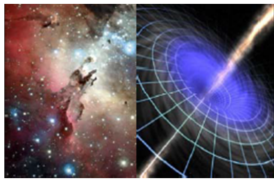


Курс лекций весеннего семестра 2011 года:

«Современные Проблемы Астрономии»

Государственный Астрономический Институт им. П.К. Штернберга

Lecture 12.2:

Gravity Probe B:

History, Mission Performance and Current Status

В. Г. Турышев

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91009 USA

Государственный Астрономический Институт им. П.К. Штернберга
Университетский проспект, дом 13, Москва, 119991 Россия

Курс Лекций: «Современные Проблемы Астрономии»
для студентов Государственного Астрономического Института им. П.К. Штернберга
7 февраля – 23 мая 2011

Outline

- Gravity Probe B (GP-B):
  - History
  - Science
  - Space Vehicle
  - Launch
  - Test

April 20, 2004 Launch of GP-B from Vandenberg AFB and successful insertion into polar orbit.

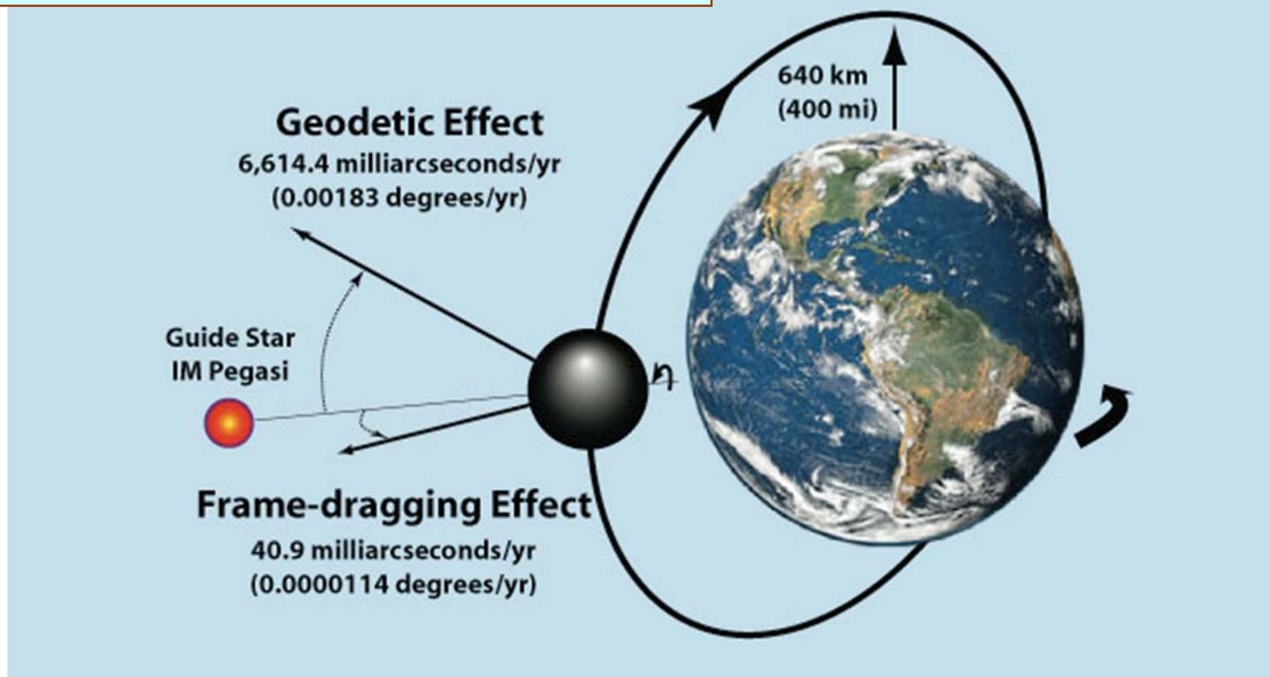
http://einstein.stanford.edu/

Gravity Probe B

- Gravity Probe B (GP-B):
  - Is a spacecraft that tests Einstein's General Theory of Relativity in new ways.
  - It experimentally measures the distortion in the space-time continuum due to the mass of the earth and its rotation.
  - The test compares the spin axis of very precise gyroscopes with a far away guide star as a reference point.
  - It is a collaboration between NASA, Stanford and LM
- GP-B Important Terms:
  - **Gyroscope** - Greek origin where the root "gyr" means rotation and the root "scope" means view. An instrument to view rotation.
  - **Superconductivity** - The flow of electric current without resistance in certain metals, alloys, and ceramics at temperatures near absolute zero.
  - **Dewar** - a type of vacuum flask, especialy one used in scientific experiments to keep a material or object at a specific temperature; Thermos.
  - **Torque** - A turning or twisting force.
  - **Relativity** - the theory that space and time are relative concepts rather than absolute concepts.

The Relativity Mission Concept

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

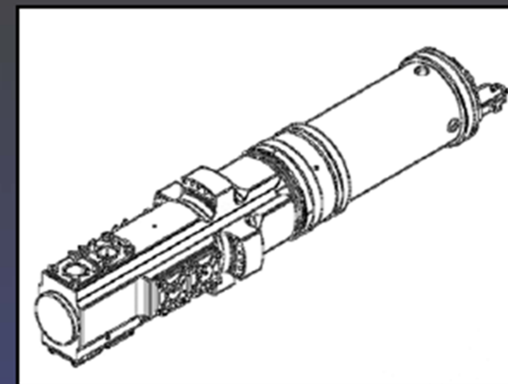


- Geodetic Effect
  - Space-time curvature ("the missing inch")
- Frame-dragging Effect
  - Rotating matter drags space-time ("space-time as a viscous fluid")

