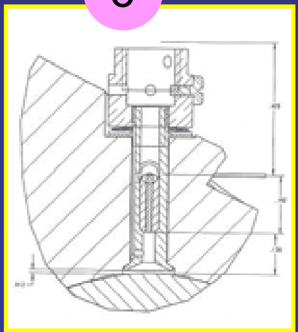
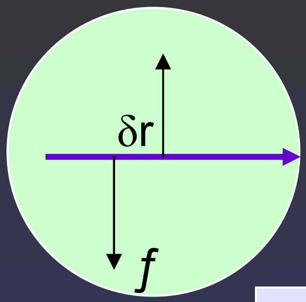


5

6



Mass-Unbalance, Drag-Free: 2 Near Zeros



Drift-rate $\Omega = T / I\omega_s$

Torque $T = M\, f\, \delta r$

Moment of Inertia $I = 2Mr^2/5$

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

$$f \,\frac{\delta r}{r} < \frac{2}{5}\, v_s\, \Omega_0$$

$v_s = \omega_s r = 950$ cm/s (80 Hz)

On Earth (f = g)	$\frac{\delta r}{r} < 5.8 \times 10^{-18}$ *(ridiculous)*
Standard satellite ($f \sim 10^{-8}$ g)	$\frac{\delta r}{r} < 5.8 \times 10^{-10}$ *(unlikely)*
GP-B drag-free ($f \sim 10^{-11}$ g cross-axis average)	$\frac{\delta r}{r} < 5.8 \times 10^{-7}$ *(attainable)*

GP-B rotor $\frac{\delta r}{r} \sim 3 \times 10^{-7}$

⇓

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

Neither Near Zero alone does it

Asphericity: 3rd Near Zero – The Making

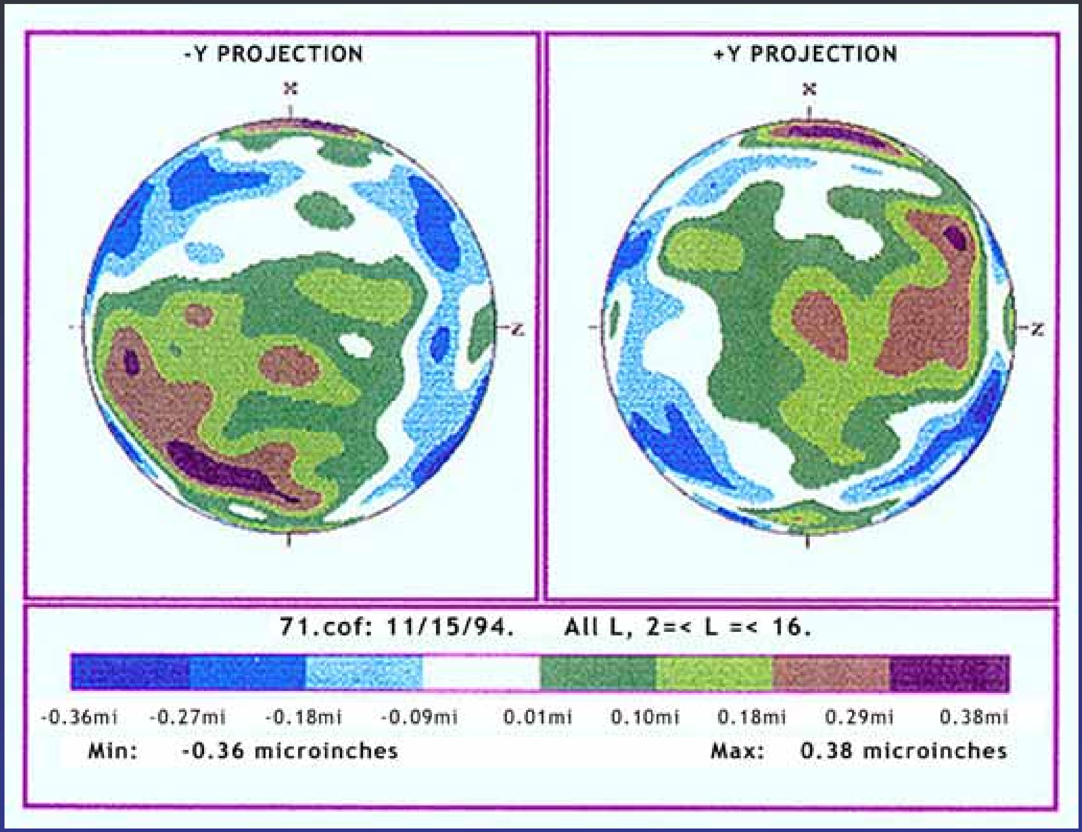
- **Self-aligning laps**
- **Uniform rotation-rate, pressure**
- **6 combinations of directions, reversed 2 & 2 every 6 seconds**
- **Continuous-feed lapping compound**
- **Controlled pH**
- **Interested, skilled operators!**

MSFC	STANFORD
Wilhelm Angele	**Thorwald van Hooydonk**
John Rasquin	**Frane Marcelja**
Ed White	**Victor Graham (visitor)**

Advanced lapping machine

Dan DeBra & 5 undergraduates, including 1 from Aachen & 1 from Munich, Germany

Asphericity: 3rd Near Zero – The Measuring

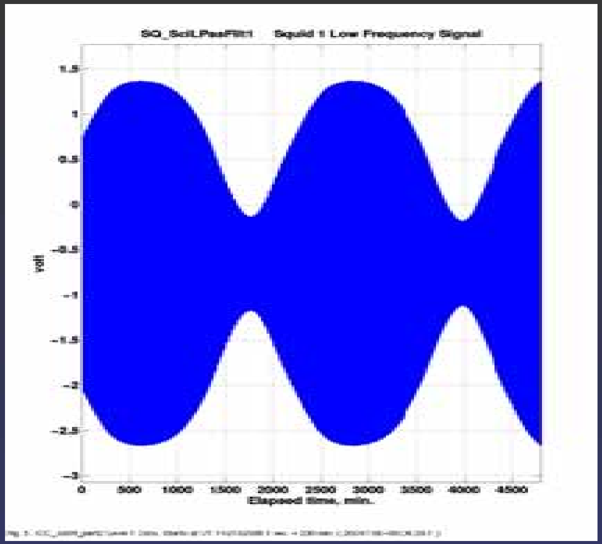


Students 1988 - 1992

- * 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

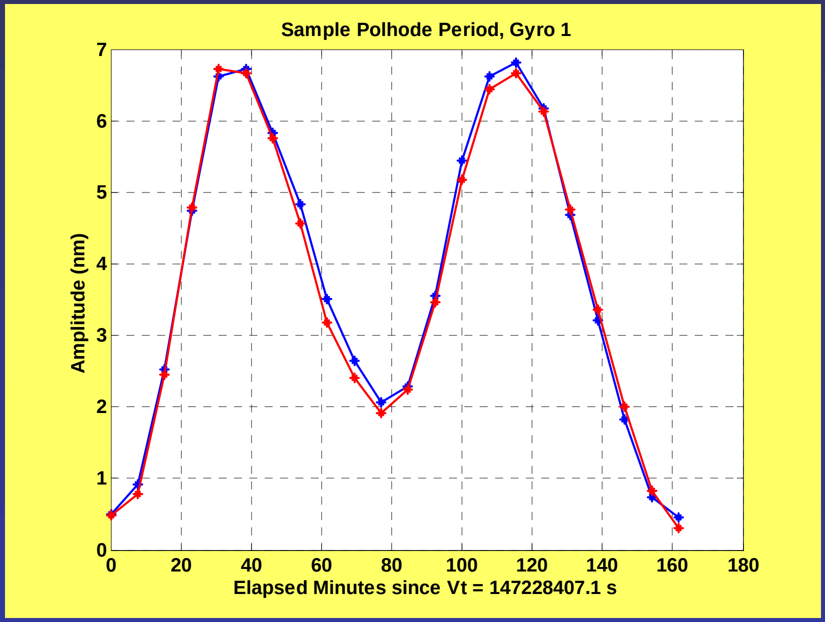


* Michael Salomon (AA), * David Santiago (Physics)

Gyro # 1 @ 3 Hz

36-hour polhode period

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



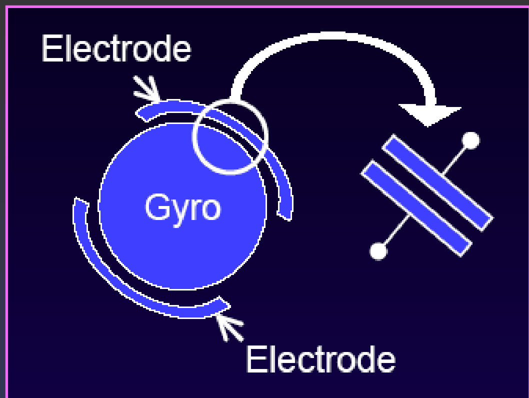
Paul Shestople, * Michael Dolphin (AA)

Gyro # 1 @ 79.3858 Hz

Mass Unbalance (nm)

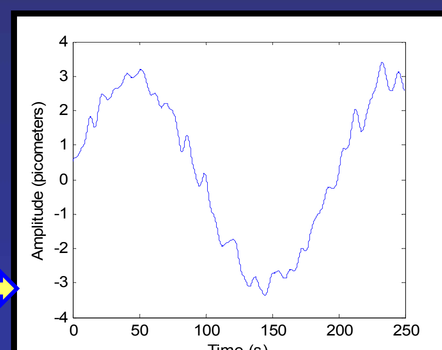
Gyro #	1	2	3	4
Prelaunch estimate	18.8	14.5	16.8	13.5
On-orbit data	10.1	4.8	5.4	8.2

Suspension System Development

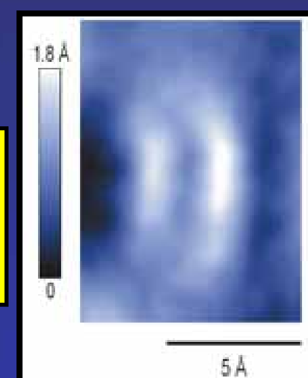


1. Honeywell analog ground-based version (1967)
2. Stanford analog ground-based version (1974)
   John Nikirk, Dick Van Patten & John Gill (AA)
3. Digital ground-based version (1991)
   **Chang-Huei Wu (AA) & Yueming Xiao*
4. Digital flight version operating over 8 orders of magnitude (1993-1996)
   **Bill Bencze (EE) & joint Stanford-LMSC team including: Ph.D.'s: Rob Brumley (EE), Mike Eglington (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.)*

