Gravity Probe B

Presentation at

KACST-Stanford Collaborative

Space Research Workshop

مدينة الملك عبدالعزيز للعلوم والتقنية

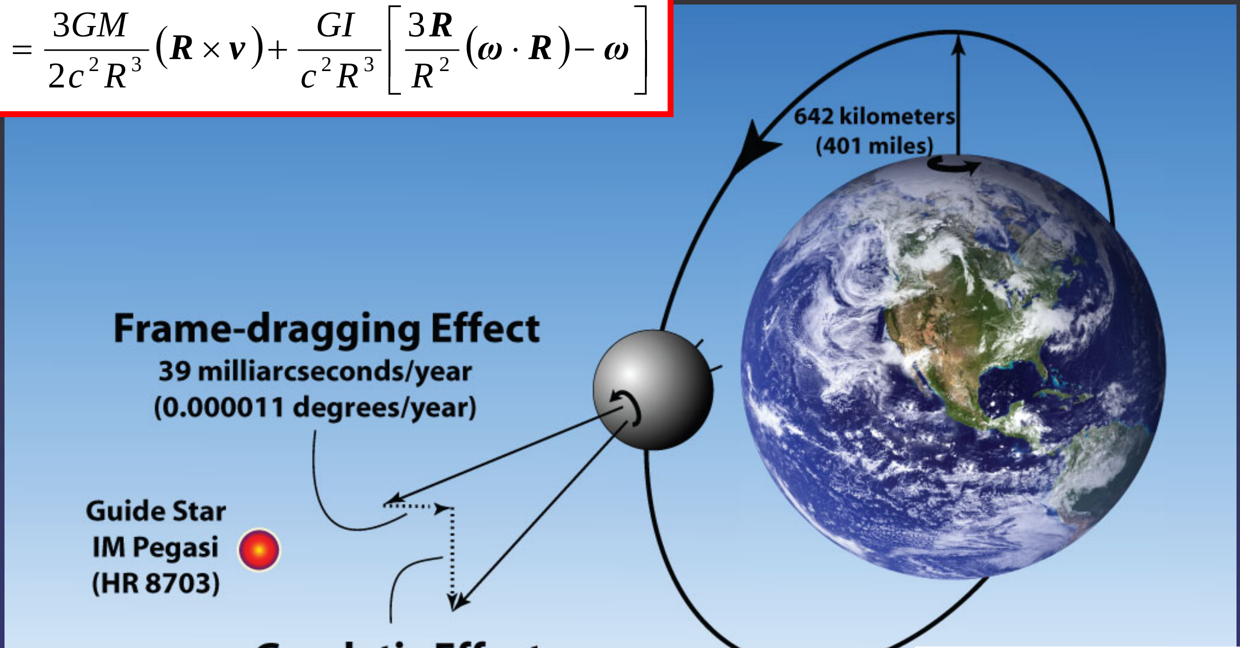
King Abdulaziz City For Science and Technology

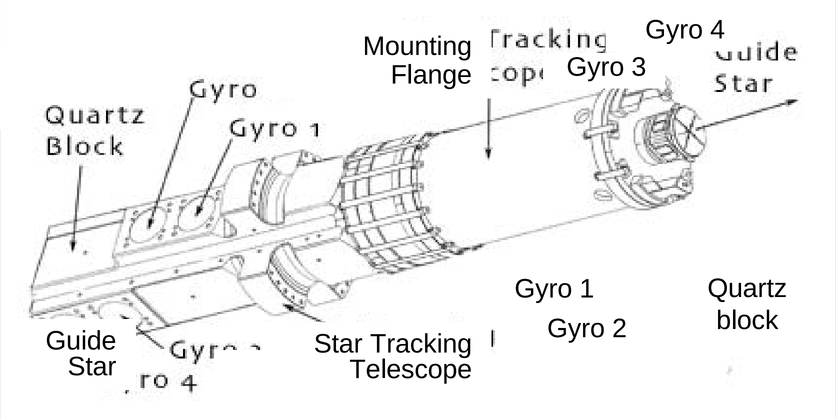
October 25, 2008

C.W. Francis Everitt

The Relativity Mission Concept

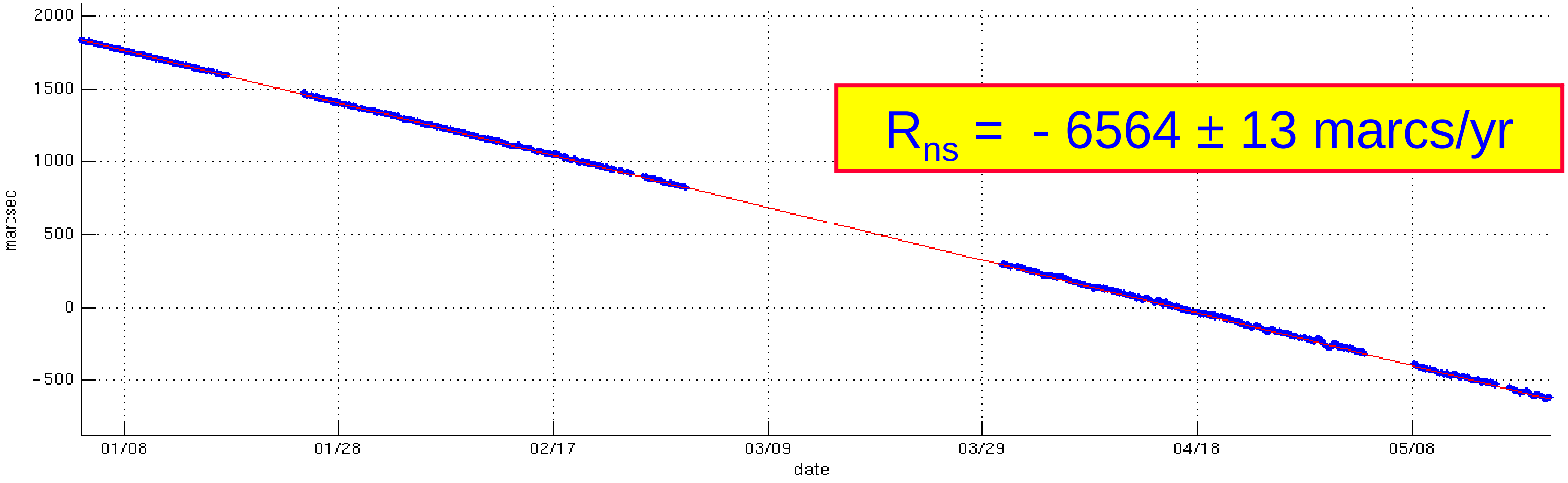
$$\boldsymbol{\Omega} = \frac{3GM}{2c^2R^3}\left(\boldsymbol{R}\times\boldsymbol{v}\right) + \frac{GI}{c^2R^3}\left[\frac{3\boldsymbol{R}}{R^2}\left(\boldsymbol{\omega}\cdot\boldsymbol{R}\right) - \boldsymbol{\omega}\right]$$





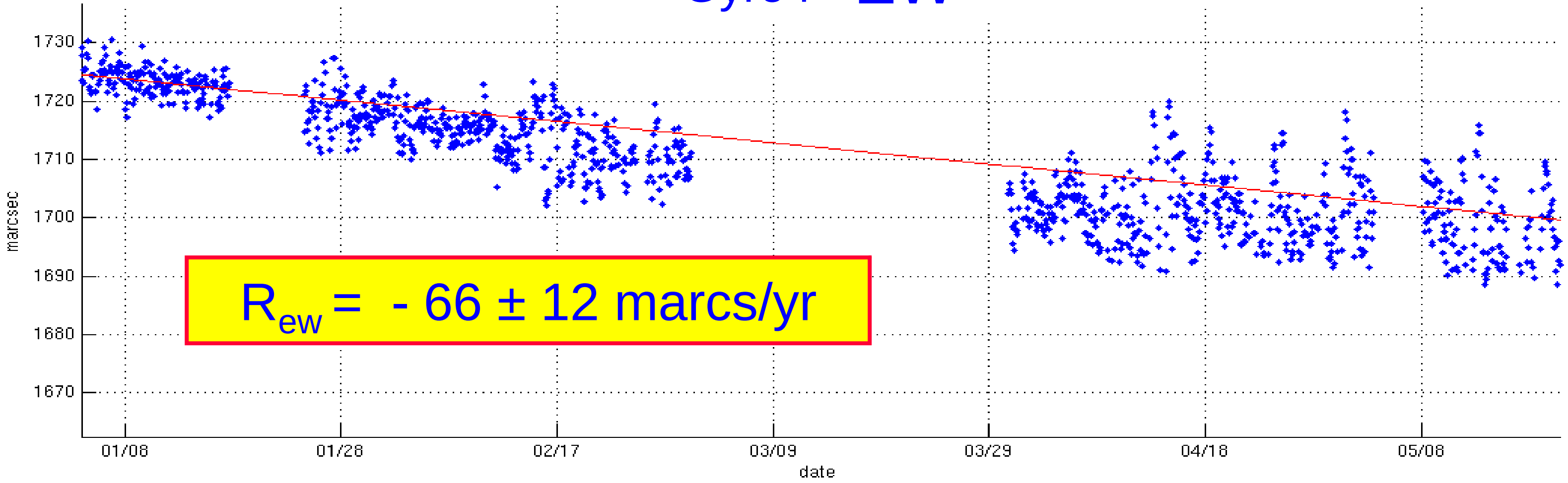
- Geodetic Effect
  - Space-time curvature ("the missing inch")
- Frame-dragging Effect
  - Rotating matter drags space-time ("space-time as a viscous fluid")

Seeing GR Directly NS & Now EW



Gyro4 NS

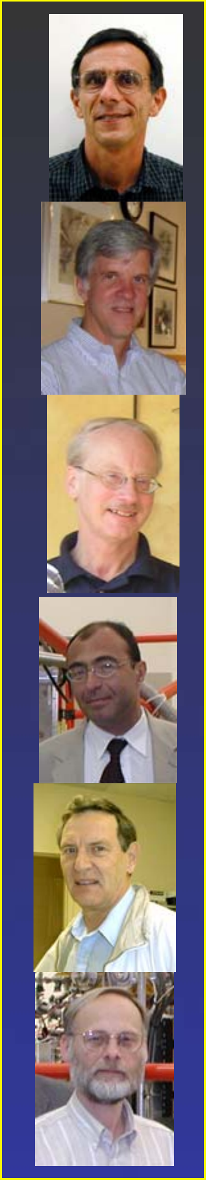
R_{ns} = - 6564 ± 13 marcs/yr



Gyro4 EW

R_{ew} = - 66 ± 12 marcs/yr

GP-B: 7 Interfolded Stories



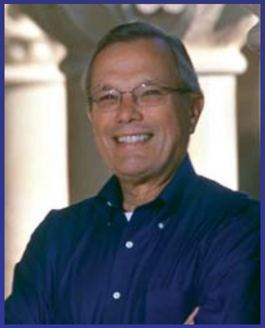
- **Testing Einstein**
- **Unexpected Technologies**
- **Two SU Departments: *Physics & Aero-Astro***
- **Students: *84 + 13 PhDs, 353 U/G, 55 high school***
- **Spin-Offs: *drag-free, porous plug, autofarm,* + + + +**
- **NASA-Stanford-Industry Symbiosis**
- ***"A very interesting management experiment"* – J. Beggs, 1984**

Co-PI's

Co-I's

Dan DeBra

Charbel Farhat

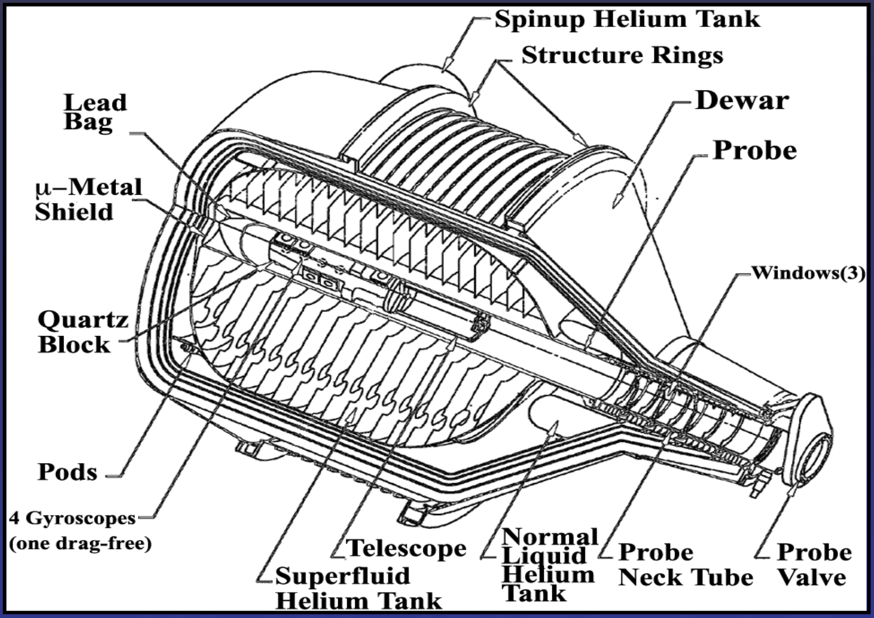


Brad Parkinson

John Turneaure

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

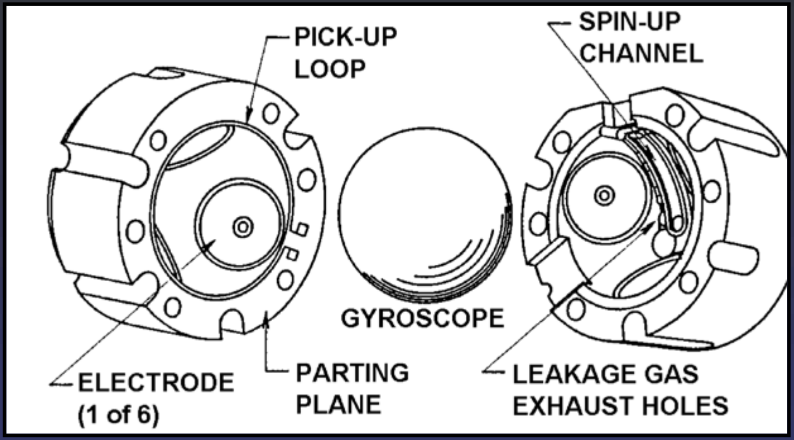
- reduced support force, "drag-free"
- roll about line of sight to star