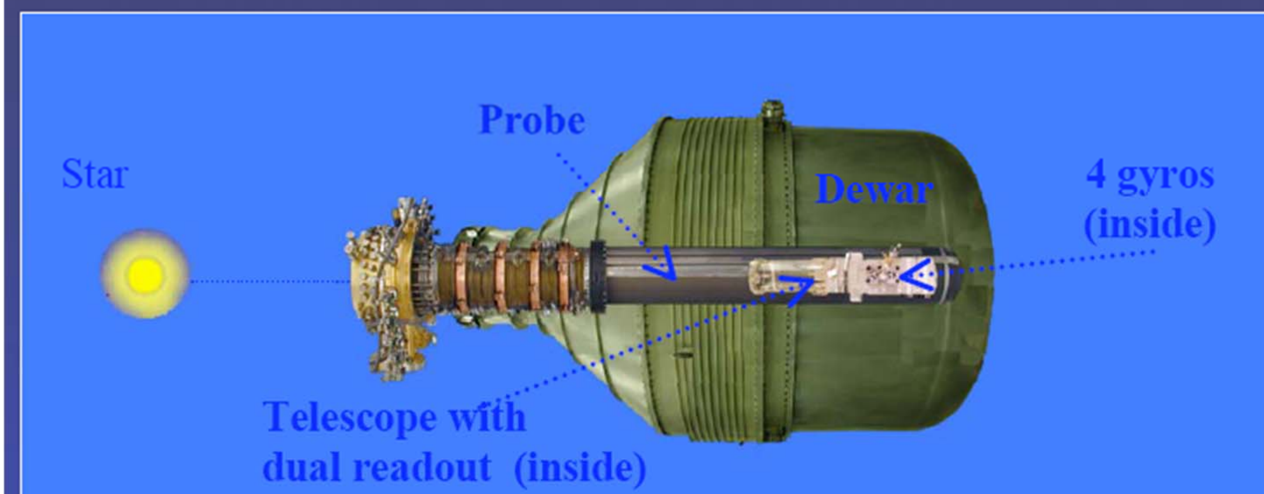
GP-B: the Main Systems

Gyroscope

Telescope

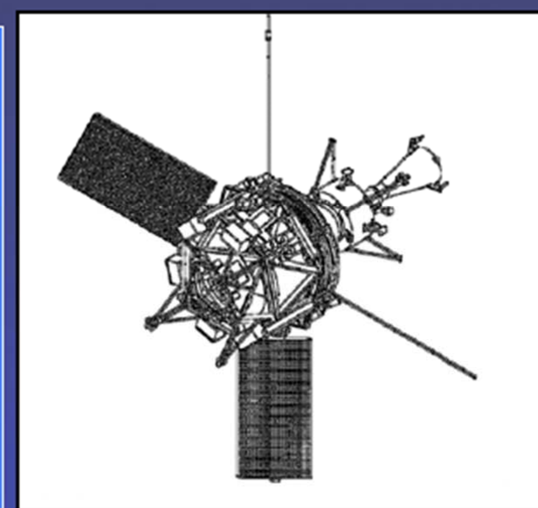


Science Instrument



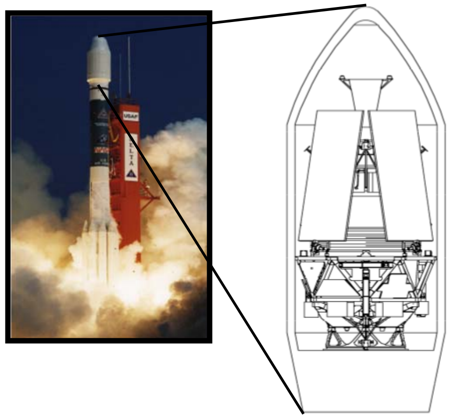
Cryogenic Probe

Payload



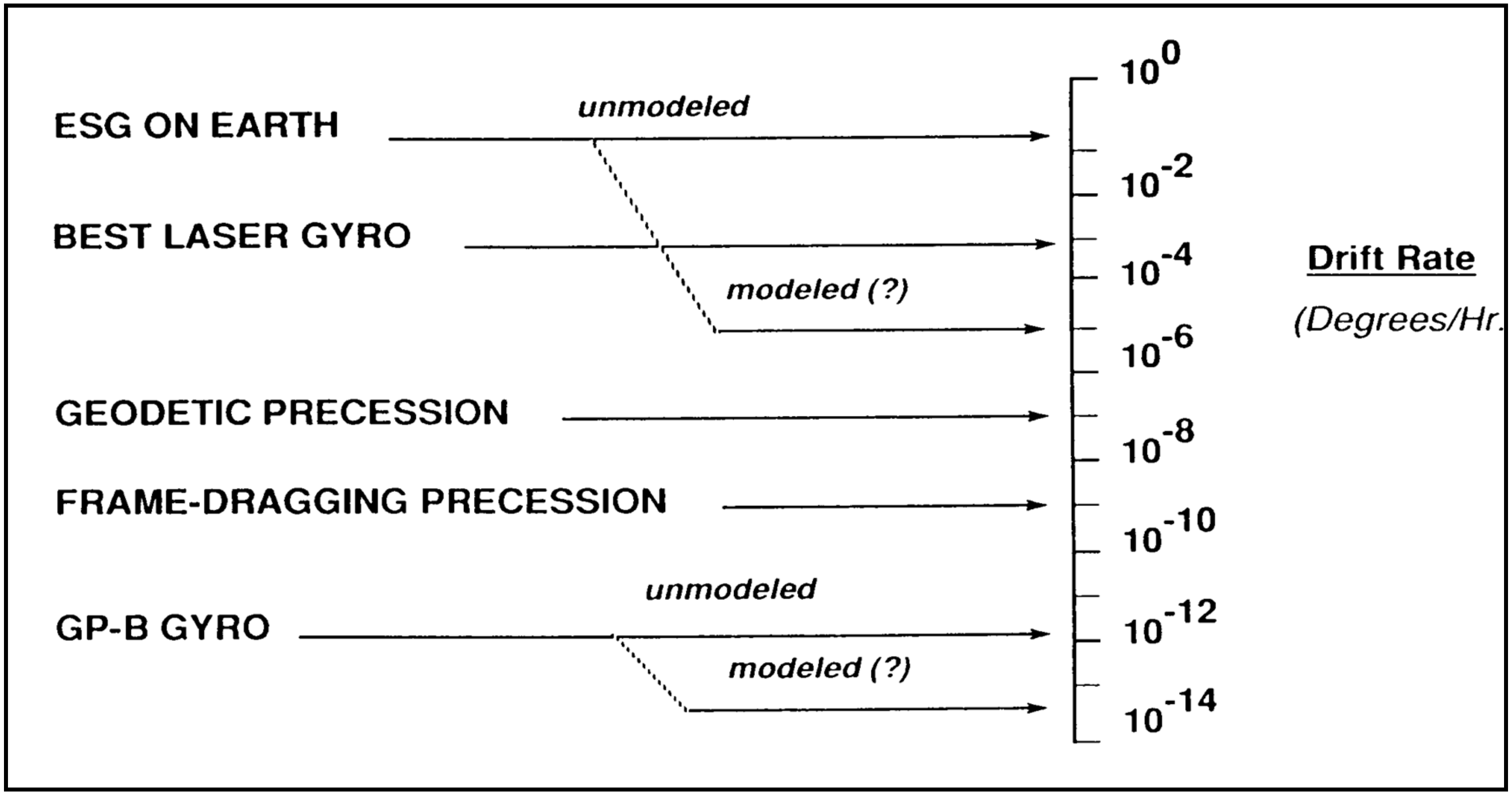
Space Vehicle

Vital Statistics



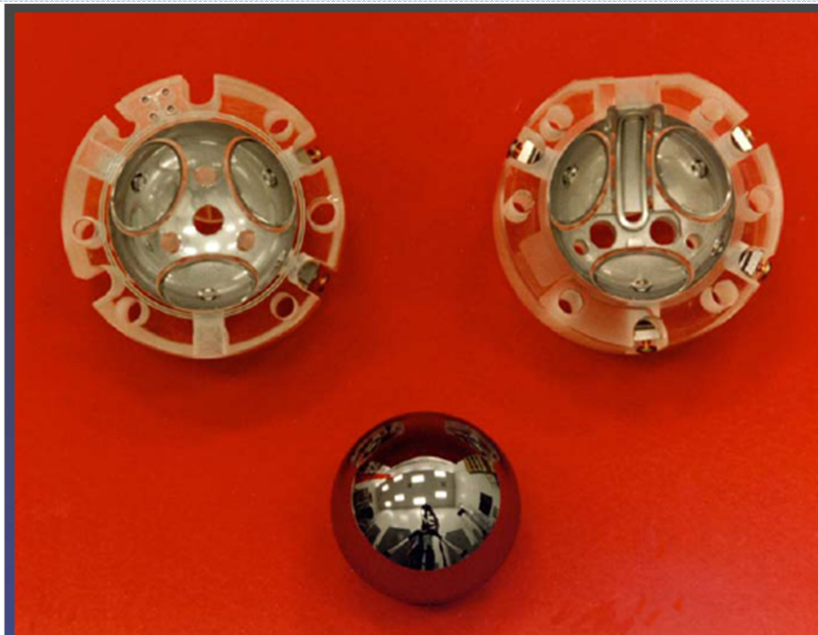
- Mass - 3144.8 kg [~7000 lbs]
- Length - 6.43 meters [~21 feet]
- Diameter - 2.7 meters [~9 feet]
- Power - ~550 watts
- Duration - ~18 months
- Guide Star - HR8703 IM Pegasus
- Launch Vehicle: Delta II 7920-10 from VAFB into 400 mile Polar Orbit
- Dewar
  - 2441 Liters [~650 gallons] liquid Helium
  - Superfluid Helium temperatures: 1.6 Kelvin [-271.55 C] [-456.79 F]

Why go to space?