Commanded sine-wave position of Gyro Hardware Simulator

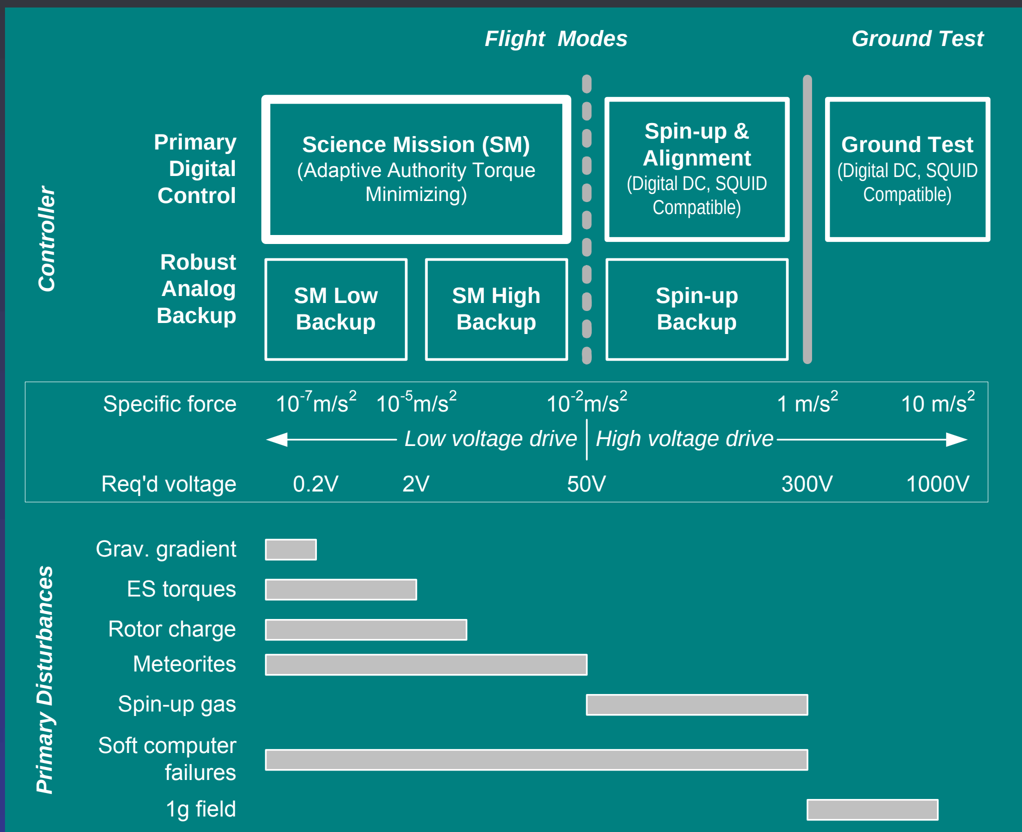


Simulator Resolution 1/50 dia. of silicon atom!



Flight Suspension Characteristics

Operates over 8 orders of magnitude of g levels



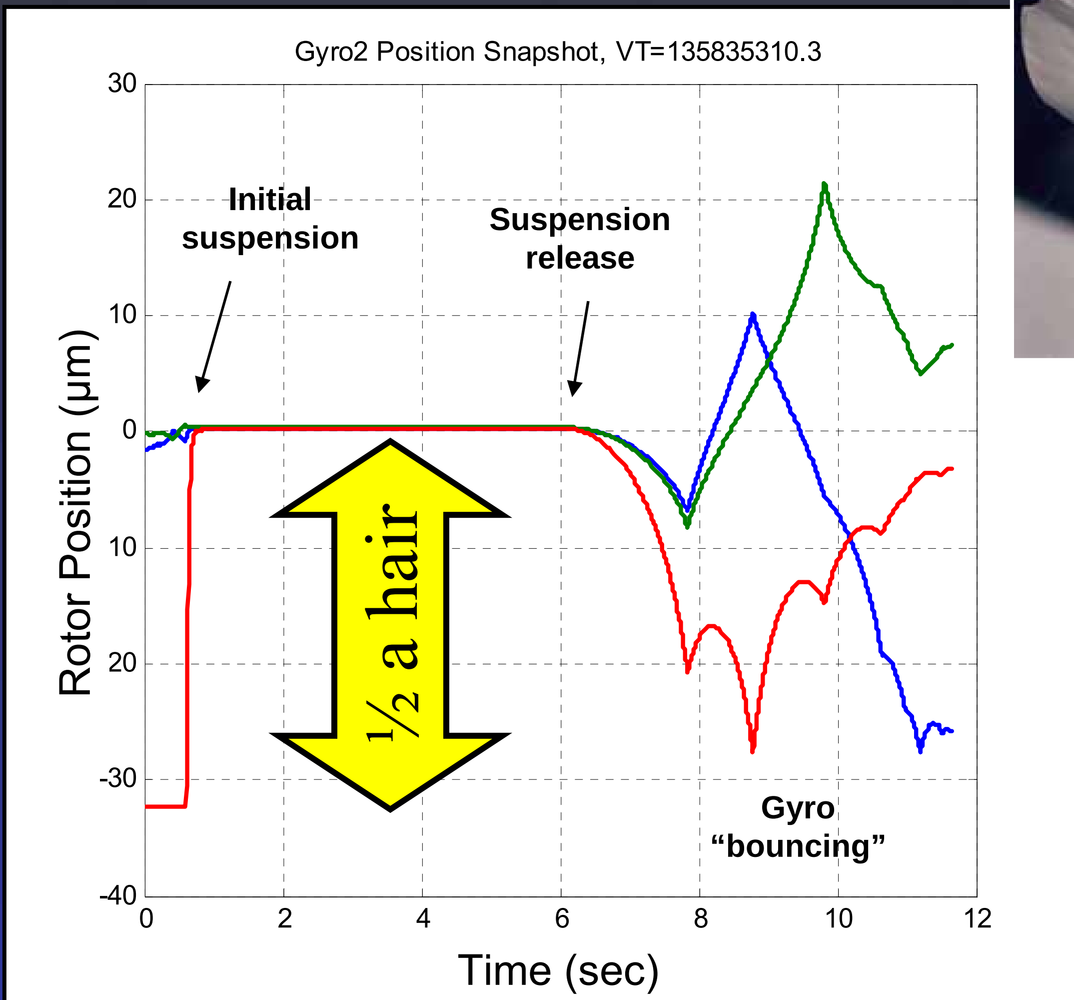
DSP + Power Supply

Analog drive, Backup control

- 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)

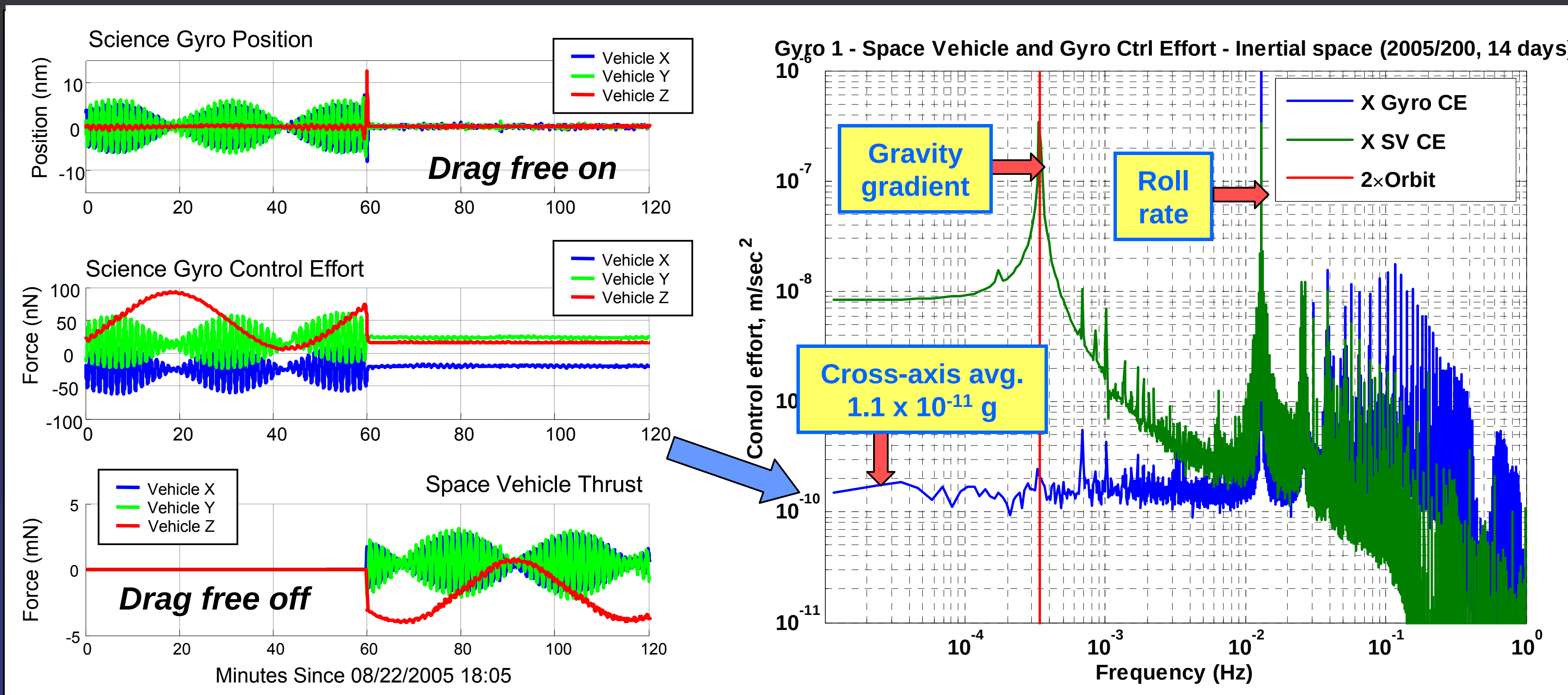
GP-B Gyro On-Orbit Initial Liftoff

Initial gyro levitation and de-levitation
using analog backup system



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



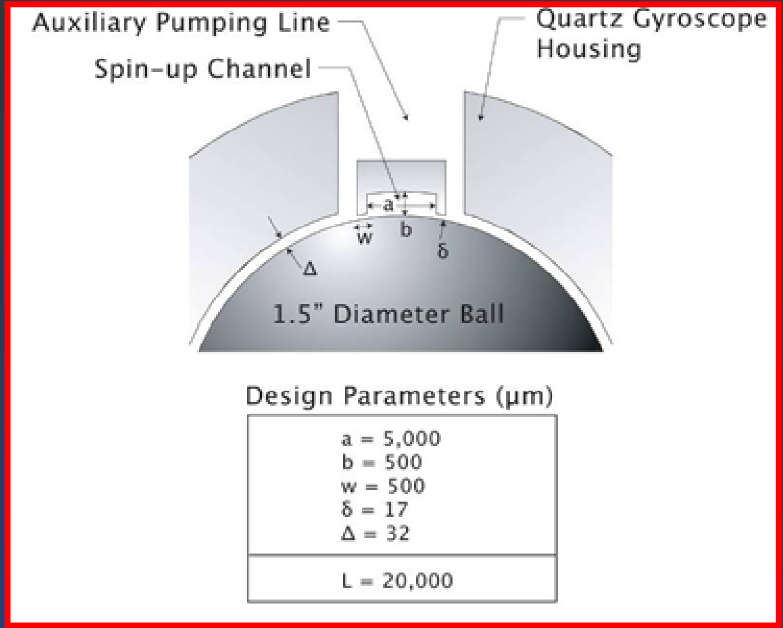
Dan DeBra, *John Bull (AA), *J-H Chen (AA),
*Yusuf Jafry (AA), Jeff Vanden Beukel + team (LM)