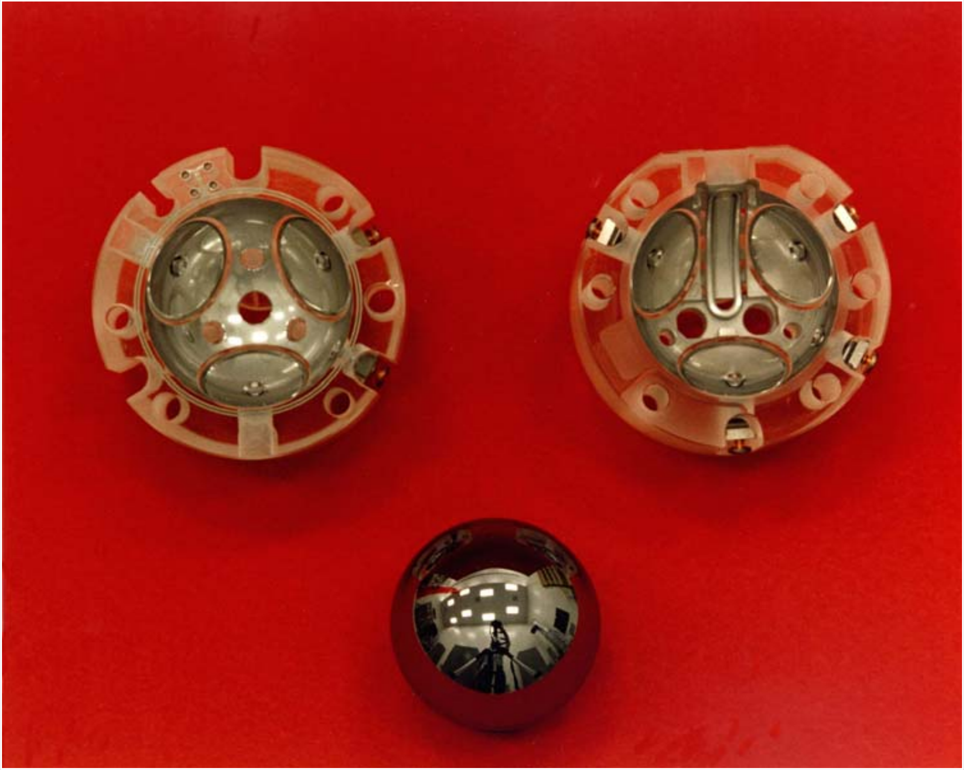
Cryogenics

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

Modeling *ad hoc* [externally calibrated] vs *physics-based*

The GP-B Gyroscope





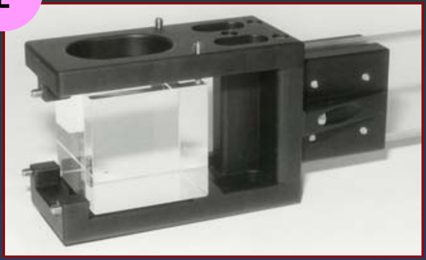
- **Electrical Suspension**
- **Gas Spin-up**
- **Magnetic Readout**
- **Cryogenic Operation**

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



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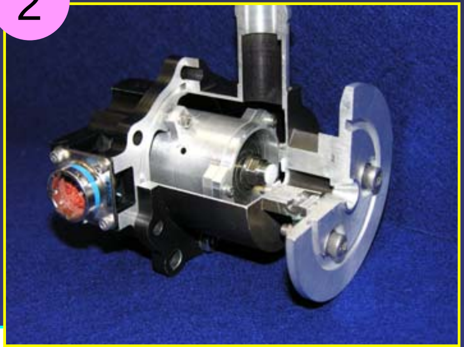

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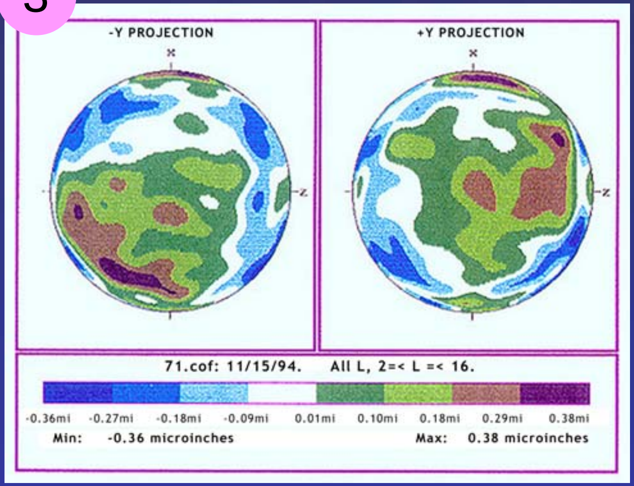

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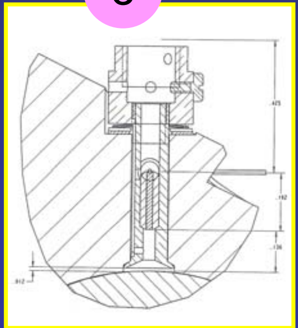


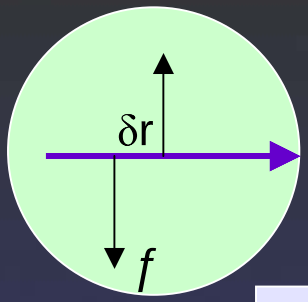
Mass-Unbalance, Drag-Free:

1st & 2nd 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* $(1.54 \times 10^{-17}$ 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 $\frac{\delta r}{r} \sim 3 \times 10^{-7}$

⇩

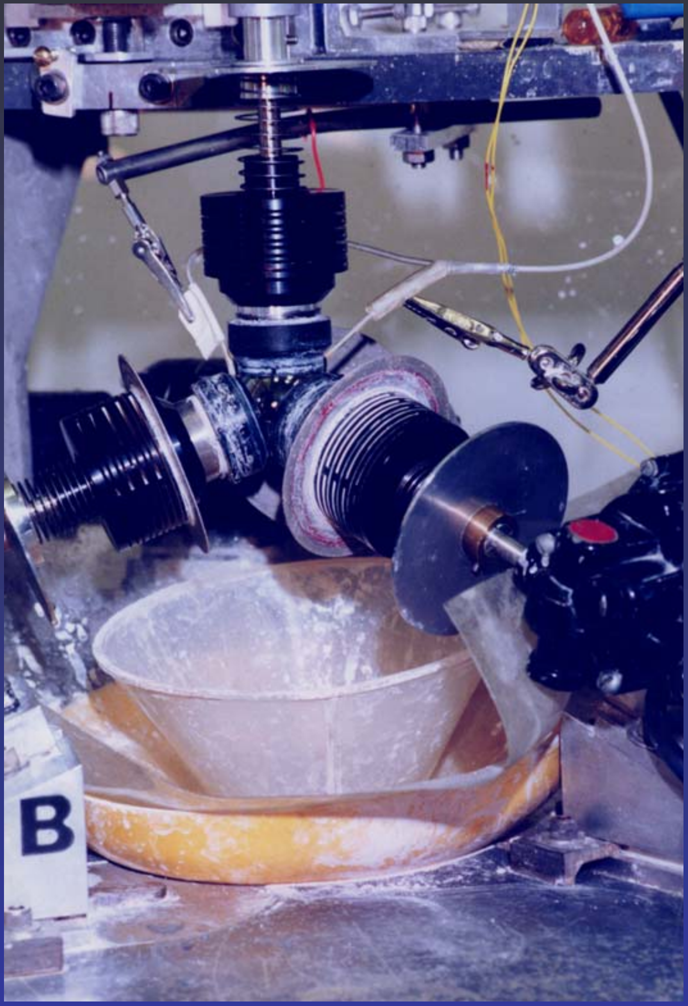
drift-rate for the drag-free GP-B < 0.05 marc-s/yr

Neither Near Zero alone does it

Sphericity: 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!**

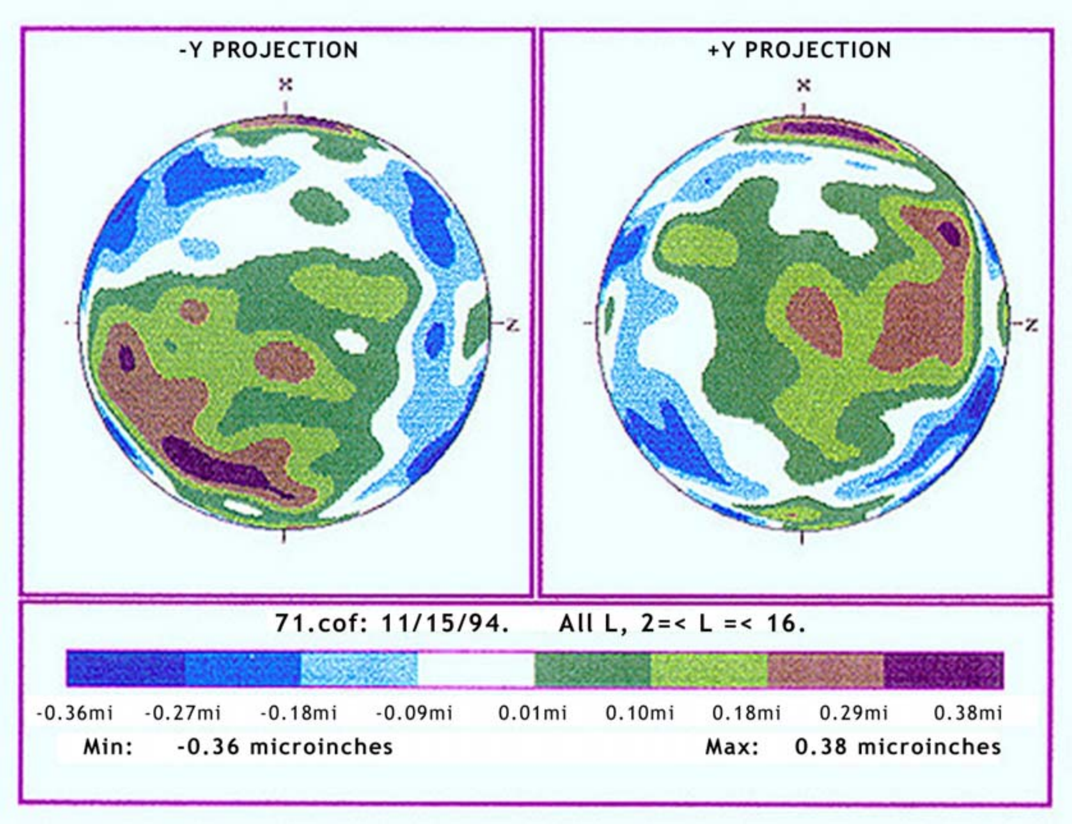
MSFC	**STANFORD**
Wilhelm Angele	**Thorwald van Hooydonk**
John Rasquin	**Frane Marcelja**
Ed White	**Victor Graham (visitor)**



Advanced lapping machine

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

Sphericity: Measuring



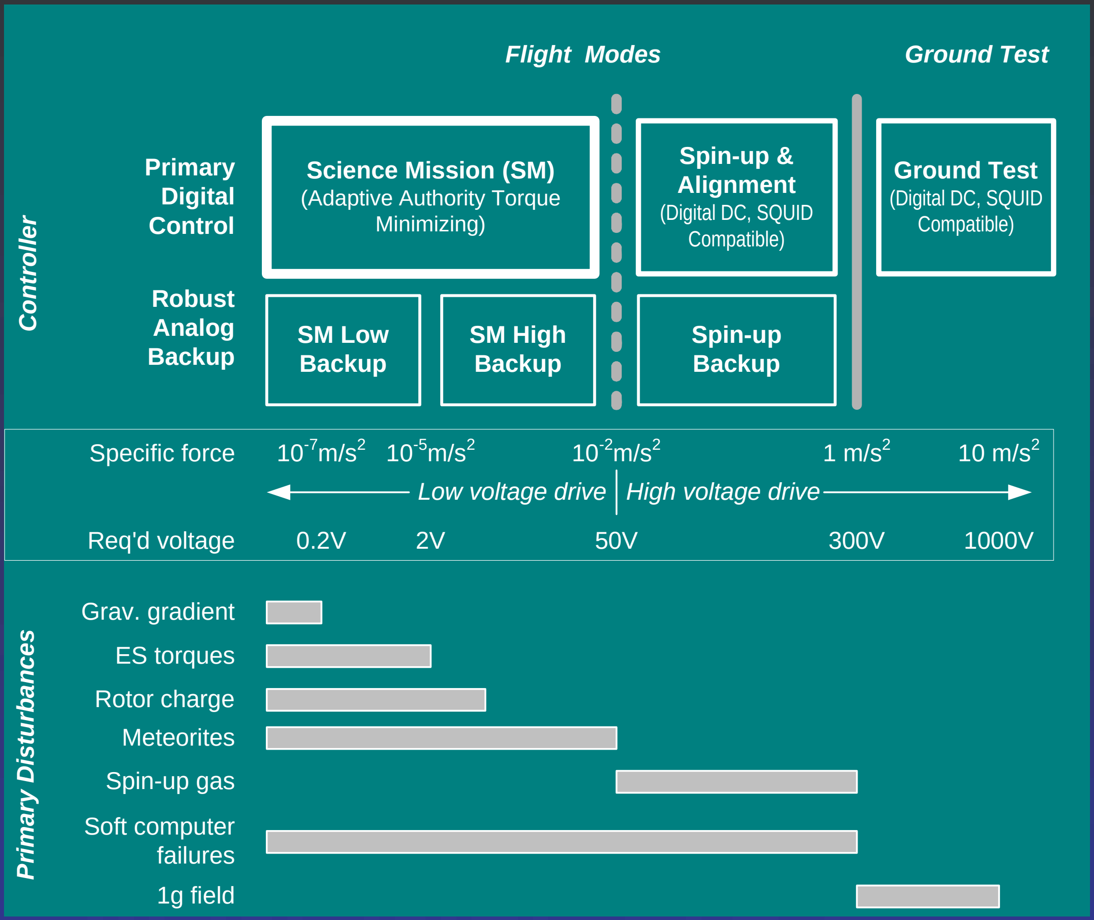
Students 1988 - 1992

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

Roundness Measurement to ~ 1 nm

Gyro Suspension

Operates over 8 orders of magnitude of g levels



Flight Modes | *Ground Test*

Controller

Primary Digital Control
- **Science Mission (SM)** (Adaptive Authority Torque Minimizing)
- **Spin-up & Alignment** (Digital DC, SQUID Compatible)
- **Ground Test** (Digital DC, SQUID Compatible)

Robust Analog Backup
- **SM Low Backup**
- **SM High Backup**
- **Spin-up Backup**

Specific force	10^{-7}m/s^2	10^{-5}m/s^2	10^{-2}m/s^2	1 m/s^2	10 m/s^2
Req'd voltage	0.2V	2V	50V	300V	1000V