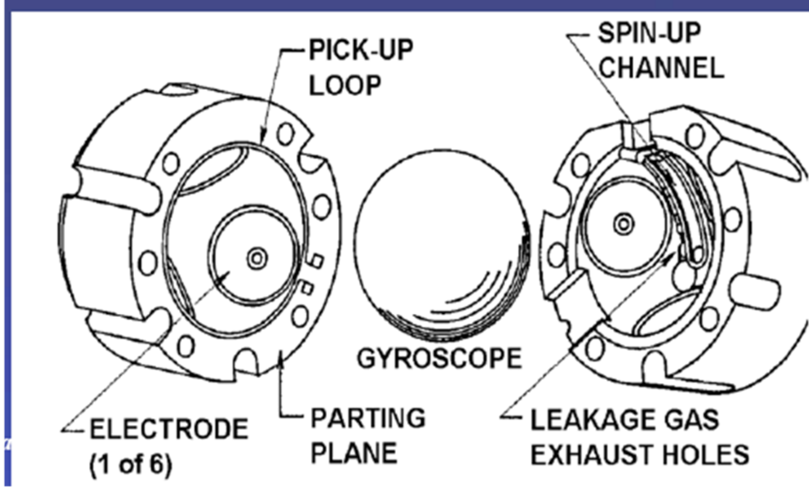


1 marcsec/yr = 3.2×10^{-11} deg/hr

The Science Gyroscopes



Gyroscope rotor and housing halves



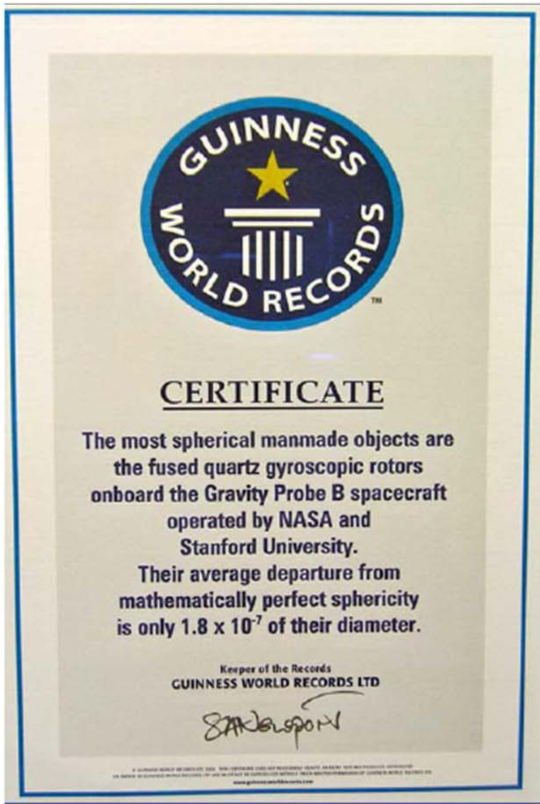
- Material: Fused quartz, homogeneous to a few parts in 10^7
- Coated with Niobium