Gyro I: The Spin-up Problem(s)

1 Torque Switching Requirement

$T_r/T_s < \Omega_0\, t_s \sim 10^{-14}$

T_s, T_r - spin & residual cross-track torques
t_s - spin time; Ω_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)

3

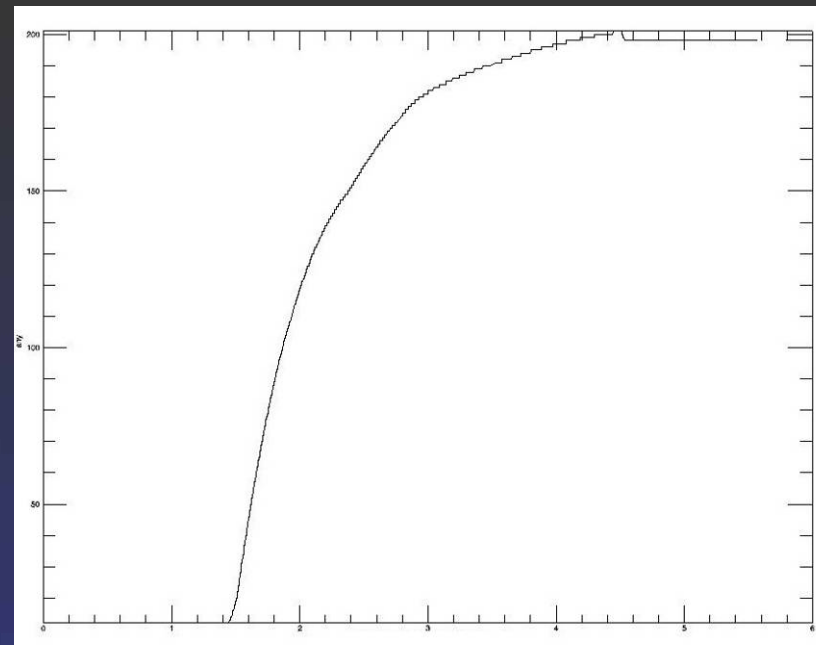
"Any fool can get the steam into the cylinders; it takes a clever man to get it out again afterwards." -- G. J. Churchward, ~ 1895

Full Speed Spin of Gyro 4 to 106 Hz

110

Spin Speed (Hz)

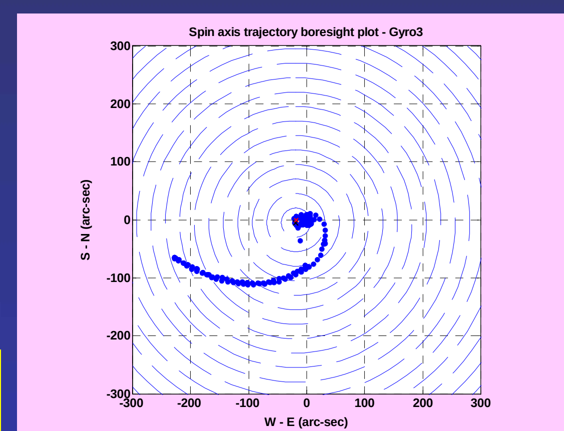
55



Time in hours

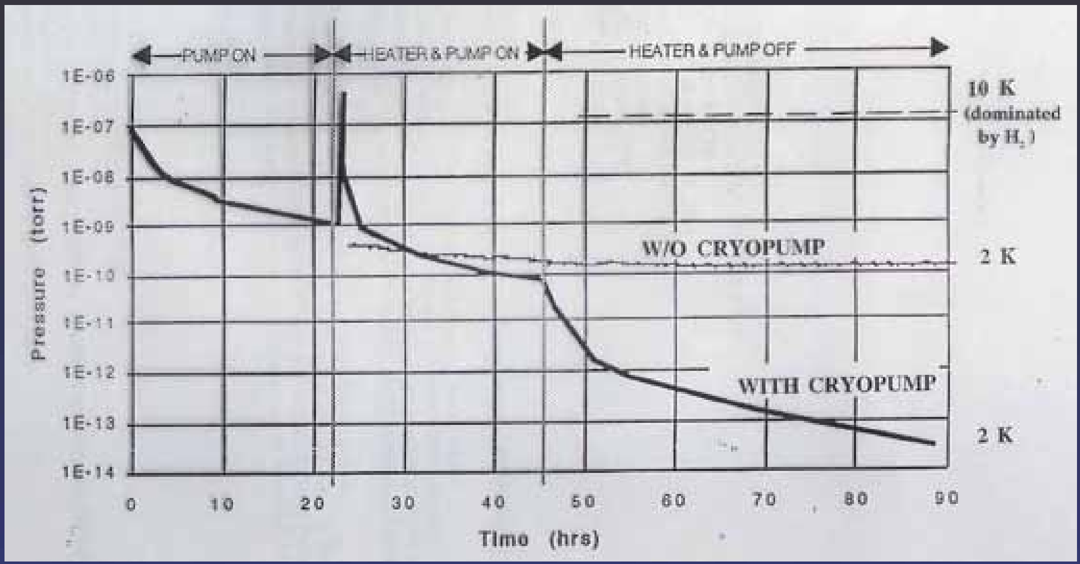
Spin gas manifold

… and then torquing it into alignment (W. Bencze thesis)



Ultra-low Pressure: 5th Near Zero

Low Temperature Bakeout (ground demonstration)



The Cryopump

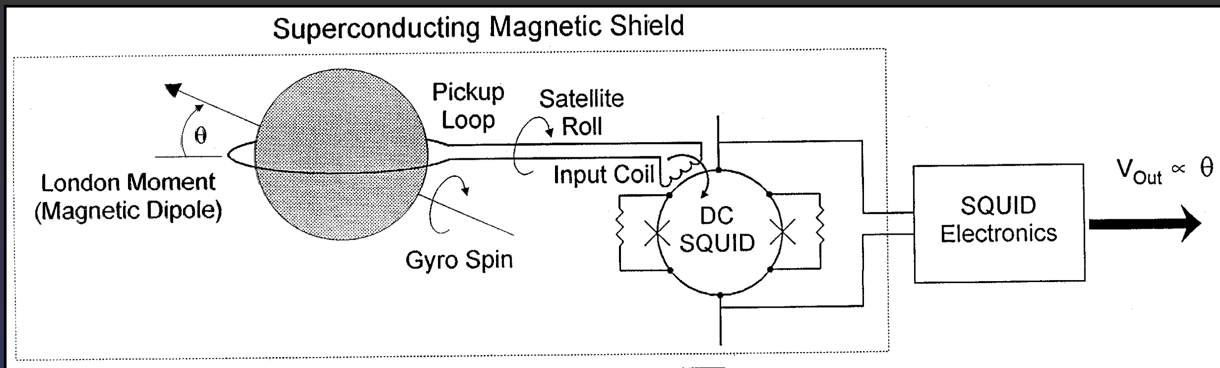
Gyro spindown periods on-orbit (years)

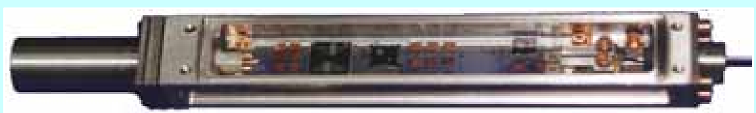
	before bakeout	after bakeout
Gyro #1	~ 50	15,800
Gyro #2	~ 40	13,400
Gyro #3	~ 40	7,000
Gyro #4	~ 40	25,700

John Lipa, John Turneaure (Physics) + students; adsorption isotherms for He at low temperature,* Eric Cornell, (undergraduate honors thesis)

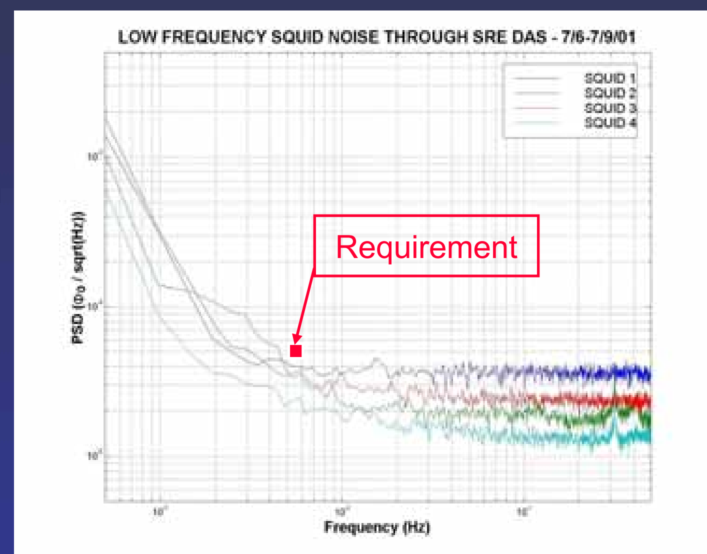
pressure ~ 10^{-14} torr
(+ minute patch-effect dampings)

Gyro II: London Moment Readout





"SQUID" ⟶ 1 marc-s in 5 hours

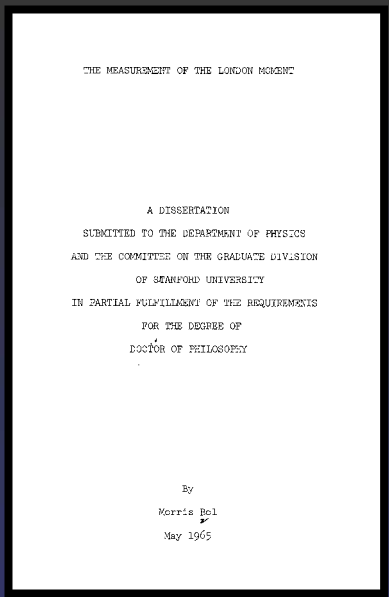


4 Requirements/Goals

- SQUID noise 190 marc-s/√Hz
- Centering stability < 50 nm
- DC trapped flux < 10^{-6} gauss
- AC shielding > ~ 10^{12}

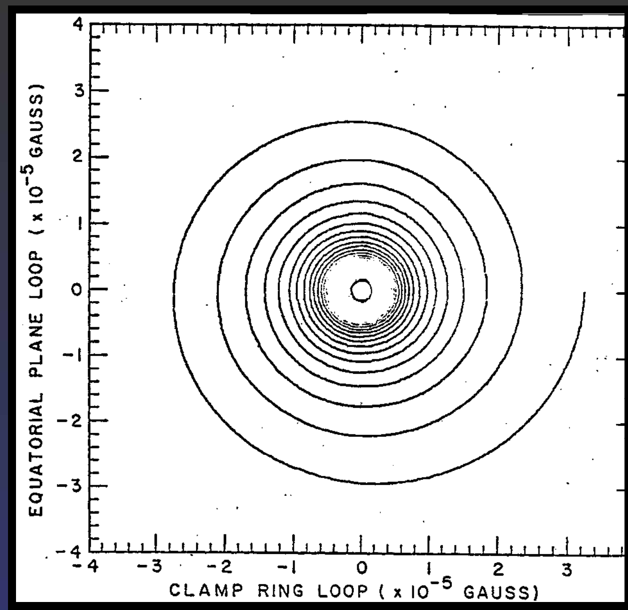
Key students: G. Gutt (EE), M. Condron (Physics) + 7 SF State Masters' degrees