← *Low voltage drive* | *High voltage drive* →

Primary Disturbances

Grav. gradient

ES torques

Rotor charge

Meteorites

Spin-up gas

Soft computer failures

1g field

DSP + Power Supply

Analog drive, Backup control

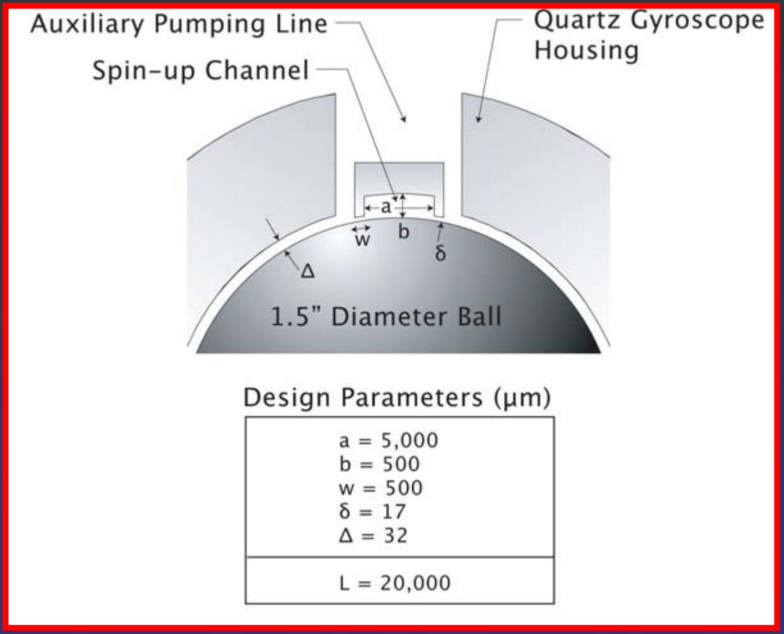
- Range of motion within cavity (15,000 nm) for:
  - science (centered in cavity)
  - spin-up (offset to spin channel ~ 11,000 nm)
  - calibration (offset, 200 nm increments)

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



Design Parameters (μm)

a = 5,000
b = 500
w = 500
δ = 17
Δ = 32

L = 20,000

② Differential Pumping Requirement

spin channel ~ 10 torr (sonic velocity)

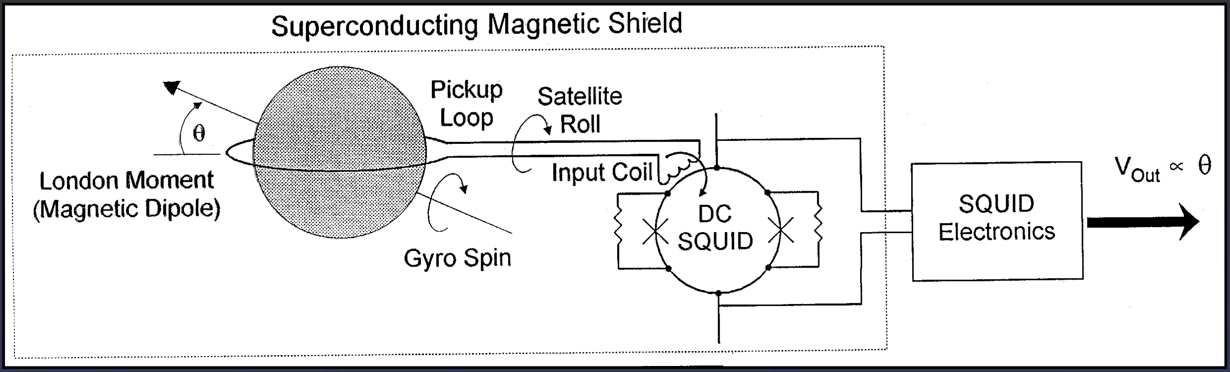
electrode region < 10^{-3} torr

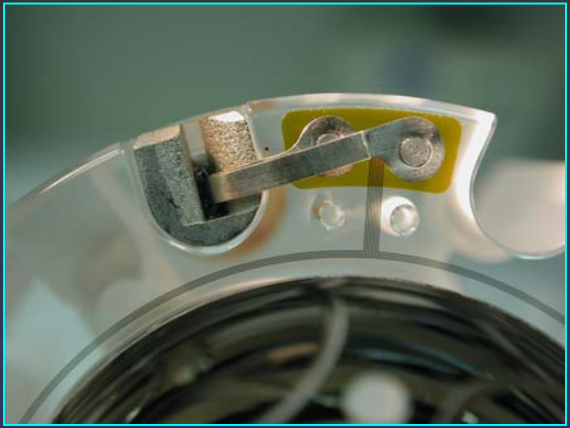
* Dan Bracken (Physics)
Don Baganoff (Aero/Astro)
\+ Gerry Karr (MSFC), John Lipa,
John Turneaure & 4 students

③

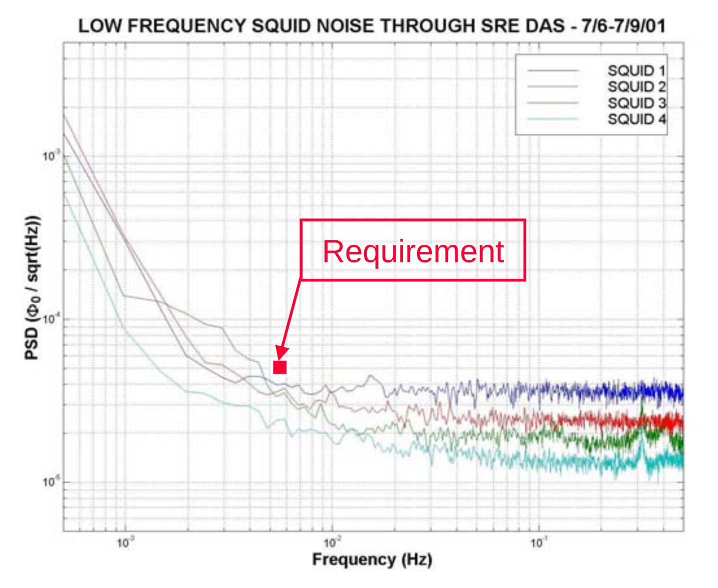
"Any fool can get the steam into the cylinders; it takes a clever man to get it out again afterwards." -- G. J. Churchward, ~ 1895

London Moment Readout





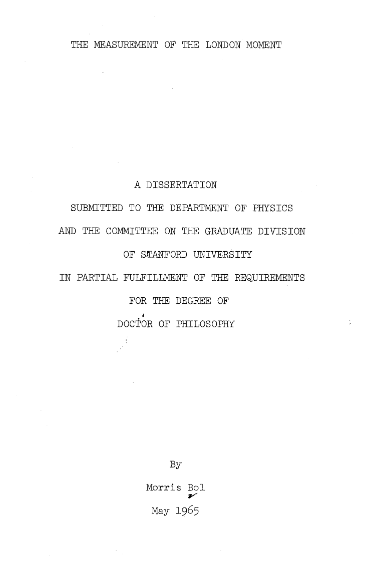
“SQUID” ⟶ 1 marc-s in 5 hours



4 Requirements/Goals

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

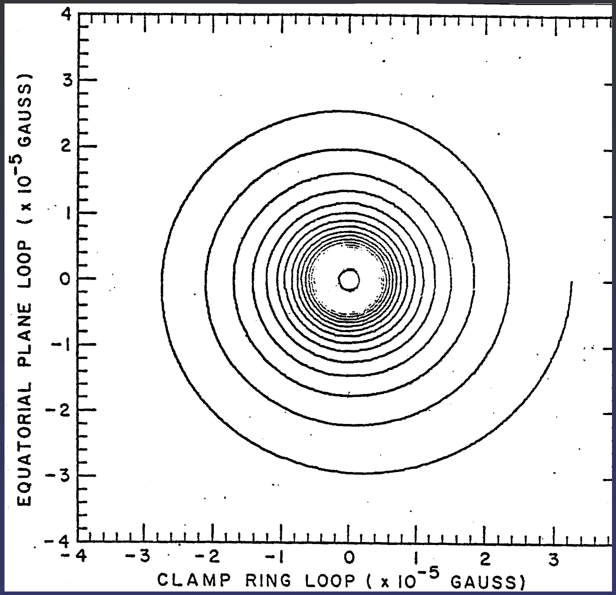
L M Readout: Some of the Many Steps



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

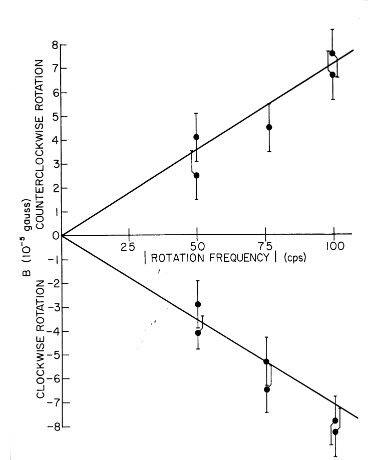
By
Morris Bol
May 1965



Laboratory Demo (1/26/79)

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

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

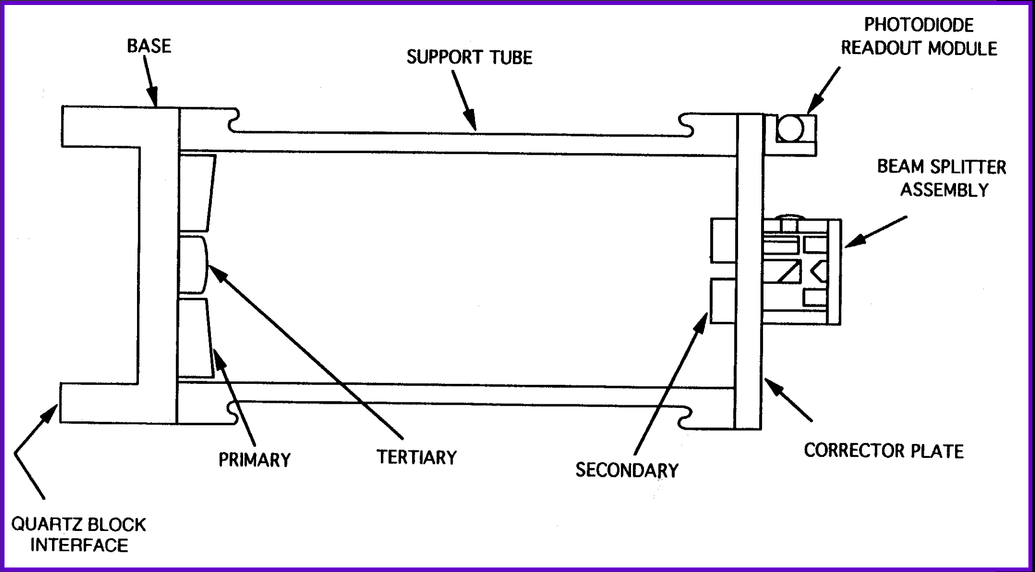


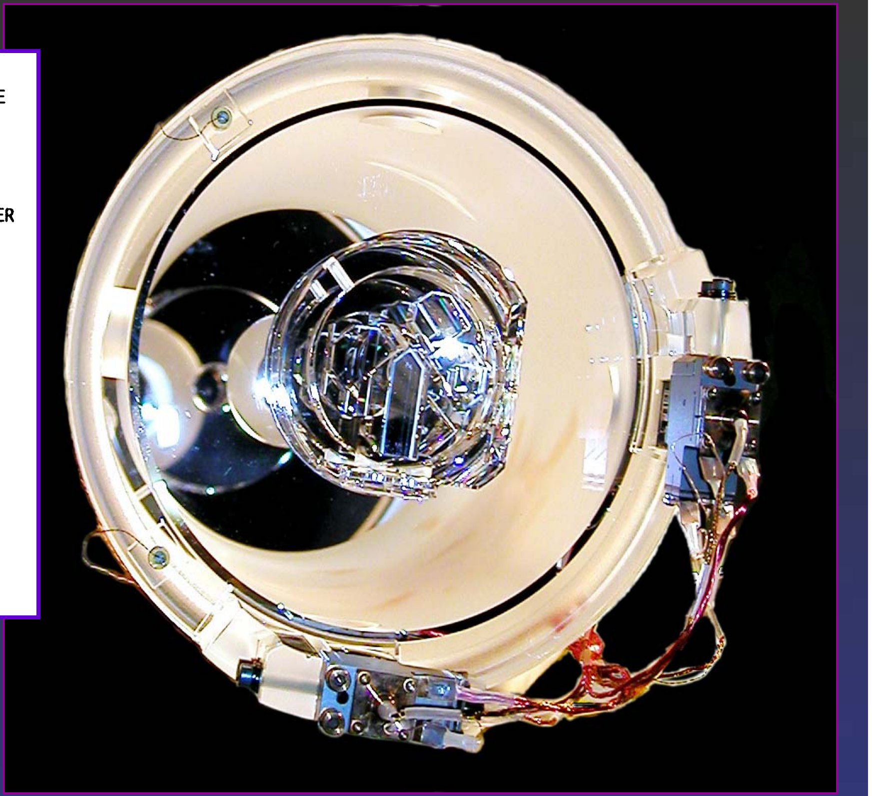
Five Major Developments to a Flight Instrument

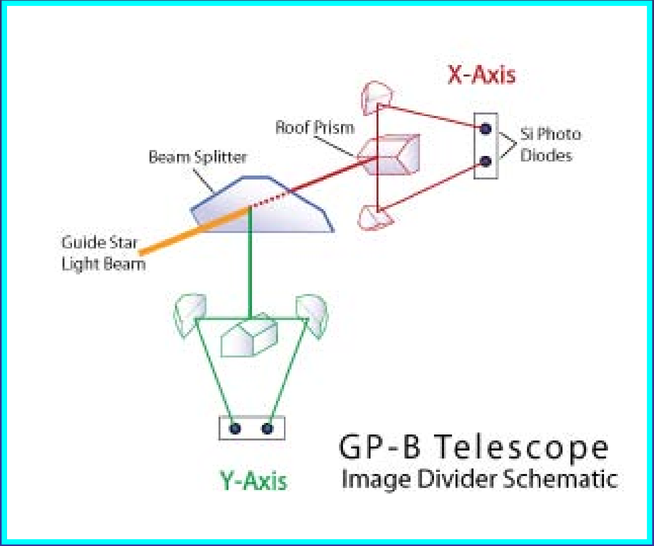
- From ac to dc SQUIDs (100 x lower noise)
- 2 µK control of SQUID & SQUID electronics @ S/C roll
- Non-interfering gyro suspension system (no damping cylinder)
- 240 dB magnetic shielding
- Highest possible S/C roll-rate to beat SQUID 1/f noise