- Diameter: 38 mm.
- Electrostatically suspended.
- Spherical to 10 nm – minimizes suspension torques.
- Mass unbalance: 10 nm – minimizes forcing torques.
- All four units operational on orbit.

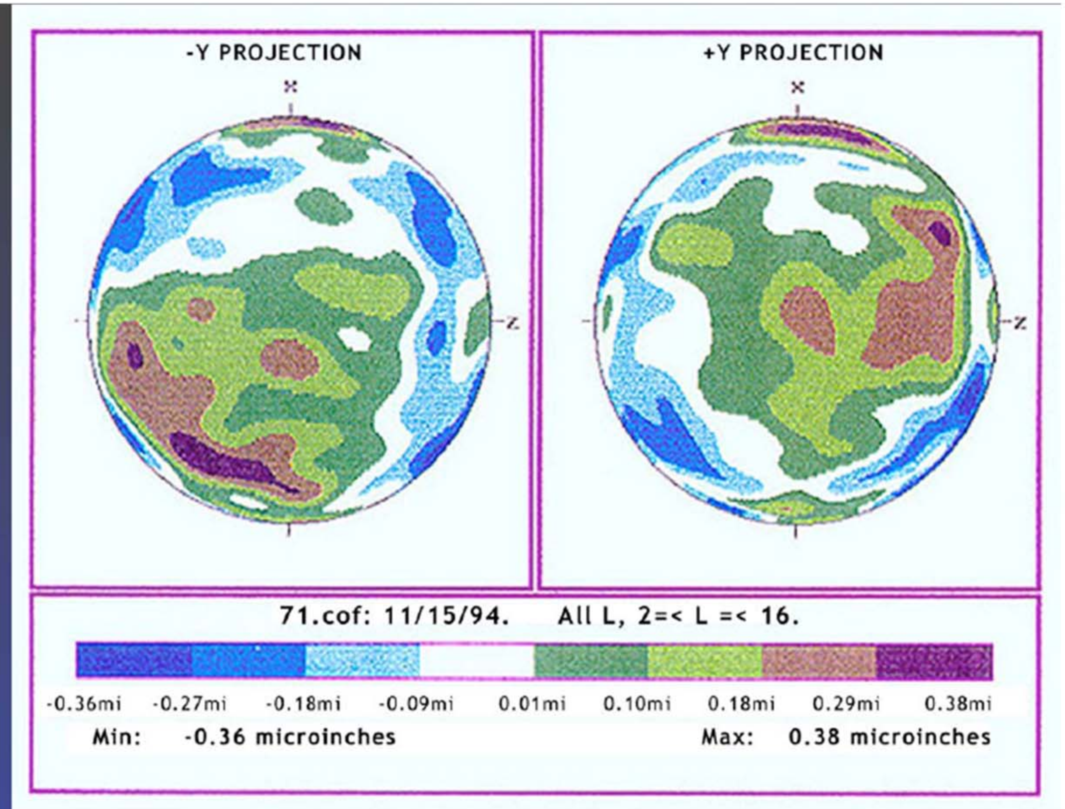
Demonstrated performance:

- Spin speed: 60 – 80 Hz.
- 1 μHz/hr spin-down.

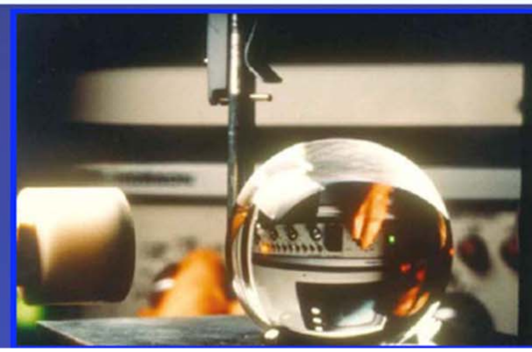
If a GP-B rotor was scaled to the size of the Earth, the largest peak-to-valley elevation change would be only 2 meters!

Gyro Asphericity Ground Verification



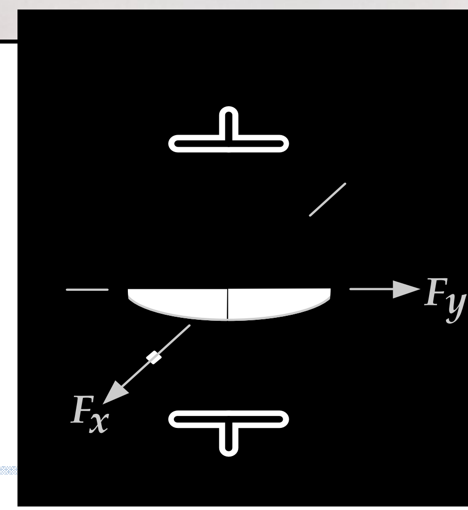


Talyrond sphericity measurement resolution ~1 nm

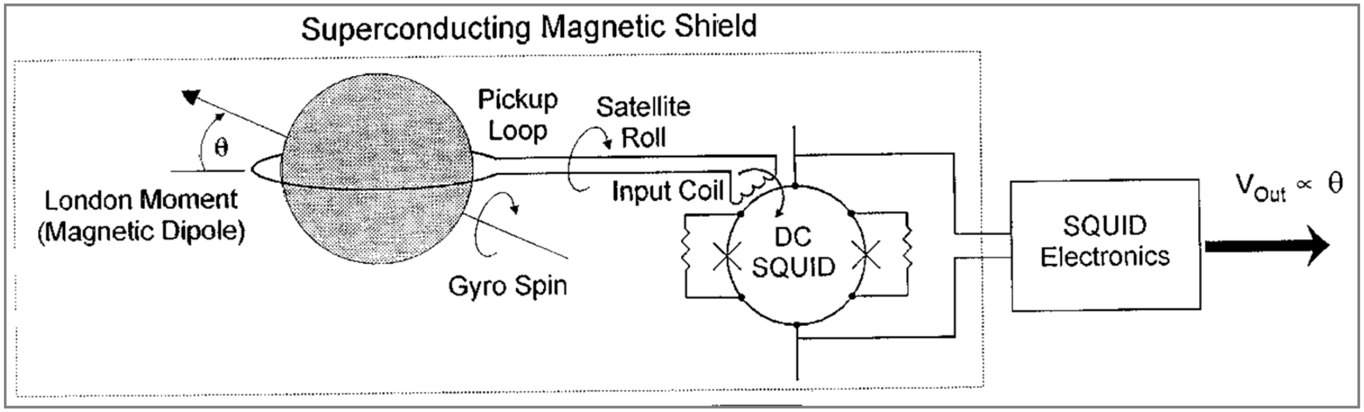