L M Readout: Some of the Many Steps


THE MEASUREMENT OF THE LONDON MOMENT

A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF PHYSICS
AND THE COMMITTEE ON THE GRADUATE DIVISION
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

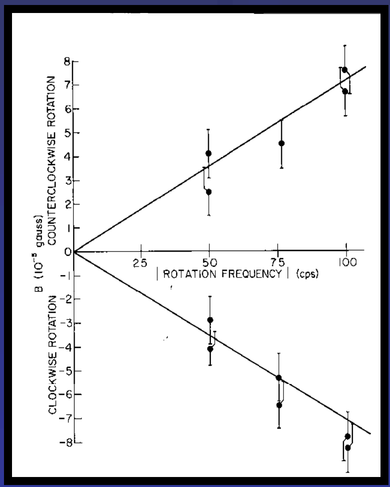
By
Morris Bol
May 1965



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

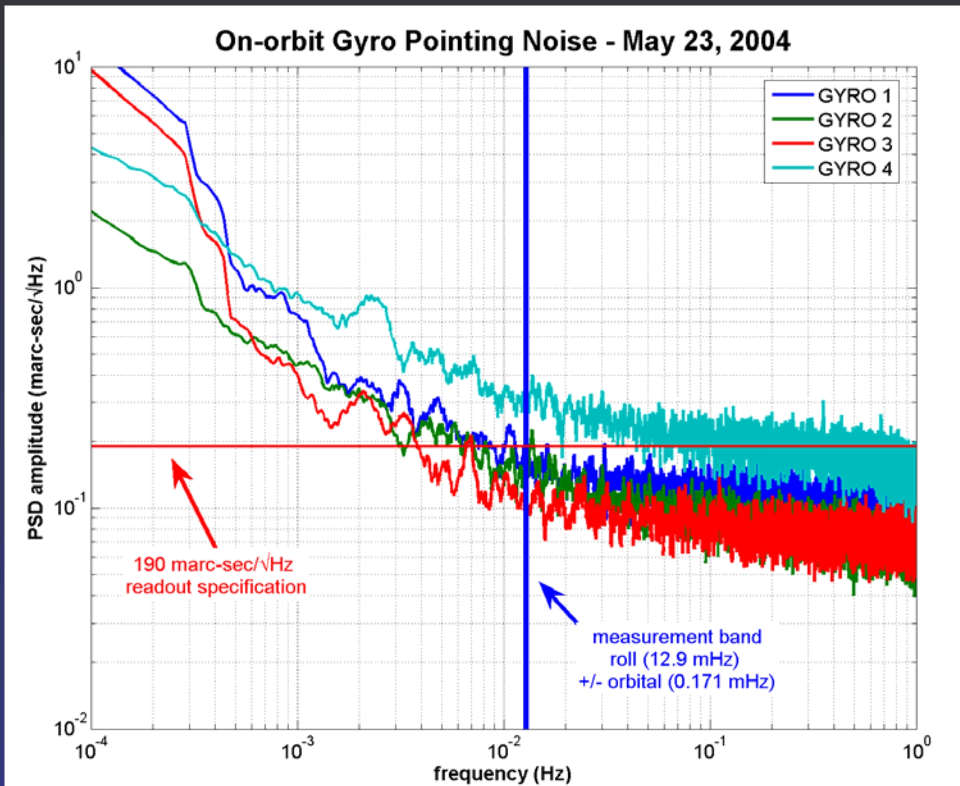


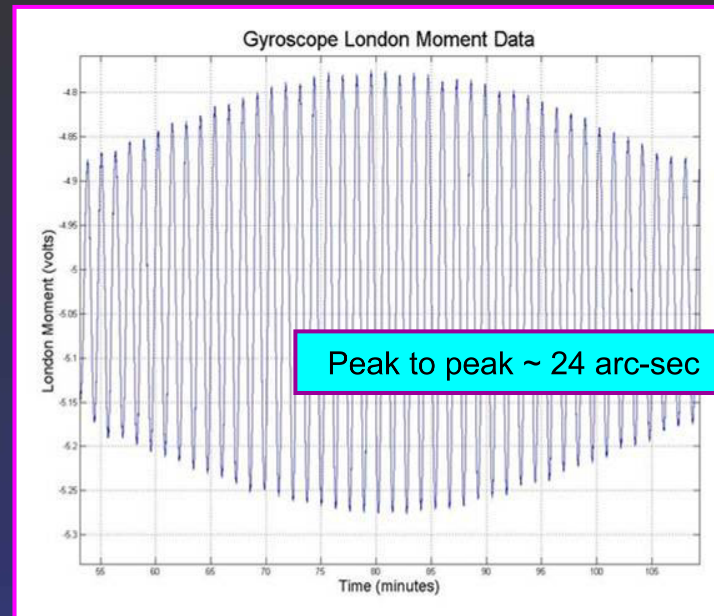
Five Major Developments to a Flight Instrument

- 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

Gyro Readout Performance On-Orbit



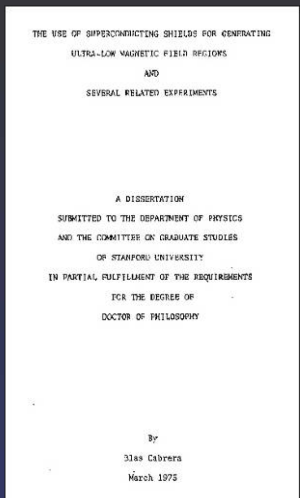


Gyro	Experiment Duration (days)	SQUID Readout Limit (marc-s/yr)
1	353	0.198
2	353	0.176
3	353	0.144
4	340	0.348

Bruce Clarke, Barry Muhlfelder (HEPL), James Lockhart (SF State), Terry McGinnis (LMSC),

NASA
STANFORD UNIVERSITY
LOCKHEED MARTIN

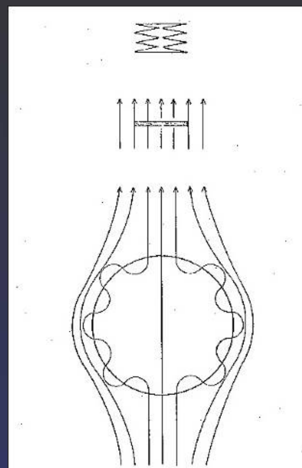
Ultra-Low Magnetic Field Technology



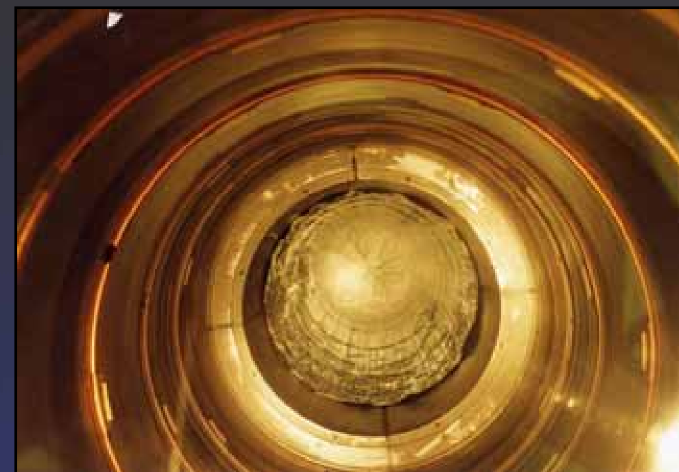
THE USE OF SUPERCONDUCTING SHIELDS FOR GENERATING
ULTRA-LOW MAGNETIC FIELD REGIONS
AND
SEVERAL RELATED EXPERIMENTS

A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF PHYSICS
AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