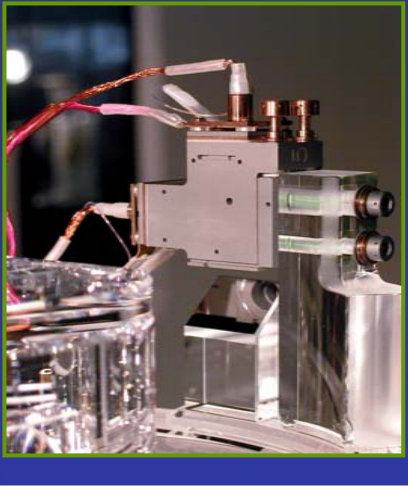
+"Niobium Bird": Hiro Uematsu (AA), Gordy Haupt (AA), Greg Gutt (EE) + ~ 6 undergraduates

Challenge 2: Sub-milliarc-s Star Tracker







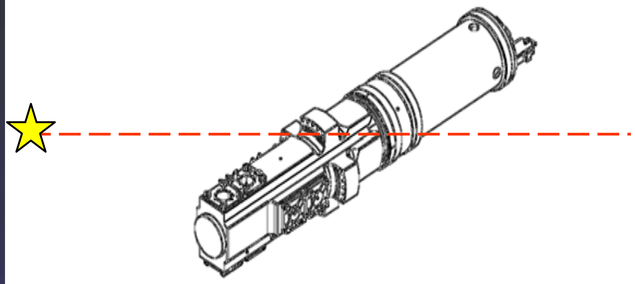


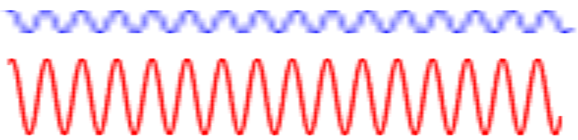
Detector Package

Dual Si Diode Detector

Challenges 3 & 4: Matching & Calibration

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

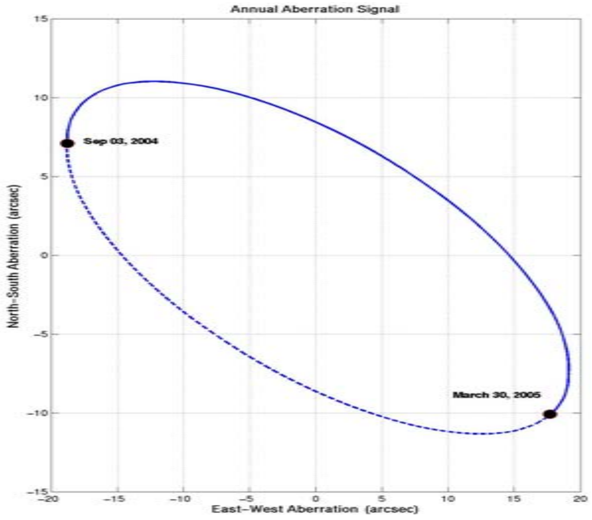




{ **gyro output**
telescope output

→ *scale factors matched for accurate subtraction*

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

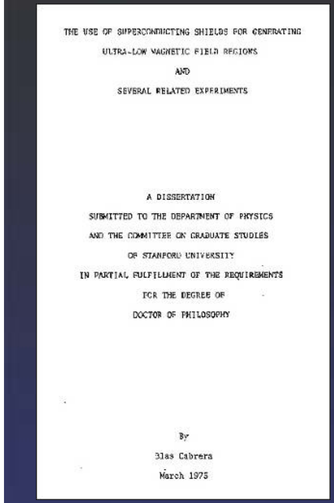


Orbital motion → varying apparent position of star
(v_{orbit}/c + special relativity correction)

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

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
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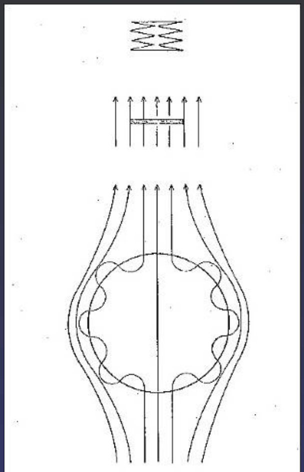
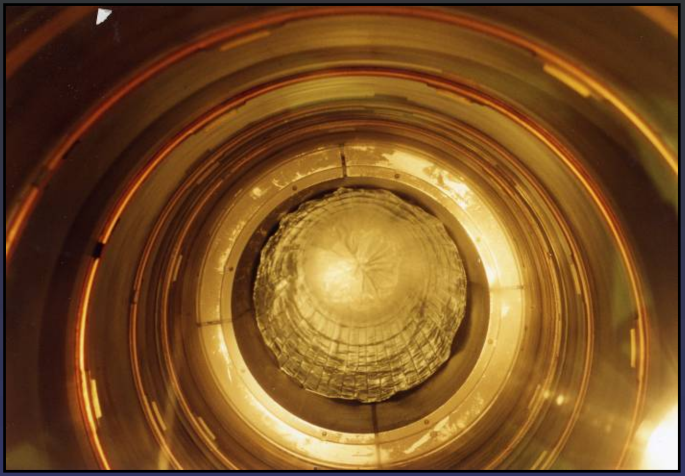
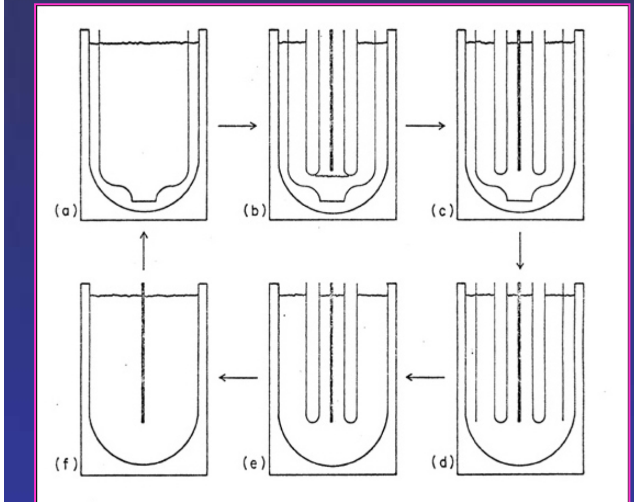
By
Blas Cabrera
March 1975



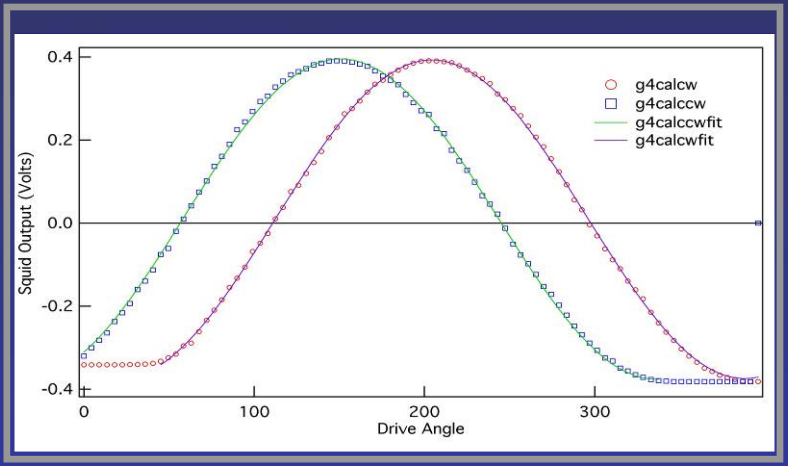
Expanding shield reduces field



Final flight lead bag (M. Taber)



Cyclic Bag Expansions



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	$\leq 4.0\times10^{-7}$	7.0×10^{-7}
Ti 99.6%, Grade 2	Goodfellow, TiCo	$\leq 2.5\times10^{-7}$	3.1×10^{-6}
Nb Type 1	Teledyne Wah Chang	$\leq 4.0\times10^{-7}$	2.5×10^{-6}
Copper 10100 99.99%	Sequoia Copper & Brass	$\leq 3.0\times10^{-7}$	2.5×10^{-7}
BeCu 25 C17200	Brush Wellman, NGK	$\leq 3.1\times10^{-6}$	4×10^{-7}
BeCu 125	Brush Wellman	1.7×10^{-7}	1.5×10^{-7}
binary BeCu	NGK Berylco	$\leq 1.9\times10^{-7}$	2×10^{-8}
binary BeCu	Ames Research Iowa St.	$\leq 9.7\times10^{-8}$	4.3×10^{-8}
BeCu 3HP	Brush Wellman	$\leq 6.5\times10^{-7}$	8.3×10^{-8}
TI Cu unsc19900	Yamaha Metals	$\leq 3.0\times10^{-7}$	3.7×10^{-7}
Si Bronze	Sequoia Copper & Brass	$0.3 - 2\times10^{-4}$	-4.5×10^{-7}
Phos Bronze C-51000	Copper & Brass Sales	$\leq 2\times10^{-5}$	$\leq 3.0\times10^{-6}$
Phos Bronze Custom	Ames Research Iowa St.	$1- 4.7\times10^{-7}$	$1\times10^{-6}-3\times10^{-6}$
Molybdenum 99.97%	CSM Industries	$\leq 4.5\times10^{-7}$	9.6×10^{-7}
Structural Dielectrics			
Teflon	Dupont	$\leq 9.0\times10^{-7}$	$- 5.0\times10^{-8}$
Delrin	Laird Plastics	$\leq 5\times10^{-8}$	$- 4.7\times10^{-7}$
Kapton	Dupont	$\leq 2.0\times10^{-7}$	1.6×10^{-7}
Vespel	Dupont	$\leq 6.6\times10^{-7}$	8×10^{-7}
PEEK	E Jordon Brooks	$\leq 9.2\times10^{-7}$	1×10^{-7}
Sapphire	Saphikon Inc.	$\leq 7.4\times10^{-8}$	-1.2×10^{-7}
Quartz	Corning, Hereas Amersil	$\leq 1.5\times10^{-7}$	-1.1×10^{-7}
Wire and Ribbon			
Manganin .005"	Lakeshore Cryotronics	2.4×10^{-4}	1.8×10^{-4}
Phosphor Bronze	California Fine Wire	$\leq 2.5\times10^{-6}$	
Copper 38 Gauge	Belden	4.0×10^{-7}	$- 3.7\times10^{-8}$
Platinum-Tungsten	California Fine Wire	1.4×10^{-6}	3.3×10^{-6}
NbTi .005"/.010"	California Fine Wire	$\leq 1.8\times10^{-6}$	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	$0.5 / 2\times10^{-6}$	
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	$\leq 7.0\times10^{-8}$	2.5×10^{-8}
Poly shrink tubing	Advanced Polymers Inc	$\leq 8.0\times10^{-7}$	1.3×10^{-6}
Trabond 2115 Epoxy	Tra-Con	$\leq 2.4\times10^{-7}$	-3.5×10^{-7}
Stycast 1266 Epoxy	Emerson & Cuming	$\leq 7\times10^{-8}$	-4.6×10^{-7}
Silver Epoxy 83-C	Emerson & Cuming	$\leq 2.3\times10^{-6}$	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

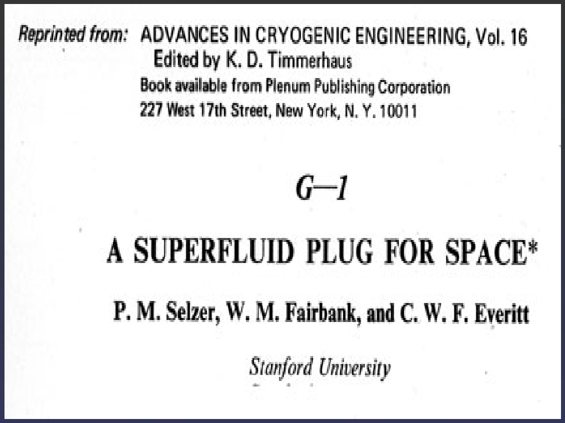
④ Insertion into dewar

⑤ Insertion complete,
removing airlock ➡

The GP-B Cryogenic Payload

Payload in ground testing at Stanford, August 2002

Controlled Boil-off of He in Space



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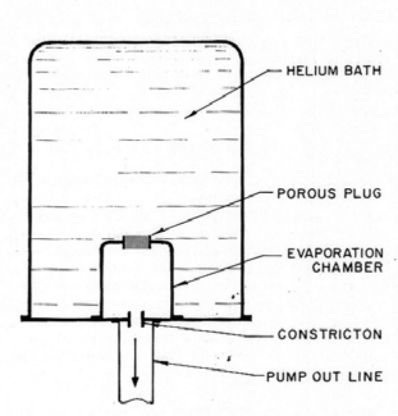
227 West 17th Street, New York, N. Y. 10011

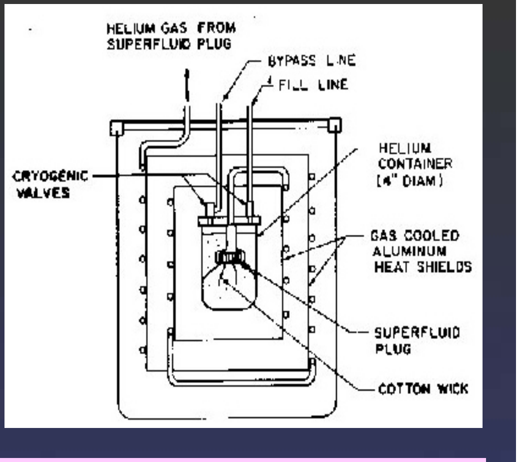
G—1

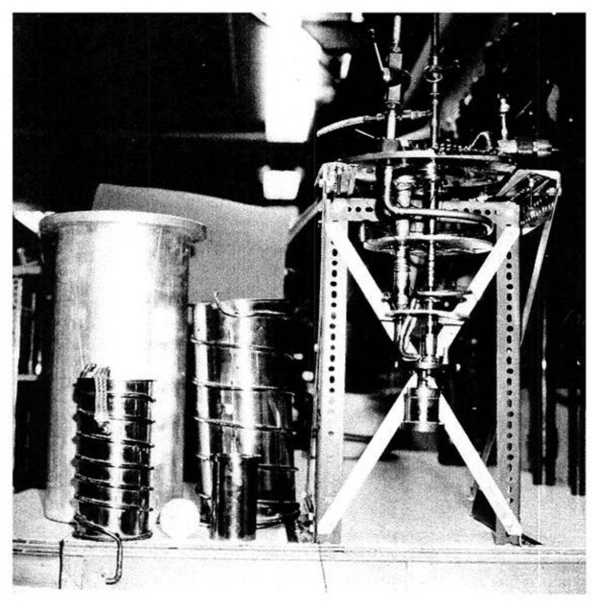
A SUPERFLUID PLUG FOR SPACE*

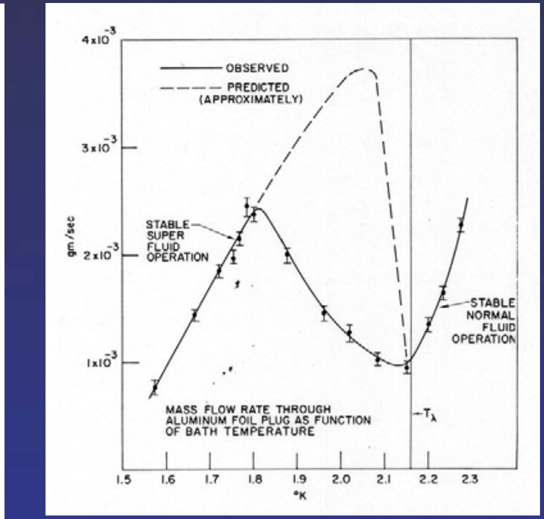
P. M. Selzer, W. M. Fairbank, and C. W. F. Everitt