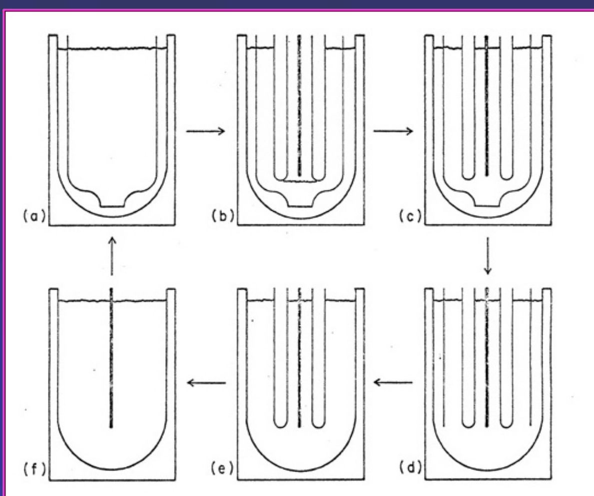
By
Blas Cabrera
March 1975



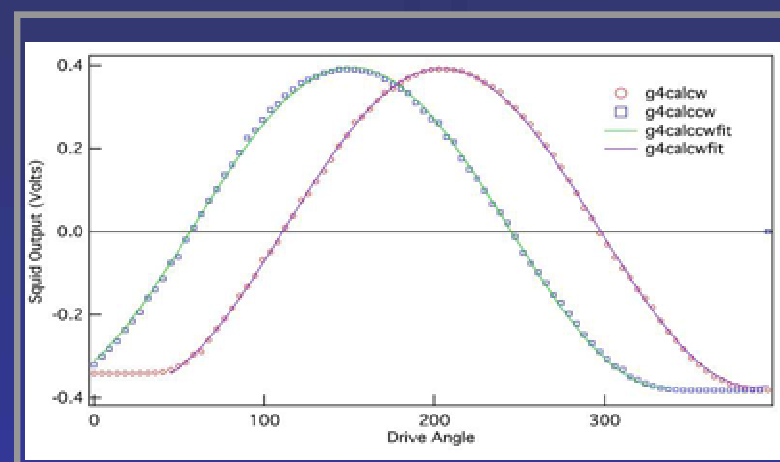
Expanding shield reduces field



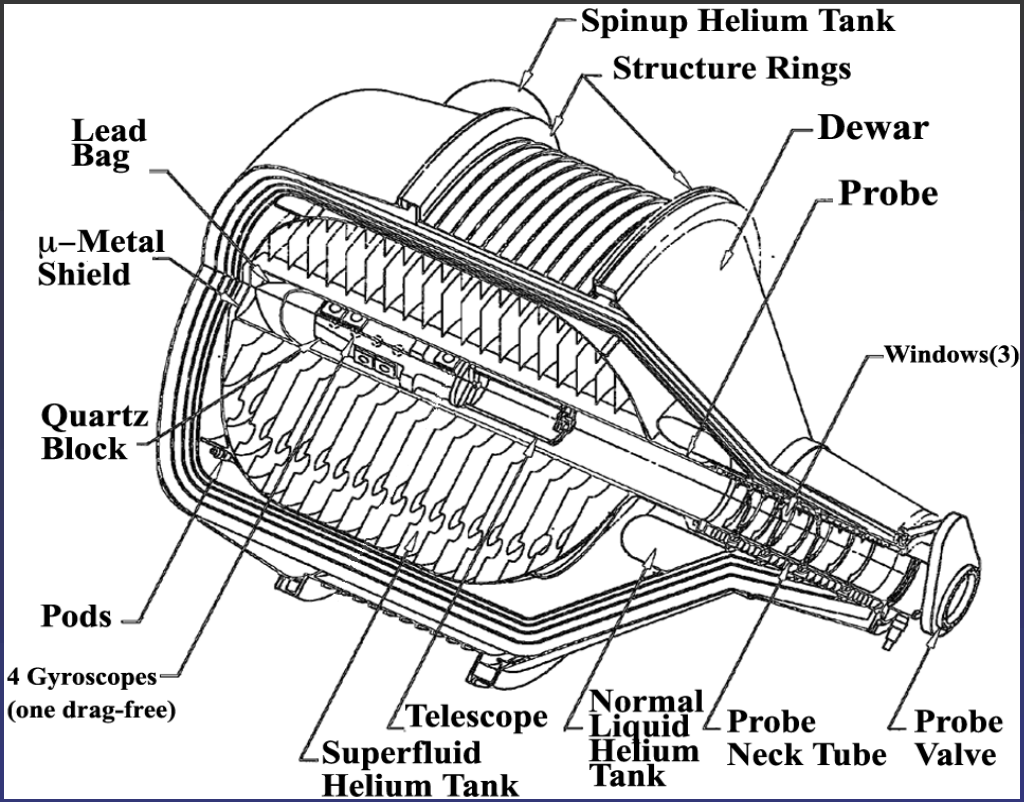
Final flight lead bag (M. Taber)



Cyclic Bag Expansions



The GP-B Cryogenic Payload



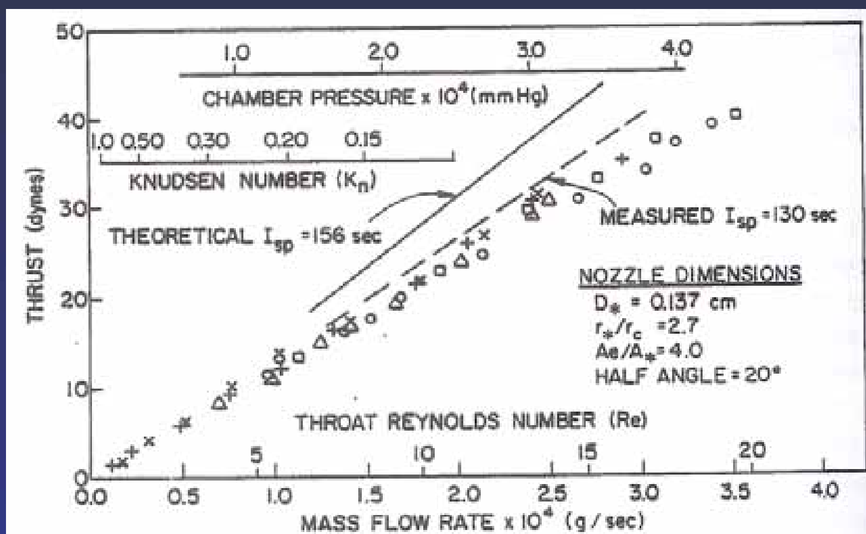
Notable doctoral dissertations:

* 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

Payload in ground testing at Stanford, August 2002

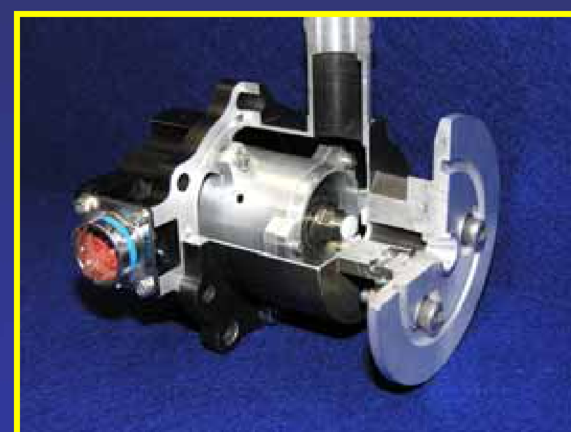
Boil-off, Altitude & Thrust - A Subtle Combination

- **A very different control system**
  - Continuous flow ➡ proportional thrusters
  - Reynolds' # ρv*l*/η ~ 10!! -- flowing like honey
- **Thrust calibration:** * John Bull (AA) + * Jen Heng Chen (AA)



He specific impulse vs.mass flow rate

- **Lockheed Martin thrusters:** Jeff Vanden Beukel



* Yusuf Jafry (AA) with LM team

The GP-B Cryogenic Probe

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

Material	Supplier	Remanent (emu)	Susceptibility (emu/g)
Structural Metals			
Al 6061	Alcoa, Reynolds	$\leq 4.0 \times 10^{-7}$	7.0×10^{-7}
Ti 99.6%, Grade 2	Goodfellow, TiCo	$\leq 2.5 \times 10^{-7}$	3.1×10^{-6}
Nb Type 1	Teledyne Wah Chang	$\leq 4.0 \times 10^{-7}$	2.5×10^{-6}
Copper 10100 99.99%	Sequoia Copper & Brass	$\leq 3.0 \times 10^{-7}$	2.5×10^{-7}
BeCu 25 C17200	Brush Wellman, NGK	$\leq 3.1 \times 10^{-6}$	4×10^{-7}
BeCu 125	Brush Wellman	1.7×10^{-7}	1.5×10^{-7}
binary BeCu	NGK Berylco	$\leq 1.9 \times 10^{-7}$	2×10^{-8}
binary BeCu	Ames Research Iowa St.	$\leq 9.7 \times 10^{-8}$	4.3×10^{-8}
BeCu 3HP	Brush Wellman	$\leq 6.5 \times 10^{-7}$	8.3×10^{-8}
TI Cu unsc19900	Yamaha Metals	$\leq 3.0 \times 10^{-7}$	3.7×10^{-7}
Si Bronze	Sequoia Copper & Brass	$0.3 - 2 \times 10^{-4}$	-4.5×10^{-7}
Phos Bronze C-51000	Copper & Brass Sales	$\leq 2 \times 10^{-5}$	$\leq 3.0 \times 10^{-6}$
Phos Bronze Custom	Ames Research Iowa St.	$1 - 4.7 \times 10^{-7}$	$1 \times 10^{-6} - 3 \times 10^{-6}$
Molybdenum 99.97%	CSM Industries	$\leq 4.5 \times 10^{-7}$	9.6×10^{-7}
Structural Dielectrics			
Teflon	Dupont	$\leq 9.0 \times 10^{-7}$	$- 5.0 \times 10^{-8}$
Delrin	Laird Plastics	$\leq 5 \times 10^{-8}$	$- 4.7 \times 10^{-7}$
Kapton	Dupont	$\leq 2.0 \times 10^{-7}$	1.6×10^{-7}
Vespel	Dupont	$\leq 6.6 \times 10^{-7}$	8×10^{-7}
PEEK	E Jordon Brooks	$\leq 9.2 \times 10^{-7}$	1×10^{-7}
Sapphire	Saphikon Inc.	$\leq 7.4 \times 10^{-8}$	-1.2×10^{-7}
Quartz	Corning, Hereas Amersil	$\leq 1.5 \times 10^{-7}$	-1.1×10^{-7}
Wire and Ribbon			
Manganin .005"	Lakeshore Cryotronics	2.4×10^{-4}	1.8×10^{-4}
Phosphor Bronze	California Fine Wire	$\leq 2.5 \times 10^{-6}$	
Copper 38 Gauge	Belden	4.0×10^{-7}	$- 3.7 \times 10^{-8}$
Platinum-Tungsten	California Fine Wire	1.4×10^{-6}	3.3×10^{-6}
NbTi .005"/.010"	California Fine Wire	$\leq 1.8 \times 10^{-6}$	2.0×10^{-6}
Silver Ribbon .004"	California Fine Wire	1.5×10^{-8}	2.7×10^{-8}
Special			
Si Diode Therm	Lakeshore Cryotronics	1.0×10^{-6}	
Ge Therm 1500B	Lakeshore Cryotronics	$0.5 / 2 \times 10^{-6}$	
Permalloy 55145-A2	Magnetics Corp.	2×10^{-6}	
Indium 99.99%	Indium Corp. of America	3.0×10^{-7}	7.8×10^{-8}
Indium #150 Solder	Indium Corp. of America	7.0×10^{-8}	2.3×10^{-7}
PbSn 60-40 Solder	Kester	$\leq 7.0 \times 10^{-8}$	2.5×10^{-8}
Poly shrink tubing	Advanced Polymers Inc	$\leq 8.0 \times 10^{-7}$	1.3×10^{-6}
Trabond 2115 Epoxy	Tra-Con	$\leq 2.4 \times 10^{-7}$	-3.5×10^{-7}
Stycast 1266 Epoxy	Emerson & Cuming	$\leq 7 \times 10^{-8}$	-4.6×10^{-7}
Silver Epoxy 83-C	Emerson & Cuming	$\leq 2.3 \times 10^{-6}$	8.8×10^{-7}

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 ➡

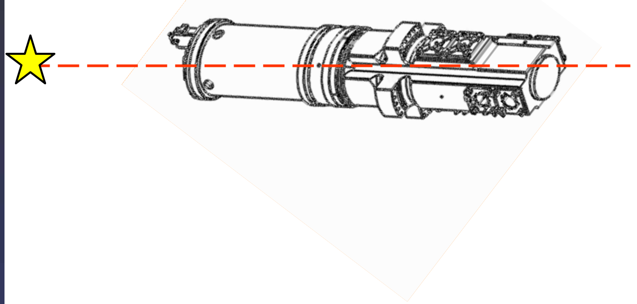
3 In airlock

5 Insertion complete, removing airlock ➡

4 Insertion into dewar

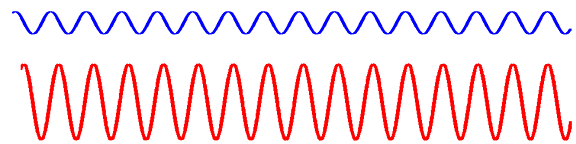
Challenges 3 & 4: Matching & Calibration