Stanford University









Further Development for Flight

E. Urban (MSFC), G. Karr (UAH)

W. B. Davis (Ball Aerospace)

P. Mason, D. Petrac, T. Wang (JPL)

S. Yuan & D. Frank (LMSC)

Also enabled IRAS, COBE, WMAP, Spitzer & ISO missions

Launch: April 20, 2004 – 09:57:24

On-Orbit: GP-B Mission Operations

Anomaly Room

Gaylord Green

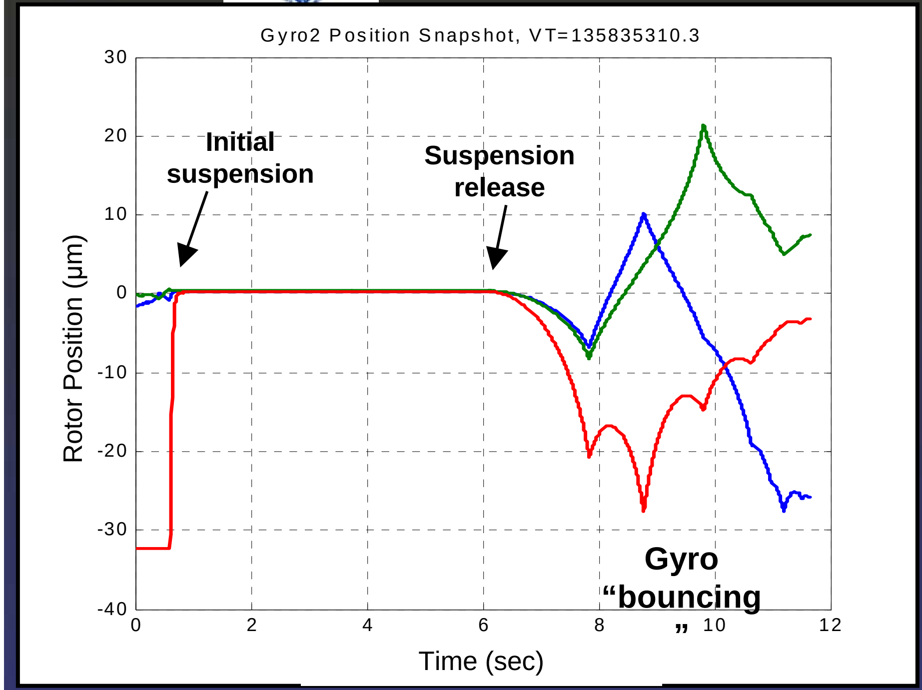
MOC

Marcie Smith

- 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)

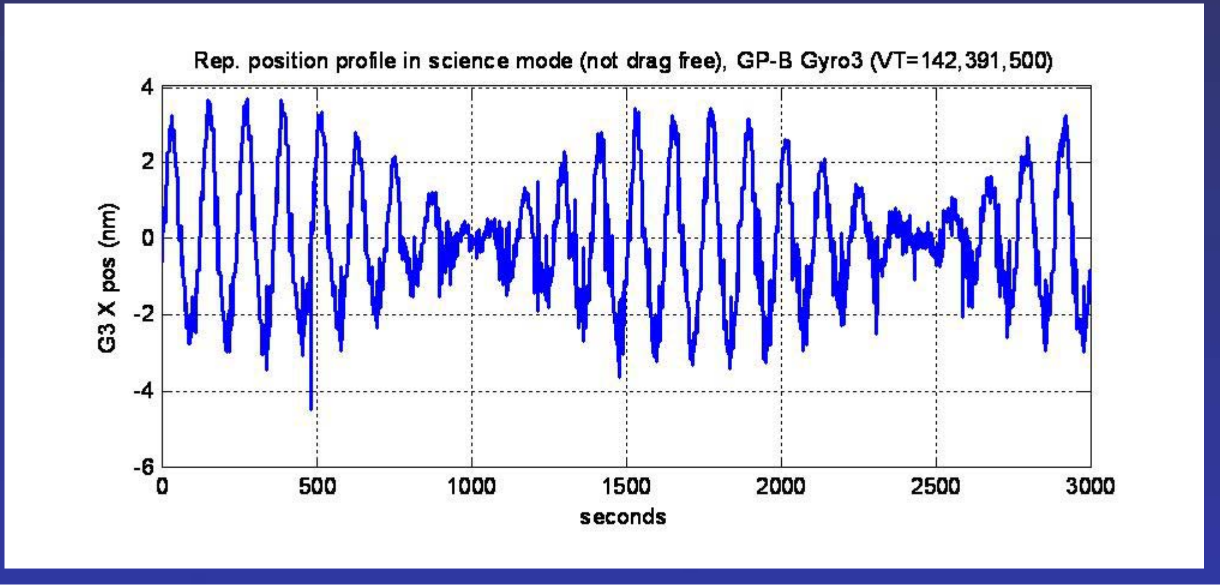
+ many more

Gyro Suspension On-Orbit

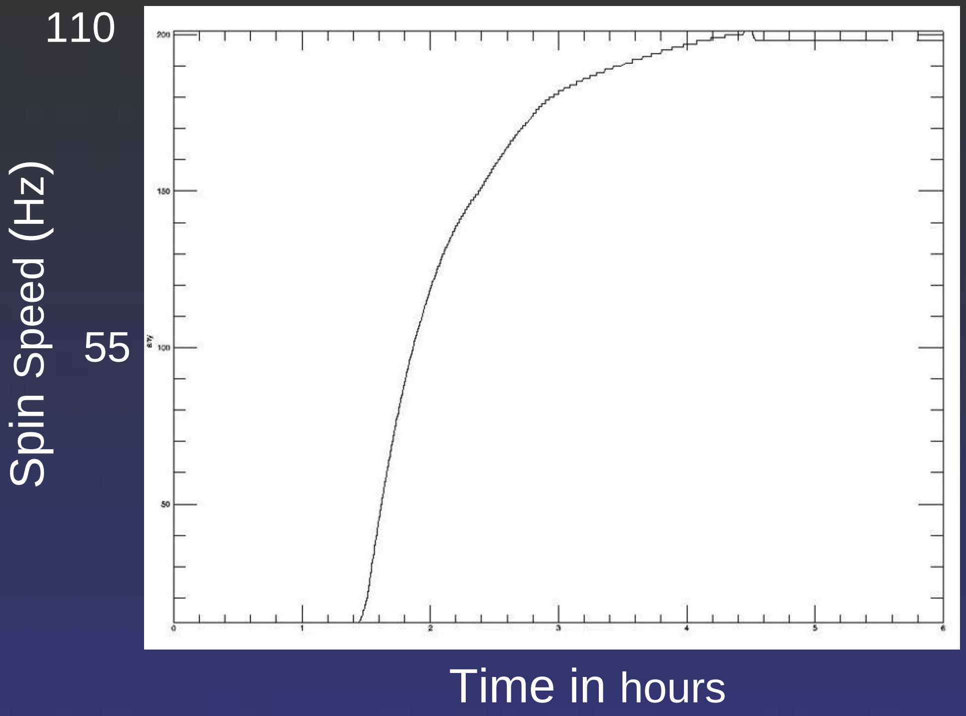


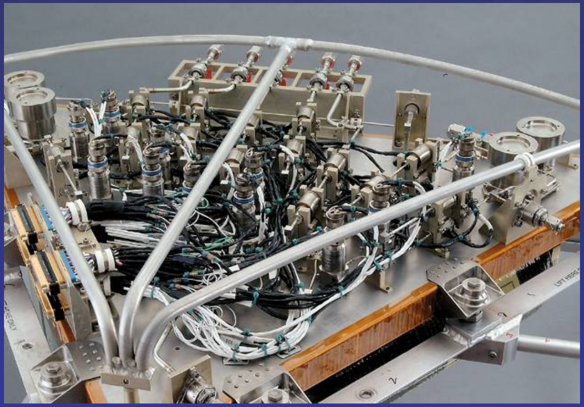
Initial liftoff

Gyro position –
non drag-free gravity
gradient effects in
Science Mission Mode



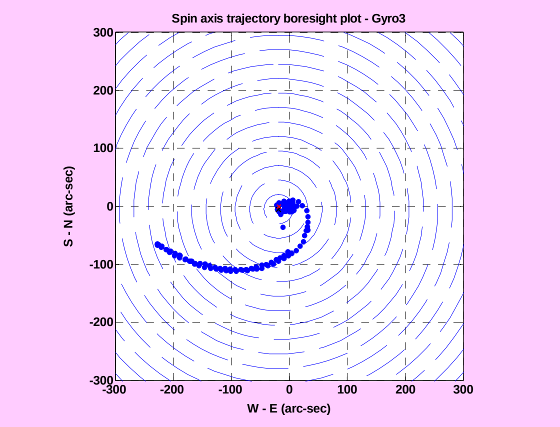
Full Speed Spin of Gyro 4 to 106 Hz





Spin gas manifold

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

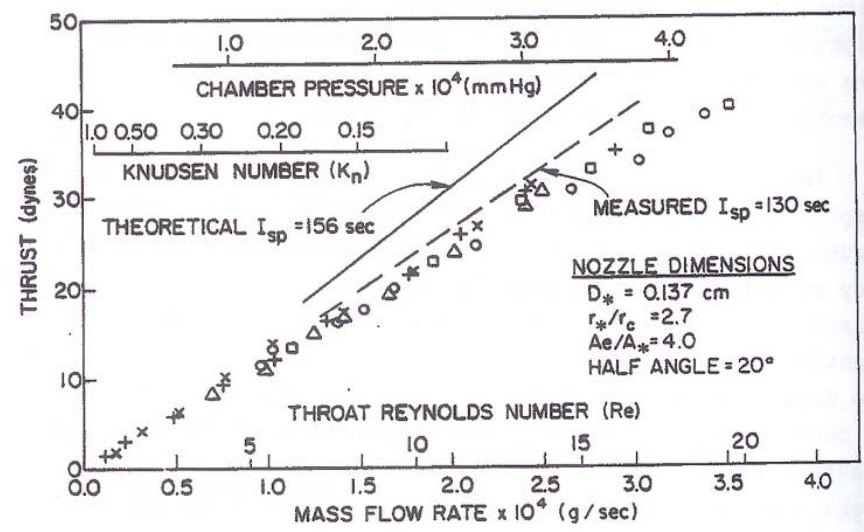


Boil-off, Altitude & Thrust

- **A very different control system**
  - Continuous flow → proportional thrusters
  - Reynolds' # ρv*l*/η ~ 10!! -- flowing like honey

- **Thrust calibration:**

* John Bull + * Jen Heng Chen (A/A)