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



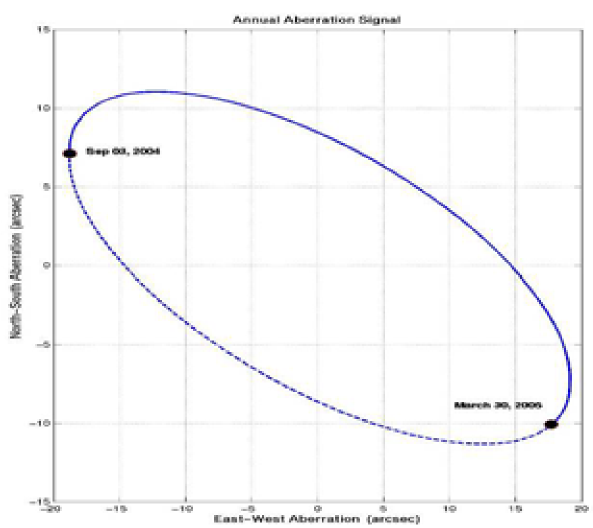
gyro output

telescope output



scale factors matched for accurate subtraction

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



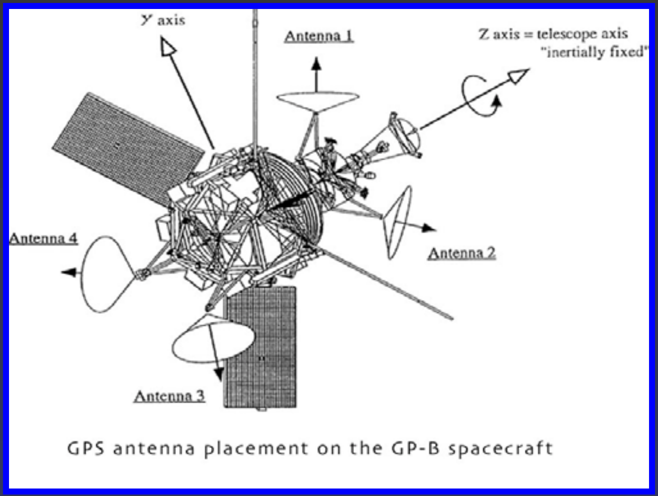
Orbital motion → varying apparent position of star (v_{orbit}/c + special relativity correction)

Earth around Sun -- 20.4958 arc-s @ 1-year period

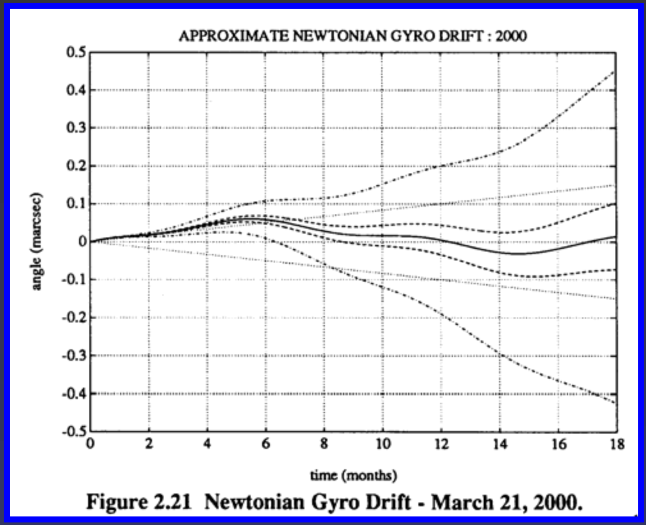
S/V around Earth -- 5.1856 arc-s @ 97.5-min period

→ Continuous accurate calibration of GP-B experiment

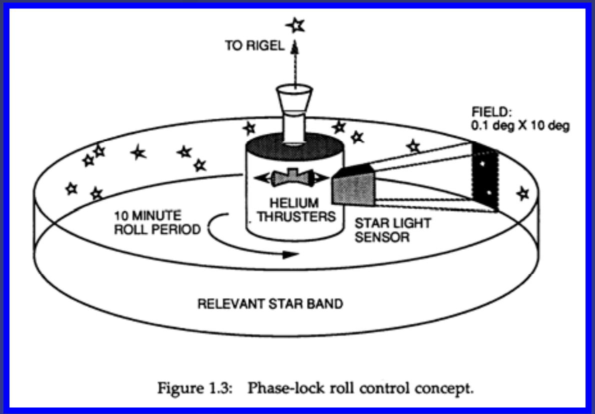
GP-B & GPS: 3 Doctoral Dissertations



Precision tracking & orientation
(Clark Cohen, 1992)



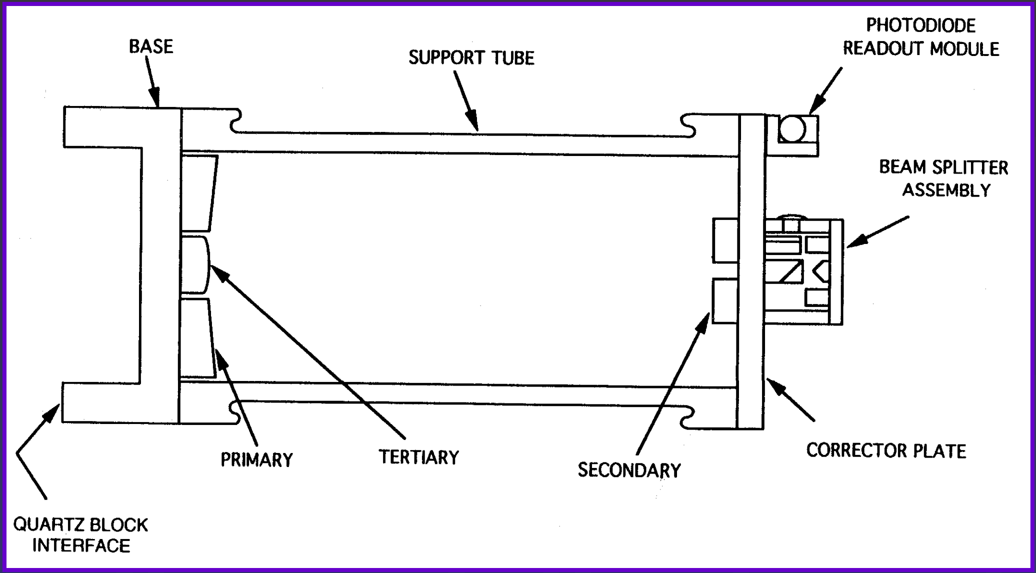
Orbit injection sensitivity
(Penina Axelrad, 1990)



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
<u>At focal plane</u>	
Image dia.	50 µm
0.1 marc-s	0.18 nm

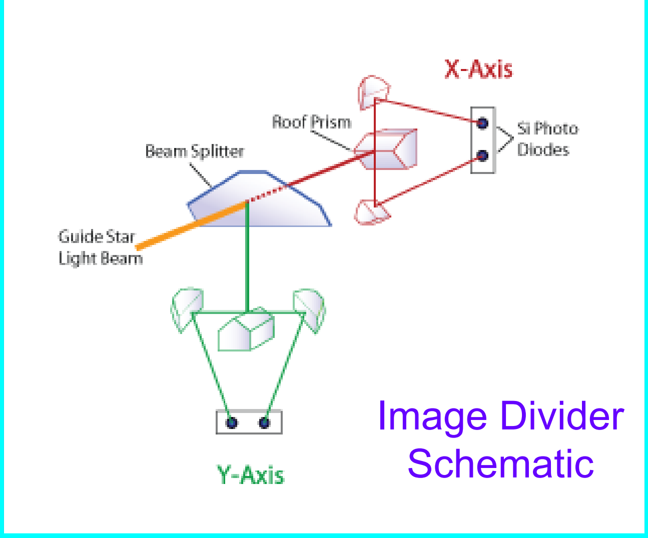
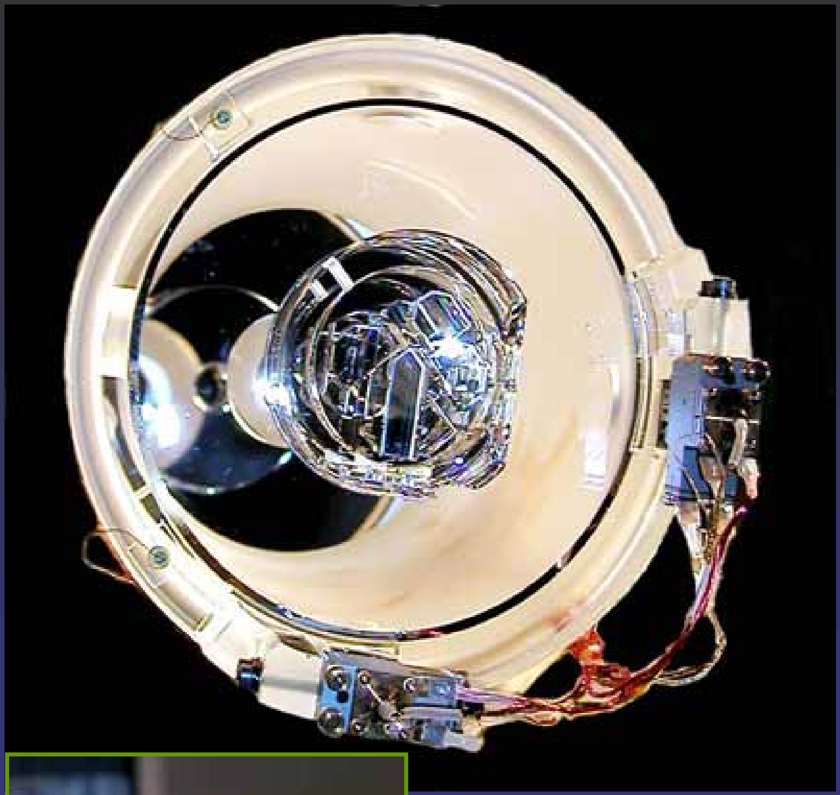


Image Divider Schematic

Don Davidson

Star Tracker II: Under Test



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

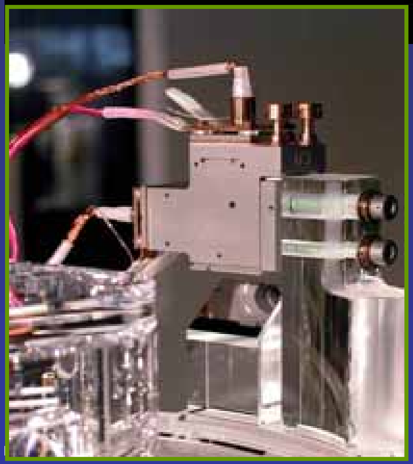
Telescope development

* 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)

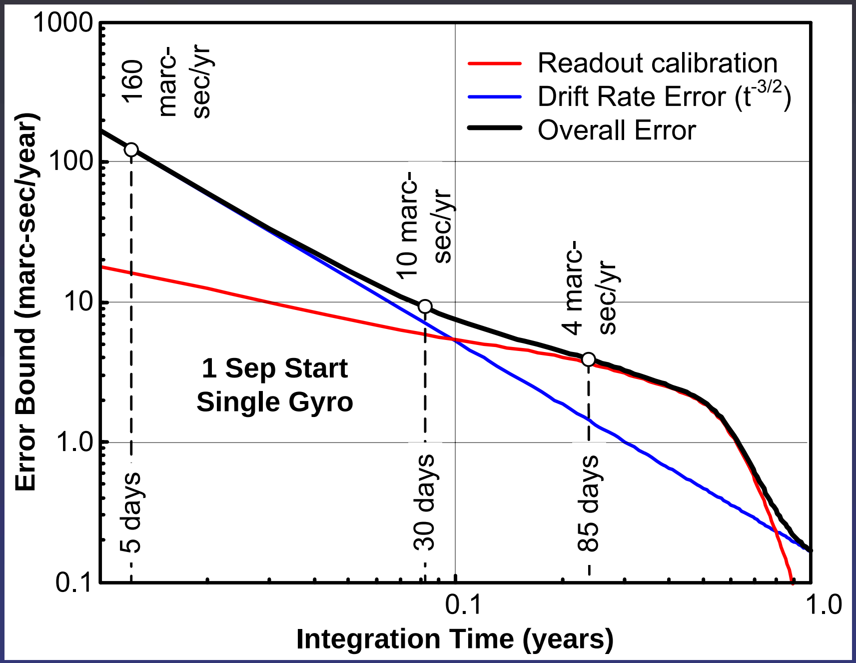
Artificial Star #3



Detector Package

Si Diode Detector

Prelaunch Error & Analysis Tool Development



Expected time evolution
of GP-B accuracy over year

- 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

Gaylord Green

Marcie Smith

MOC

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]