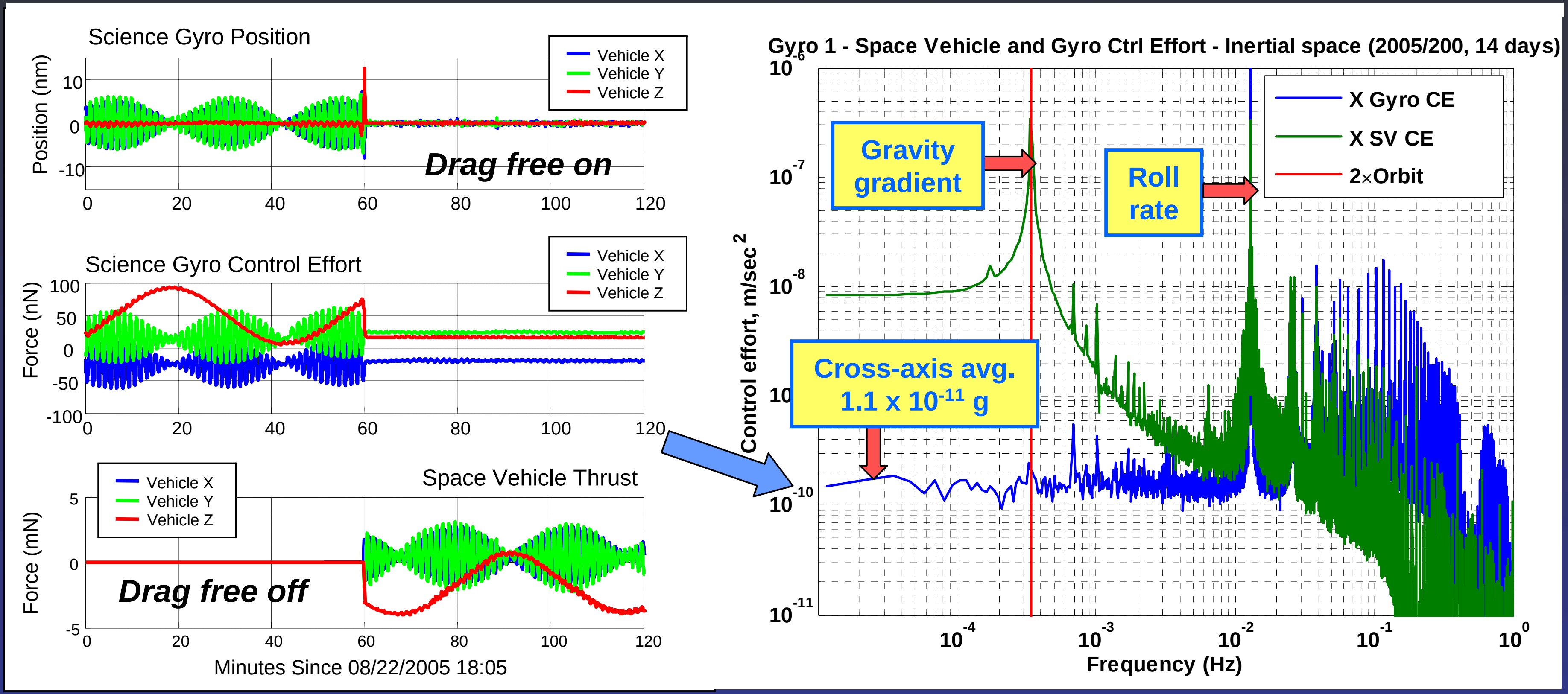
He specific impulse vs.mass flow rate

- **Lockheed Martin thrusters:**

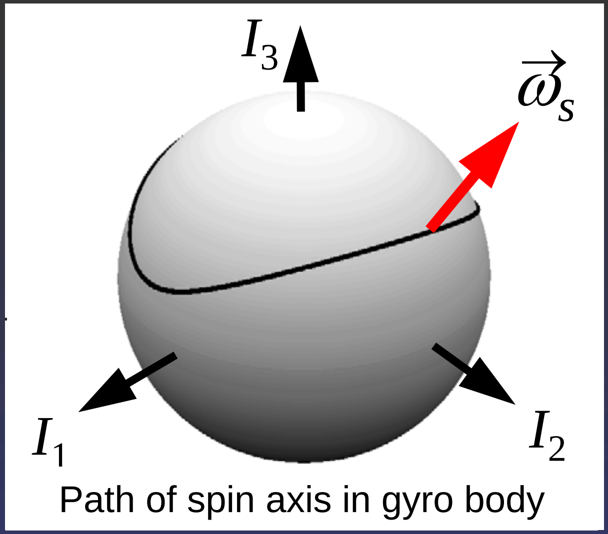
Jeff Vanden Beukel

* Yusuf Jafry (A/A) with LM team

On-orbit Drag-Free Performance



Mass Unbalance & $\Delta I/I$



Path of spin axis in gyro body

Polhode

$$\frac{\Delta I}{I} \leq \frac{\omega_p}{\omega_s}$$

$$\omega_p = 1 / 36 \text{ hr}$$

$$\omega_s = 3 \text{ Hz}$$

$$\rightarrow \frac{\Delta I}{I} \leq 2\times10^{-6}$$

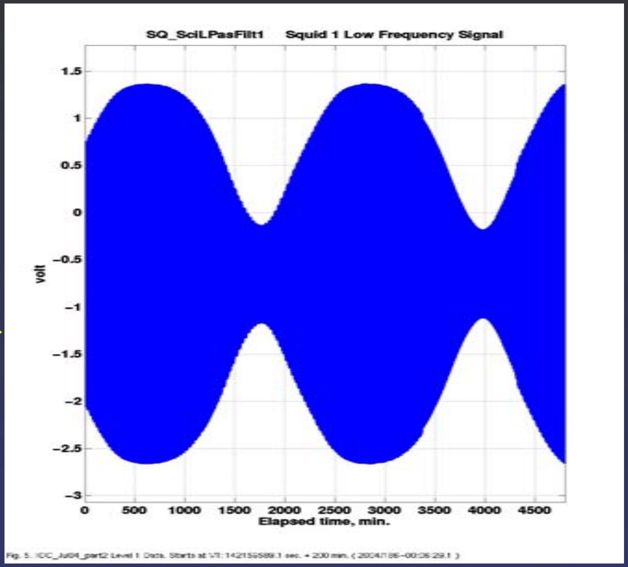
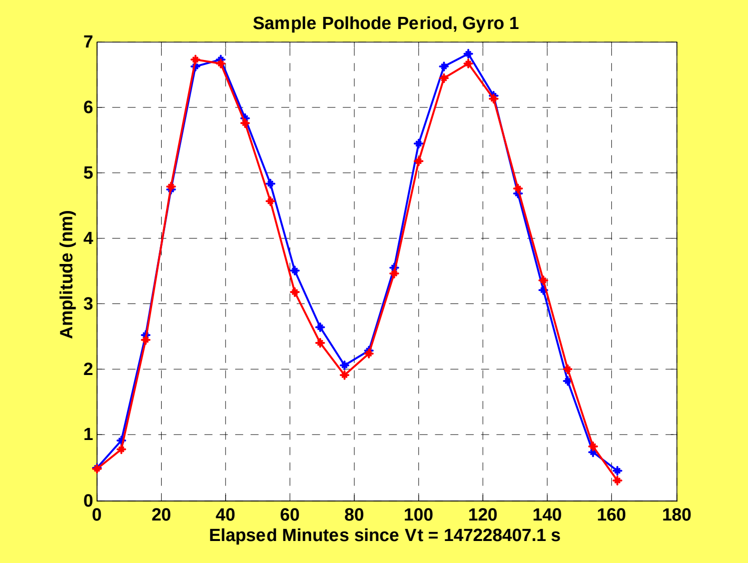


Fig. 5. IOC_Jul04_part2 Level 1 Data. Starts at VT: 142155589.1 sec. + 200 min. (2004/186–00:26:29.1)

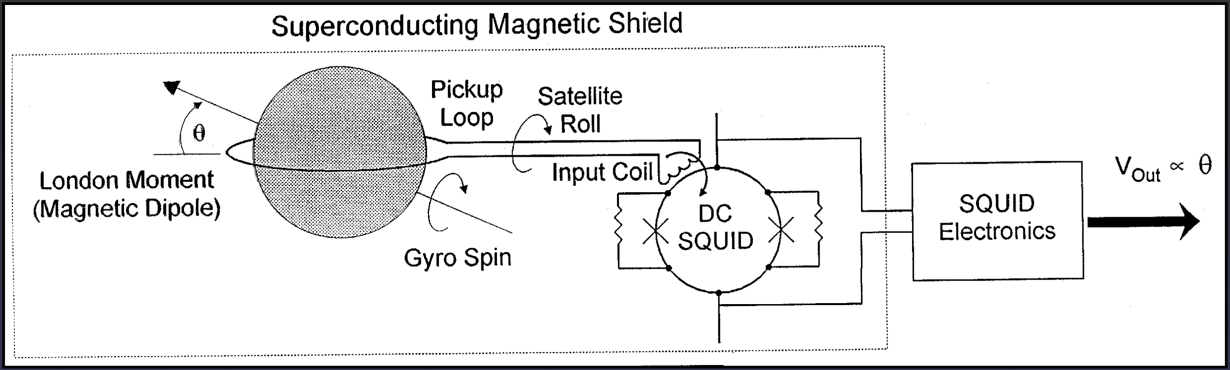


Gyro # 1 @ 79.3858 Hz

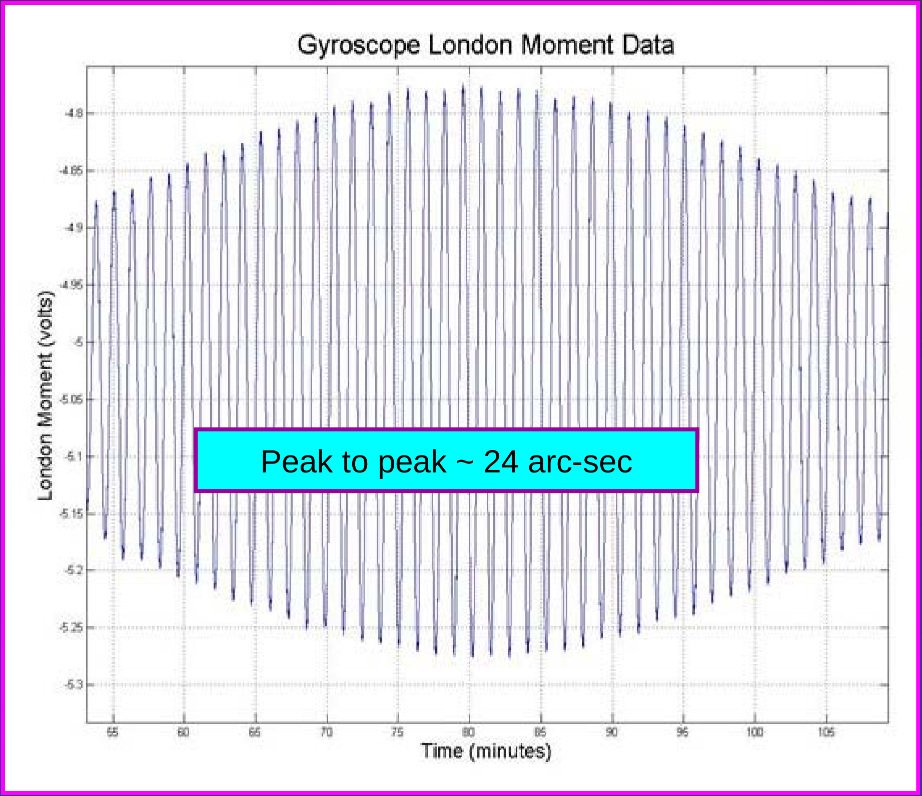
Mass Unbalance (nm)

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

Gyro Readout On-Orbit



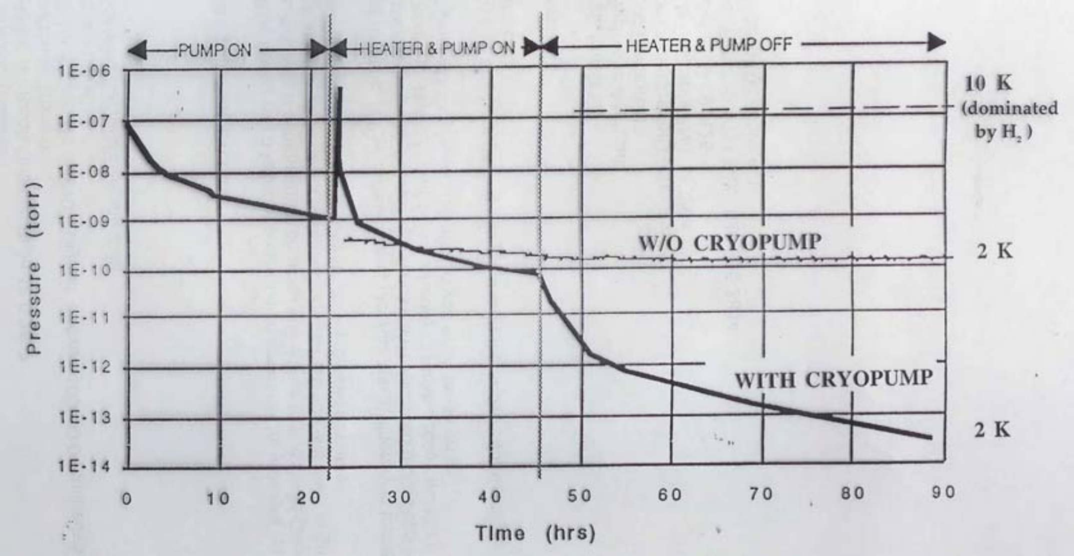
Gyro	Experiment Duration (days)	SQUID Readout Limit (marc-s/yr)
1	353	0.198
2	353	0.176
3	353	0.144
4	340	0.348



Peak to peak ~ 24 arc-sec

Ultra-low Pressure & Spin-down

Low Temperature Bakeout (ground demonstration)



The Cryopump

Gyro spindown periods on-orbit (years)

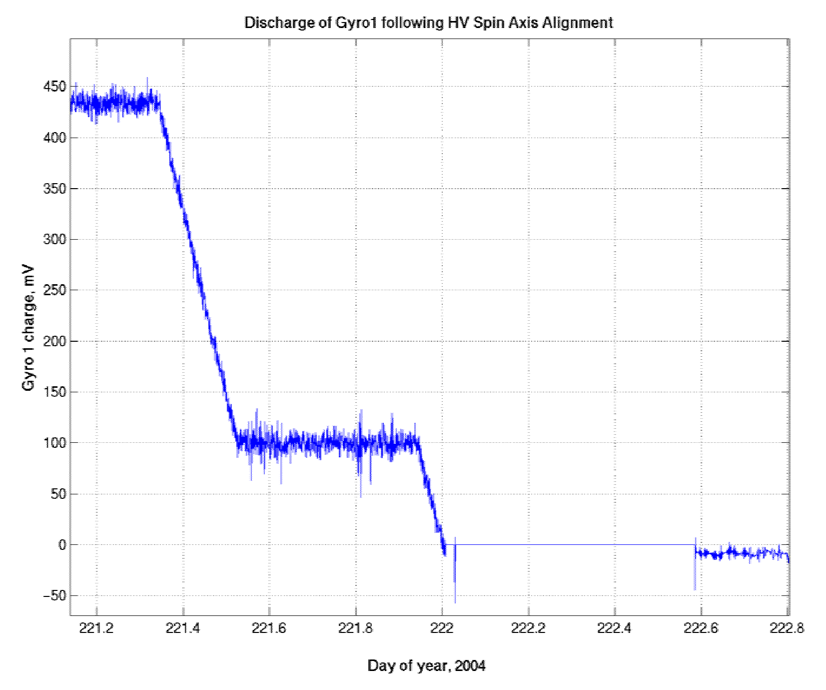
	before bakeout	after bakeout
Gyro #1	~ 50	15,800
Gyro #2	~ 40	13,400
Gyro #3	~ 40	7,000
Gyro #4	~ 40	25,700

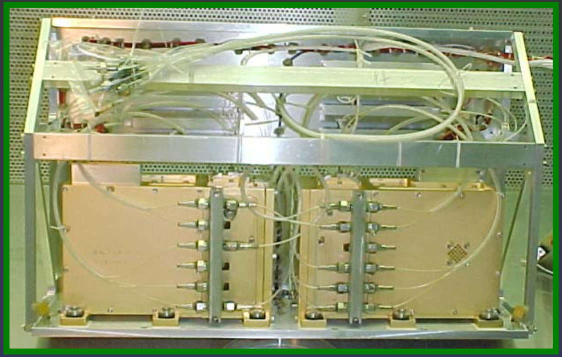
John Lipa, John Turneaure (Physics) + students; adsorption isotherms for He at low temperature,* Eric Cornell, (undergraduate honors thesis)

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

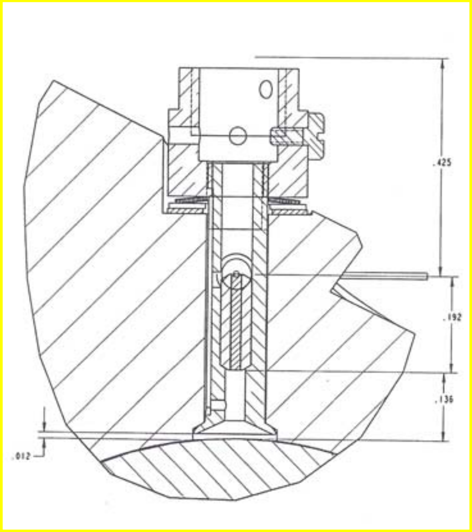
Rotor Electric Charge

Discharge of Gyro #1





Ti Steering Electrode



Sasha Buchman, Dale Gill, Bruce Clarke (Physics, HEPL)
+ * Brian DiDonna & * Ted Quinn (Physics)

Typical charge rates ~ 0.1 mV/day

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

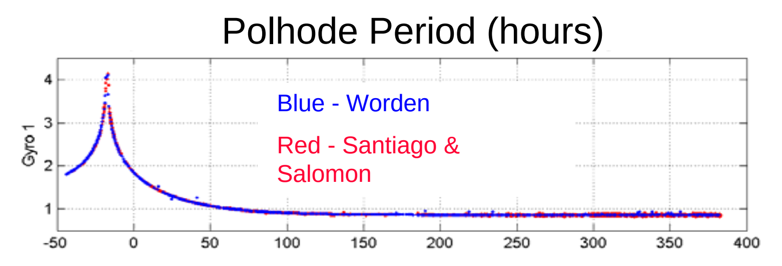
Surprise B – Larger than expected misalignment torques

Two mutually reinforcing gremlins + a third

The 3 Data Analysis Gremlins

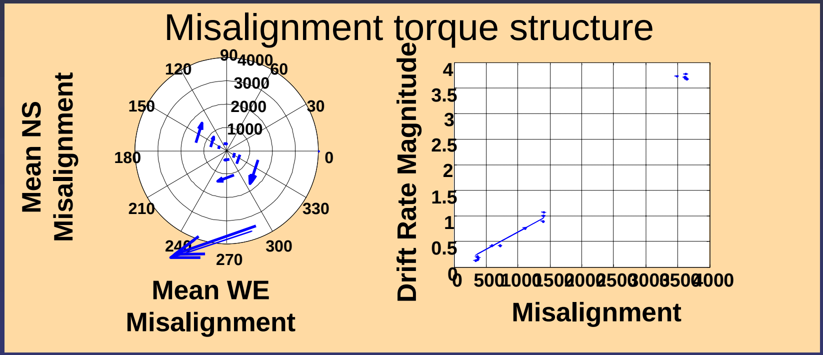
A. Polhode rate variations affect scale factor (C_g) determinations

- Discovered in early science phase



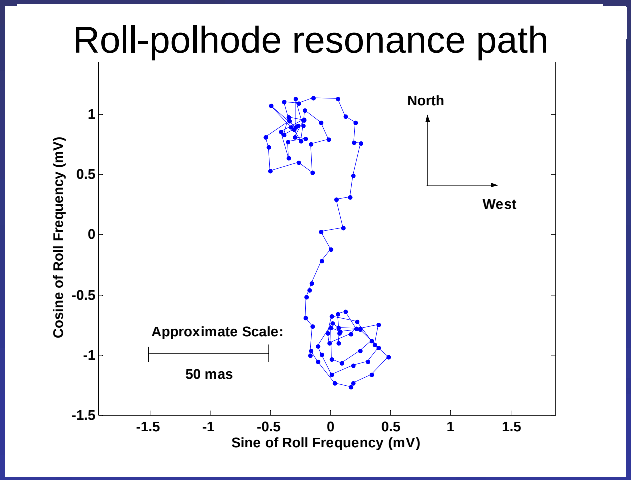
B. Misalignment torques

- Discovered in post-science calibration phase



C. Roll-polhode resonance torques

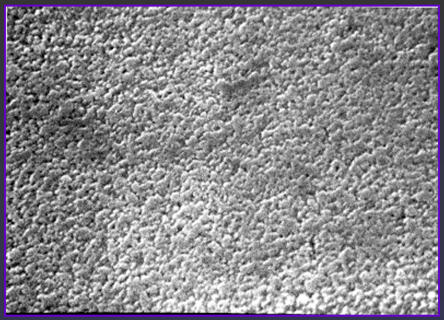
- Discovered through gyro-to-gyro comparison analysis during data reduction phase



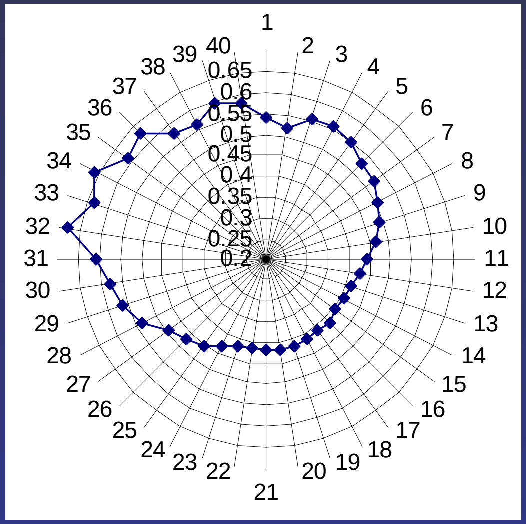
All due to one physical cause (patch effect)

The 'Patch Effect' Detective Story

- Pre-launch investigation
  - Rotor electric dipole moment + field gradient in housing
  - 100 mV contact potentials mitigated by minute grain size, 0.1 µm << 30 µm rotor-electrode gap
  - Kelvin probe measurements on flat samples
- On-orbit discoveries
  - ***Polhode damping*** (July 2004)
  - ***Drag-free z acceleration*** (Sept. 2004)
  - ***Spin down rate > gas damping*** (Feb. 2005)
  - ***Misalignment torques*** (Aug. 2005)
  - ***Roll-polhode resonance torques*** (Jan. 2007)
- Post-launch ground-based investigations
  - Work function profile via UV photoemission
  - Detailed analytical modeling



SEM image of rotor Nb film average grain size 0.1 μm



Work function polar plot

A Brief History of Gremlin-Slaying

Sep. 2005	**Geodetic effect visible in raw data**
Oct. 2006	**Geometric method: elegant separation, but batch length limited**
Nov. 2006	**Trapped Flux Mapping (TFM) starts**
Jan. 2007	**Roll-polhode resonance torques discovered**
Aug. 2007	**Incorporation of TFM reduces scatter 100 σ to 2 σ**
Sep. 2007	**Loxodromic model of resonance torques**
Nov. 2007	**Promising Algebraic results, but systematic effects remain**
Mar. 2008	**Supergeometric method**
July 2008	**TFM, loxodromic model, & advanced processing reduce scatter further 5x – 10x**

~ 100x improvement to date…

Current GP-B Data Analysis Team


Bill Bencze


Michael Heifetz


Tom Holmes


Mac Keiser


Jeff Kolodziejczak


Barry Muhlfelder


Alex Silbergleit


Vladimir Solomonik


Karl Stahl


Paul Worden

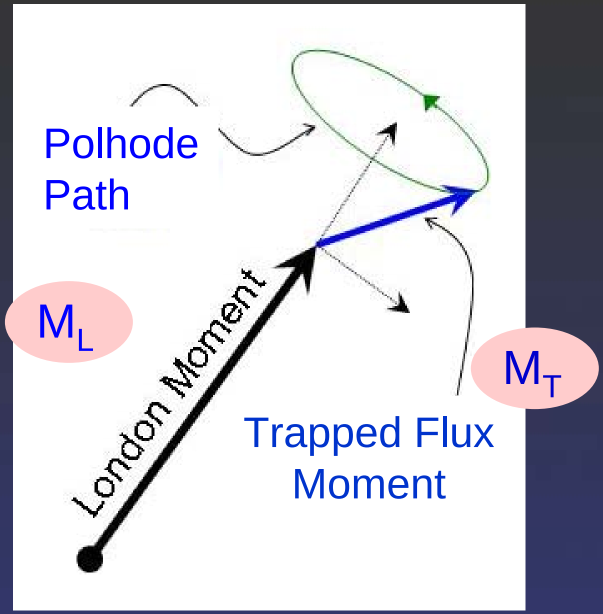
3 Key Students


John Conklin


Michael Dolphin


Michael Salomon

Ideal vs. Actual London Moment Readout



London field at 80 Hz: 57.2 μG

Trapped fields	Gyro 1	3.0 μG
	Gyro 2	1.3 μG
	Gyro 3	0.8 μG
	Gyro 4	0.2 μG

Trapped flux appears troublesome, but defeats all 3 gremlins

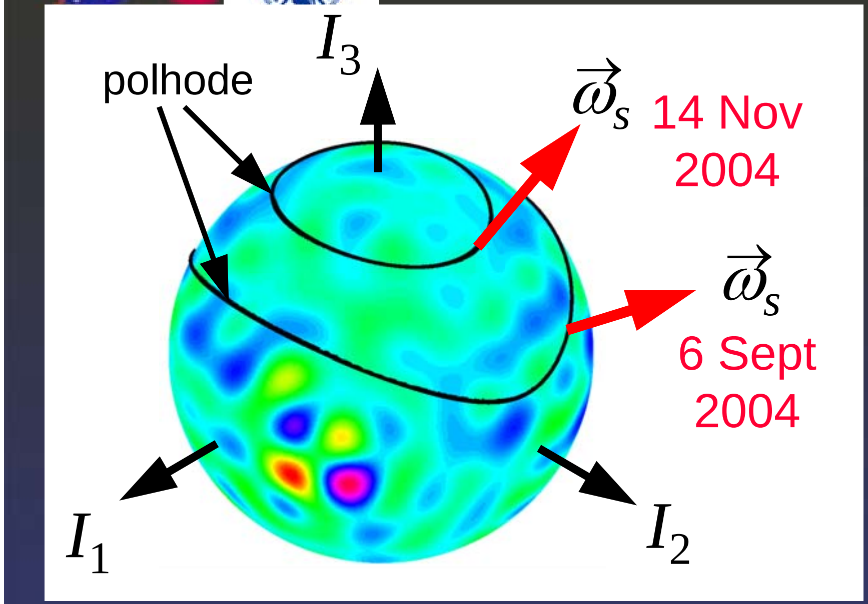
Gremlin 1: Connects data orbit-to-orbit for accurate gyro scale factor, C_g