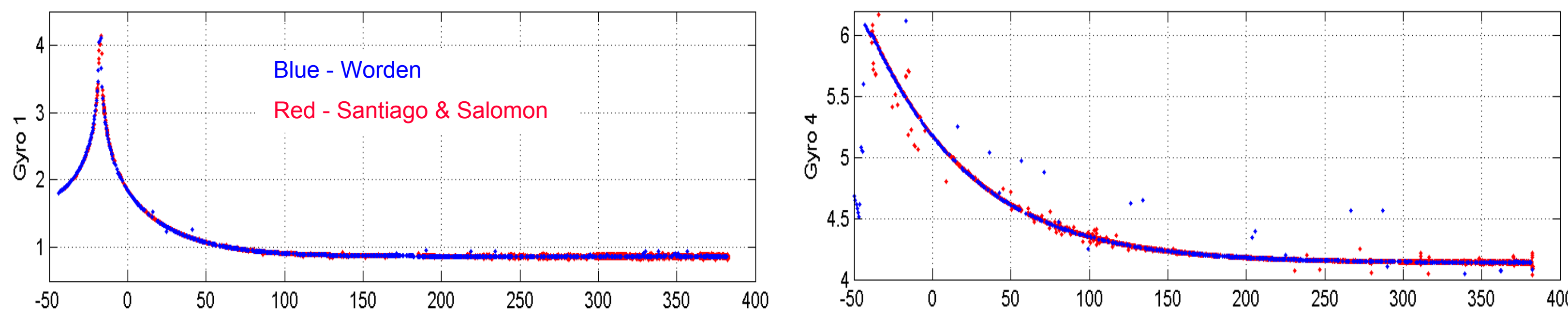
Surprise A – Polhode-rate variations ⟹ affect C_g determinations
Surprise B – Larger than expected misalignment torques

Two mutually reinforcing gremlins

Two Mutually Reinforcing Gremlins

- Polhode-rate variations → affect C_g determinations

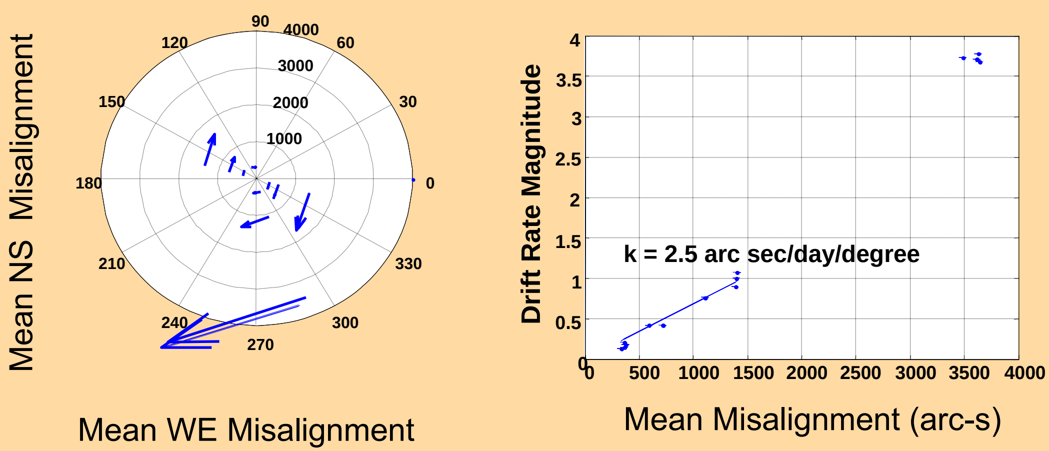
Polhode Period (hours) vs Elapsed Time (days) since January 1, 2004



Blue: Worden Red: Santiago & Salomon

- Larger than expected misalignment torques

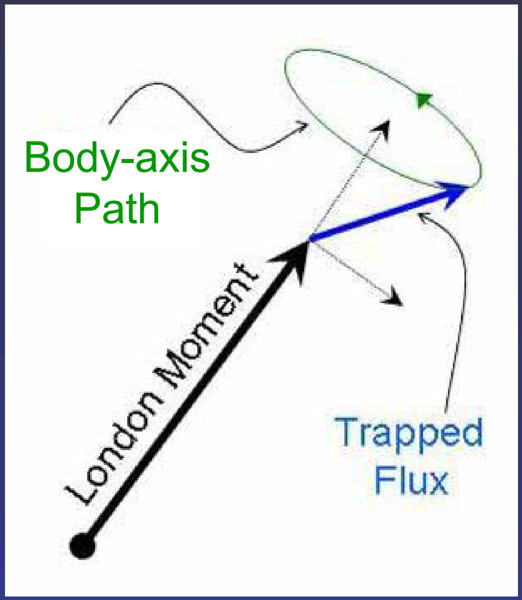
Mean Rate (marc-s/day) vs Mean Misalignment Gyro 3 (arc-s)



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:



London field at 80 Hz: 57.2 μG

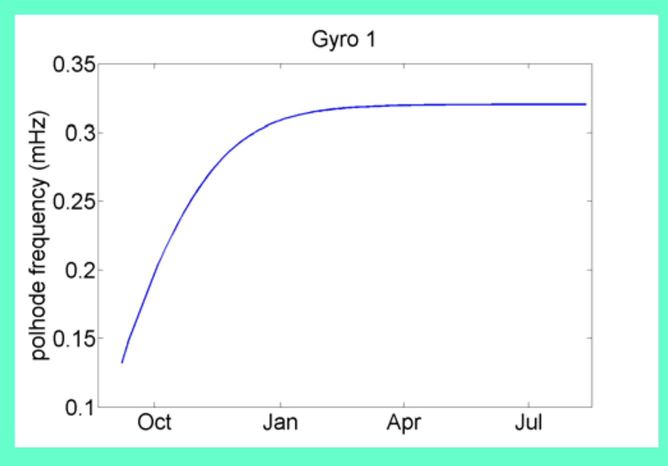
Trapped fields

Trapped fields	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 (TFM) results

Trapped Flux Mapping: 3 Key AA Dissertations

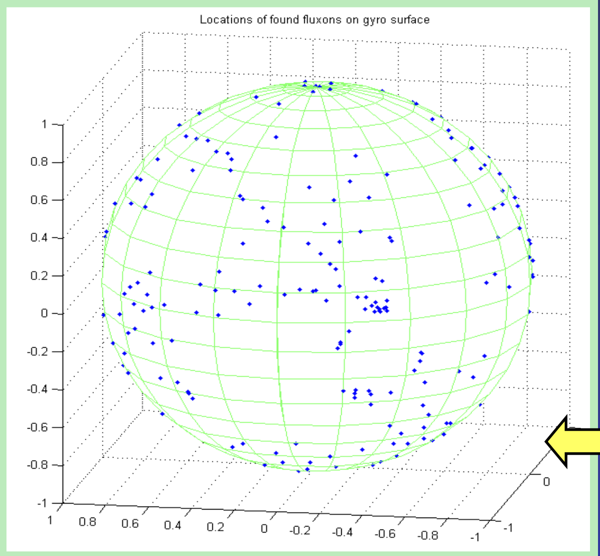
- Gyro Motion:
  - Spin speed to ~ 10 nHz (x 1000 improvement)
  - Spin down rate to ~ 1pHz/s (x 100 improvement)
  - Polhode phase to ~ 2° (x 100 improvement)