Gremlin 2: Simplifies computation of misalignment phase

Gremlin 3: Miraculously enables precision roll-polhode resonance torque modeling

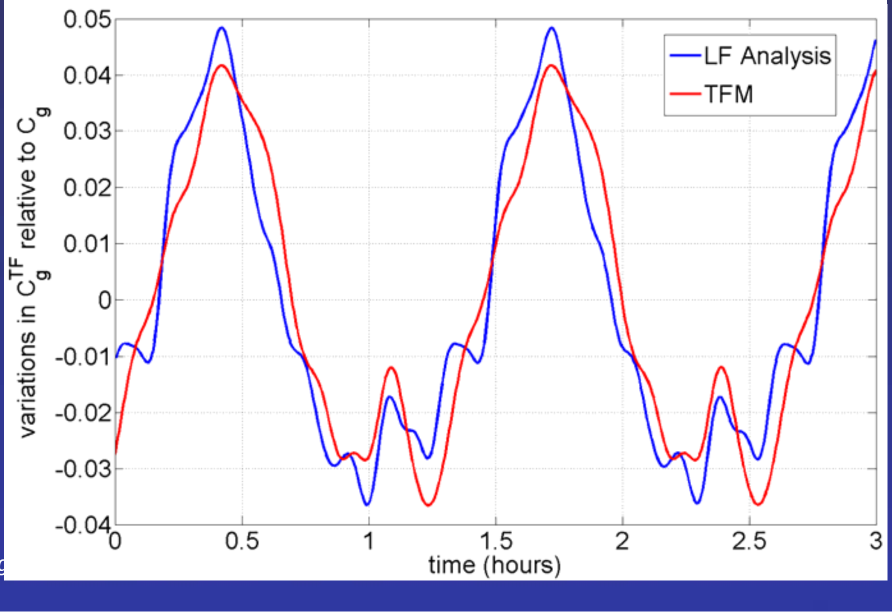
…the ‘Anti-Murphy’ Law

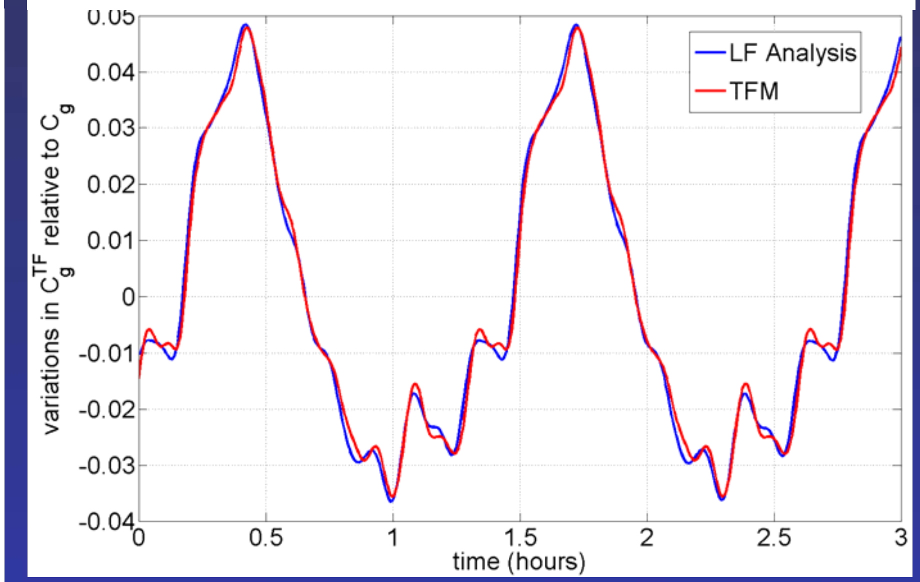
Trapped Flux Mapping: C_g Determination



TFM determines evolving polhode phase to 0.5° over the full mission

- ⇒ Fully resolves gyro scale factor
- ⇒ Crucial input for torque analysis

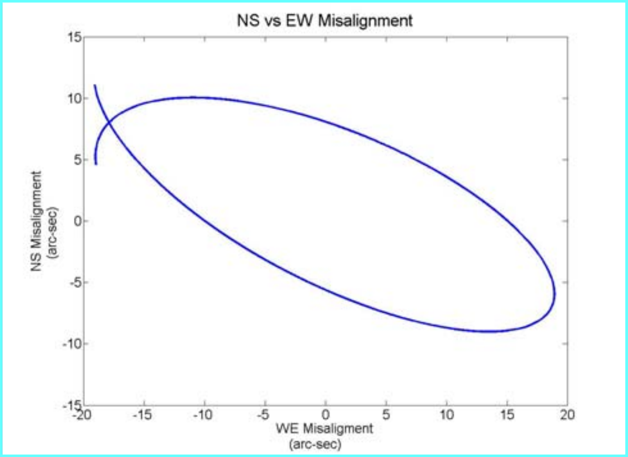

Nov. 2007, Gyro 1, Fit residuals = 14%

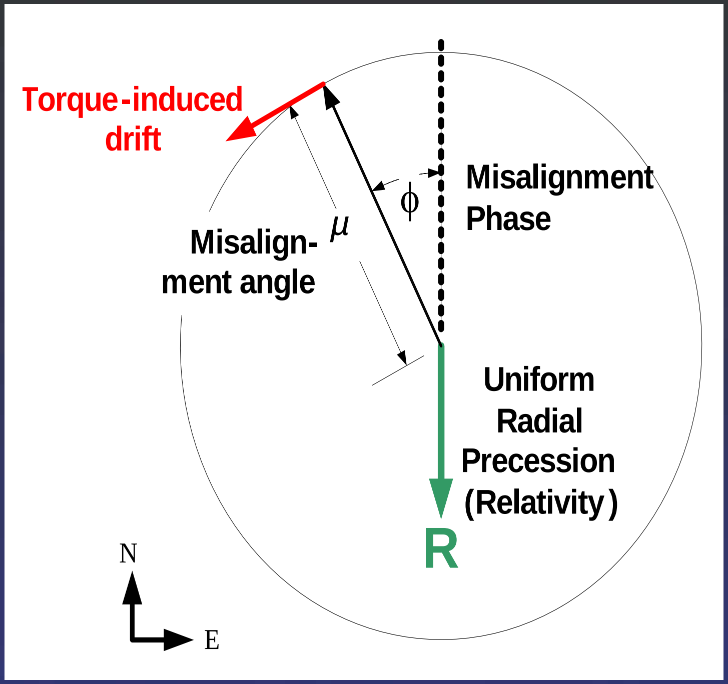

Aug. 2008, Gyro 1, Fit residuals = 1%

2 Methods of Treating Misalignment Torque

Misalignment torque structure

- Direction modulated by annual aberration
- Enables truly *physical* modeling





The 2 Methods

Geometric: Change variables to plot rates against misalignment phase

→ component of relativity free of misalignment torques

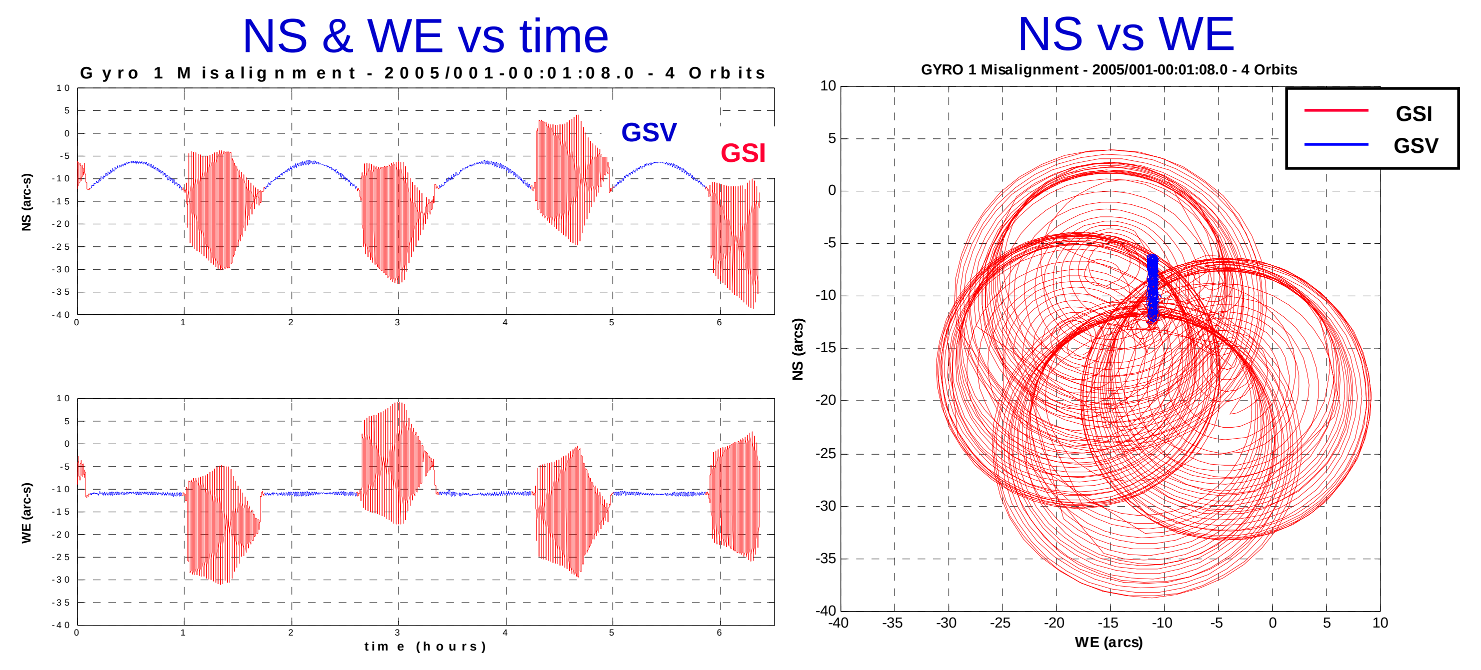
Algebraic: Filtering machinery to explicitly model torques

→ provides separation from relativity

Obtaining Continuous Misalignment History

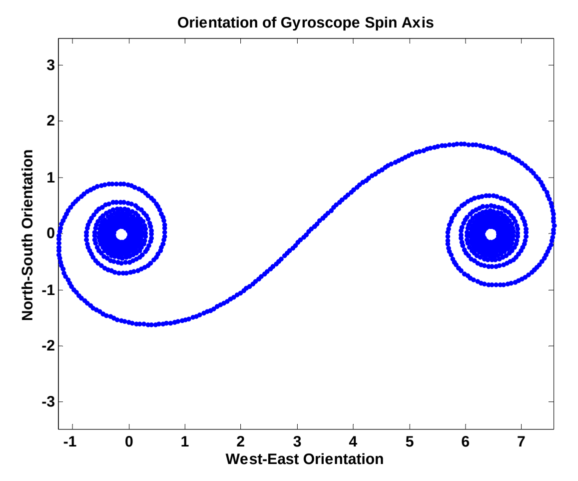
- Science gyroscopes provide precision misalignment information when guide star occulted

Continuous Guide-Star Valid / Guide-Star Invalid misalignment history

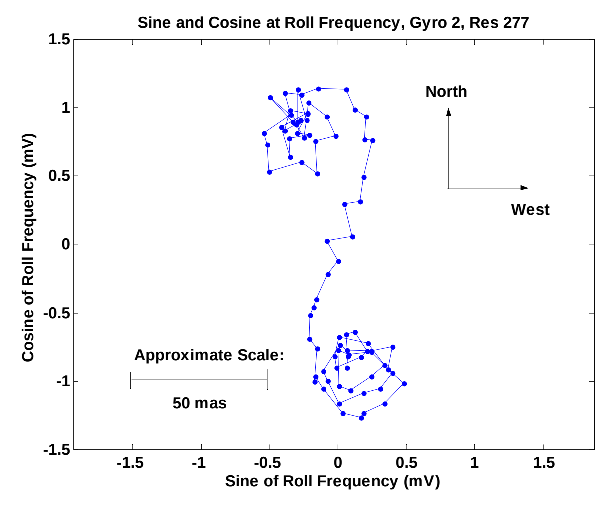


Gremlin 3: Roll-Polhode Resonance Torque

- Path predicted from rotor & housing potentials
  - Roll averaging fails when $\omega_r = n\omega_p$
  - Orientations follow loxodromic curve
  - Magnitude & direction depend on patch distribution & roll phase at resonance



- Example: Gyro 2, Resonance 277
  October 25, 2004



<u>Note:</u> Changing conditions during resonances may partially mask loxodromic curve

Torque Modeling: Gremlins 2 & 3

- Add roll-polhode resonance term to equations of motion

$$\frac{ds_{NS}}{dt} = r_{NS} + k\mu_{EW} + \boxed{[c^{-}\cos(\theta \pm \Phi_{r}) - c^{+}\sin(\theta \pm \Phi_{r})]}$$

$$\frac{ds_{EW}}{dt} = r_{EW} - k\mu_{NS} + \boxed{[c^{-}\sin(\theta \pm \Phi_{r}) + c^{+}\cos(\theta \pm \Phi_{r})]}$$

Relativity

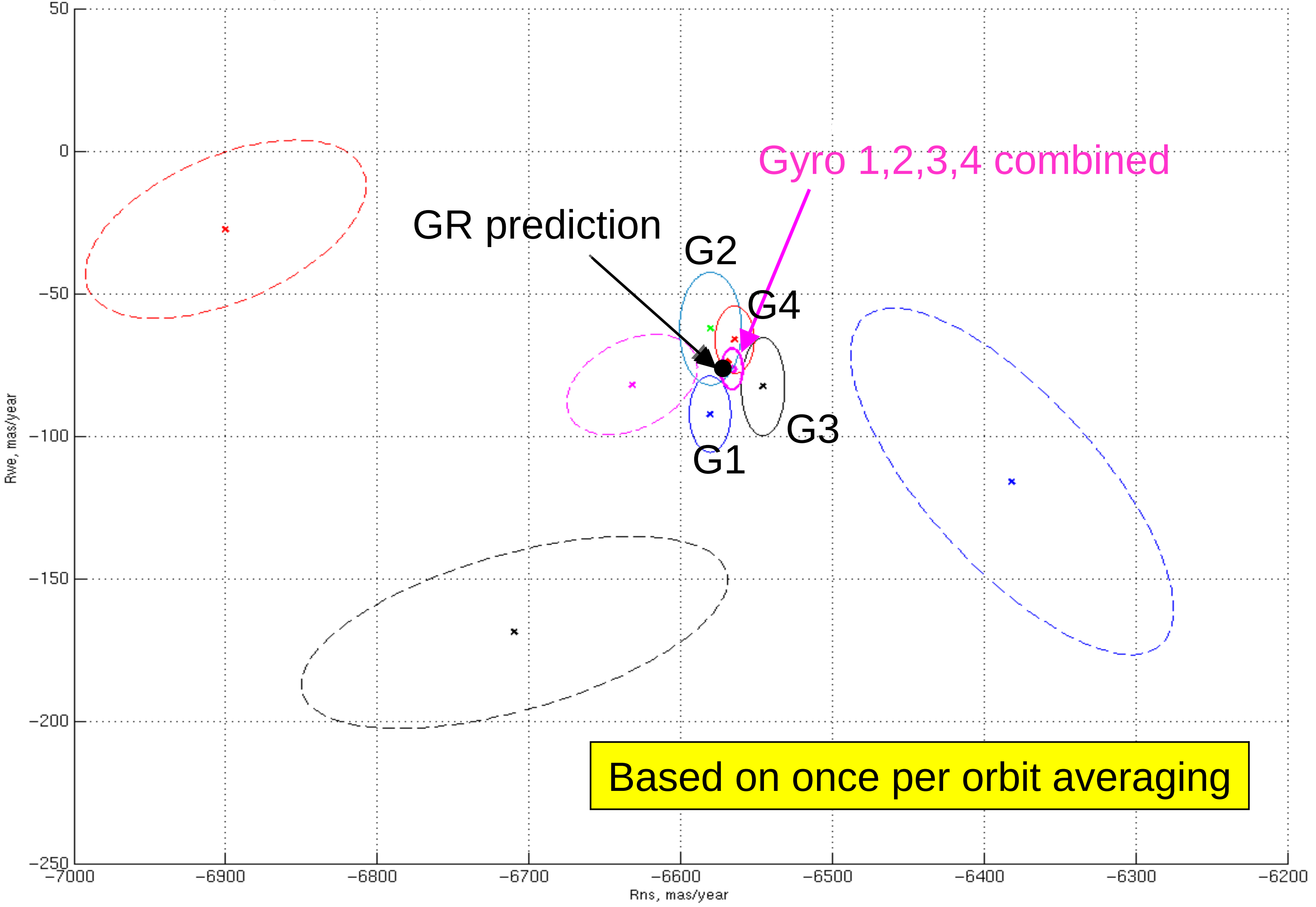
Misalignment torque

Additional term

- Implementation
  - c^{-} & c^{+} time-varying functions of polhode phase & angle
  - Hence, treatment of roll term hinges on TFM

Initial Demonstration

R_{ns} vs. R_{we} Estimates based on 154 days of data



Based on once per orbit averaging

Rel. drift estimates

Current Status

Algebraic Method

	R_{ns} (marcs/yr)	R_{we} (marcs/yr)
G1	- 6581 ± 14	- 92 ± 13
G2	- 6580 ± 21	- 62 ± 20
G3	- 6546 ± 14	- 83 ± 17
G4	- 6564 ± 13	- 66 ± 12
Weighted Mean	- 6566 ± 7	- 76 ± 7

Geometric Method

G4	- 6631 ± 16	- 77 ± 14

Einstein Prediction →

- 6571 ± 1	- 75 ± 1

From once-per-orbit to 2-sec processing ⇨

Locking down the Final Results

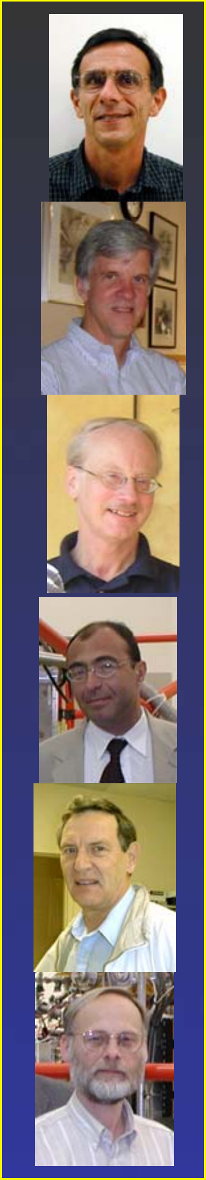
Current limit with once per orbit time step ~ 7 marcs/yr

SQUID noise limits: 0.14 – 0.35 marcs/yr (gyro dependent)

Include resonance model in SuperGeometric method	*Jan '09*
2-sec processing of roll-polhode resonance torque ⇨ **approach ultimate realizable limit (~ 1 marcs/yr ?)**	*June '09*
Removal of any remaining systematic effects	*Aug '09*
Blind test against SAO guide star orbital motion	*Sep '09*
Grand synthesis of Geometric & Algebraic results	*Mar '10*

GP-B: 7 + 1 Interfolded Stories

- **Testing Einstein**
- **Unexpected Technologies**
- **Two SU Departments: *Physics & Aero-Astro***
- **Students: *84 + 13 PhDs, 353 U/G, 55 high school***
- **Spin-Offs: *drag-free, porous plug, auto-landing, + + + +***
- **NASA-Stanford-Industry Symbiosis**
- ***"A very interesting management experiment"* – J. Beggs, 1984**
- **KACST Collaboration**

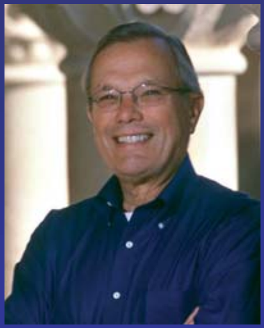


Co-I's

Co-PI's

Dan DeBra

Charbel Farhat



Brad Parkinson

John Turneaure