J. Conklin
M. Dolphin
M. Salomon

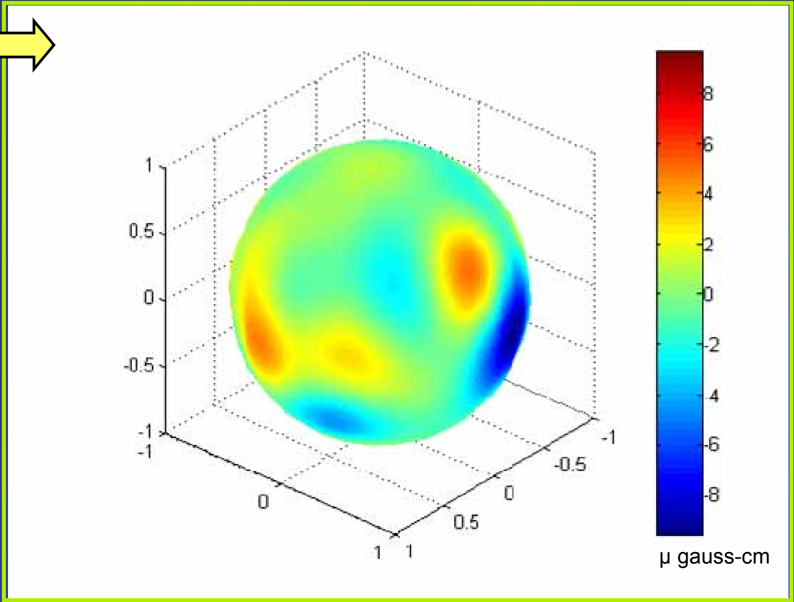
Polhode, spin parameters

- Trapped Flux Distribution



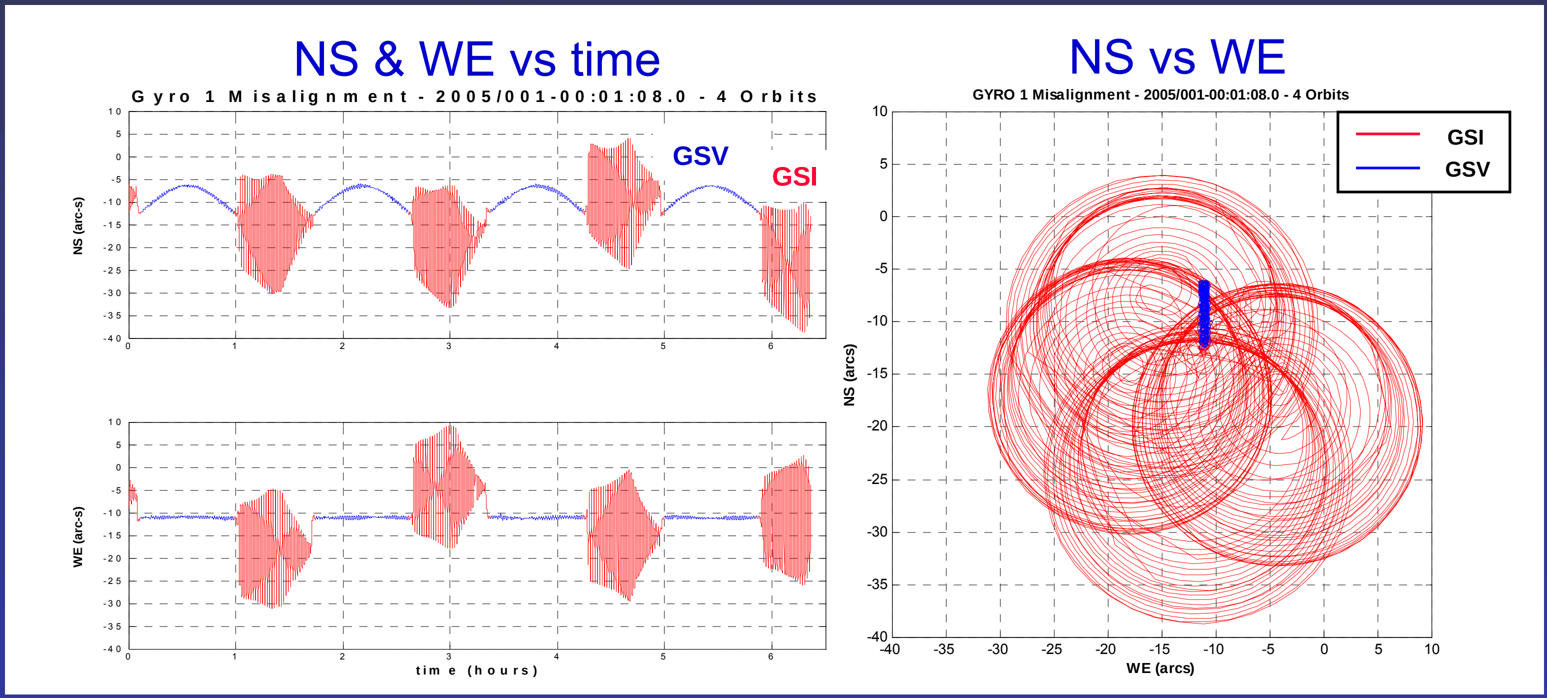
Magnetic potential map

Fluxon map

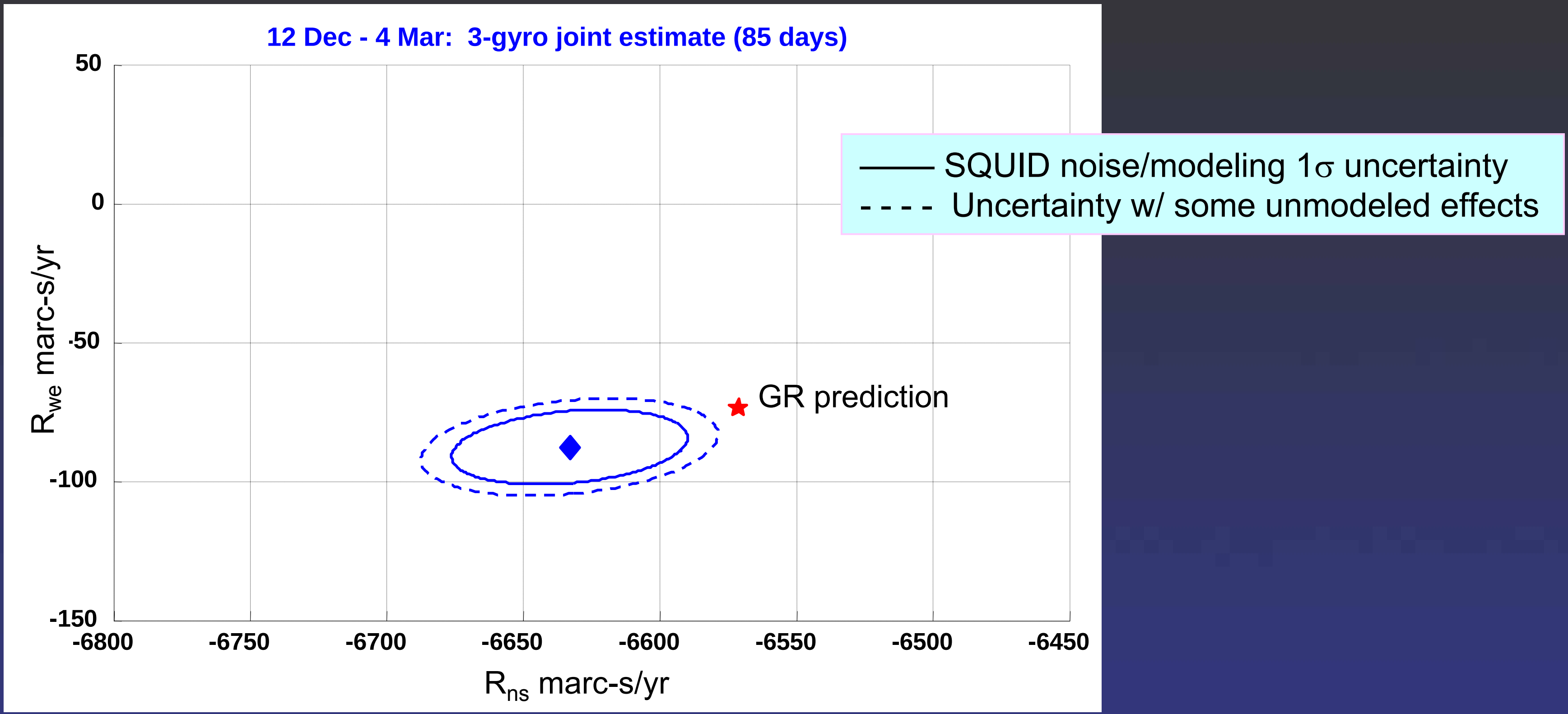


The Data Analysis Adventure Algebraic 1

- 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



R_{NS} vs R_{WE} Algebraic 3-Gyro Joint Estimate

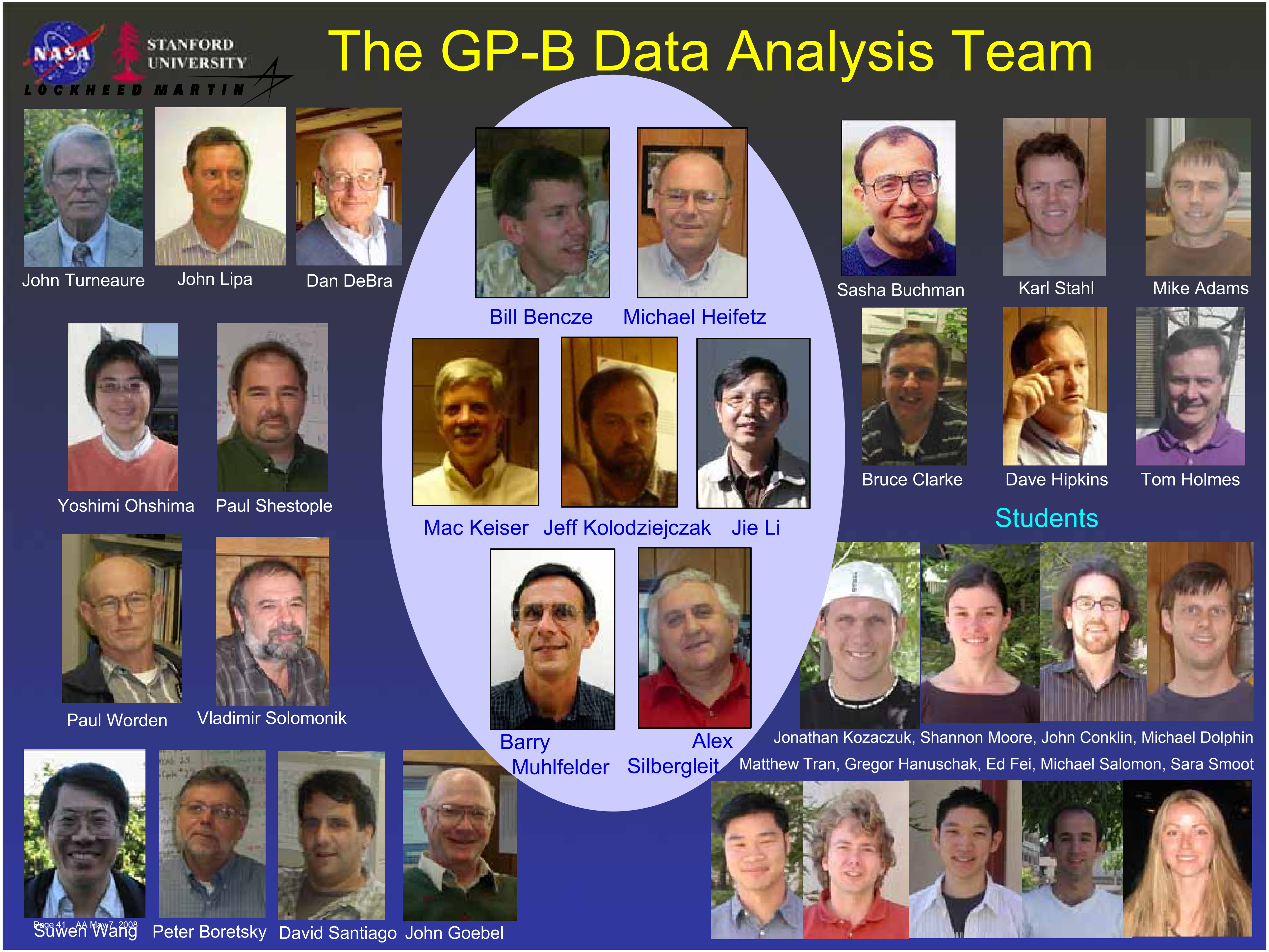


	Earth	Solar Geodetic	Proper Motion	Net Expected
NS	-6606	+7	+28 ± 1	-6571 ± 1
EW	-39	-16	-20 ± 1	-75 ± 1

85-day result

R_{NS} = -6632 ± 43 marc-s/yr

R_{WE} = -82 ± 13 marc-s/yr


NASA
STANFORD UNIVERSITY
LOCKHEED MARTIN
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John Lipa
Dan DeBra
Bill Bencze
Michael Heifetz
Sasha Buchman
Karl Stahl
Mike Adams
Yoshimi Ohshima
Paul Shestople
Mac Keiser
Jeff Kolodziejczak
Jie Li
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Students
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Vladimir Solomonik
Barry Muhlfelder
Alex Silbergleit
Jonathan Kozaczuk, Shannon Moore, John Conklin, Michael Dolphin
Matthew Tran, Gregor Hanuschak, Ed Fei, Michael Salomon, Sara Smoot
Suwen Wang
Peter Boretsky
David Santiago
John Goebel

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	**Geodetic**	**Frame-dragging**
	(marcsec/yr, % uncertainty)	
Advanced, fine-grain processing on full data set Complete systematic error bounding	~2 (0.05%)	~2 (3-6%)