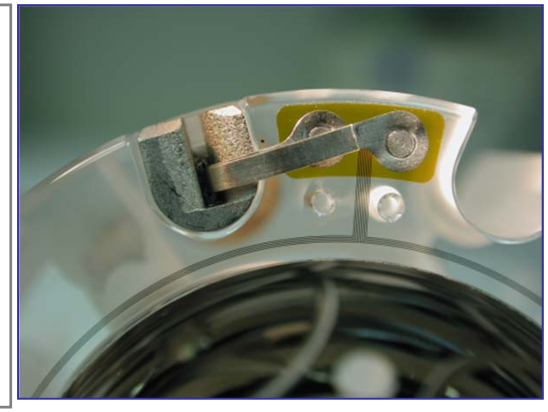
GP-B Gyroscope & Electrostatic Suspension System

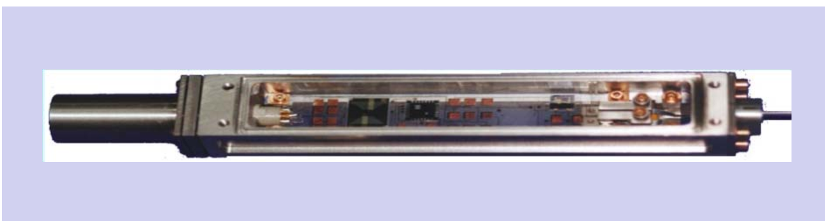
- Functions of Electrostatic Suspension System:
  - Support Rotor Spinning at 80 Hz
  - Spin Axis Alignment
  - Minimize Electrostatic Torques
  - Provide Telemetry
  - Charge Measurement and Control

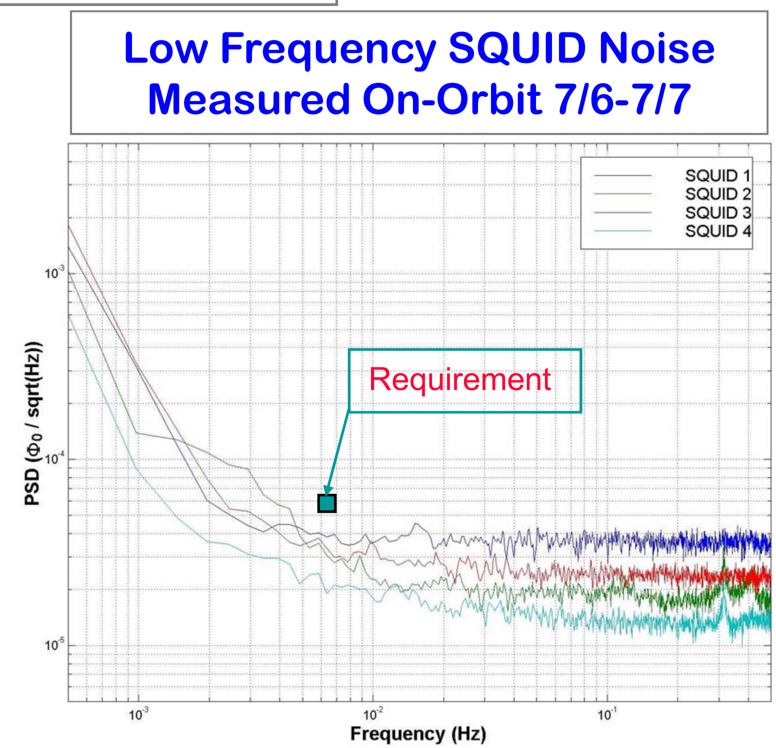


The London Moment Readout





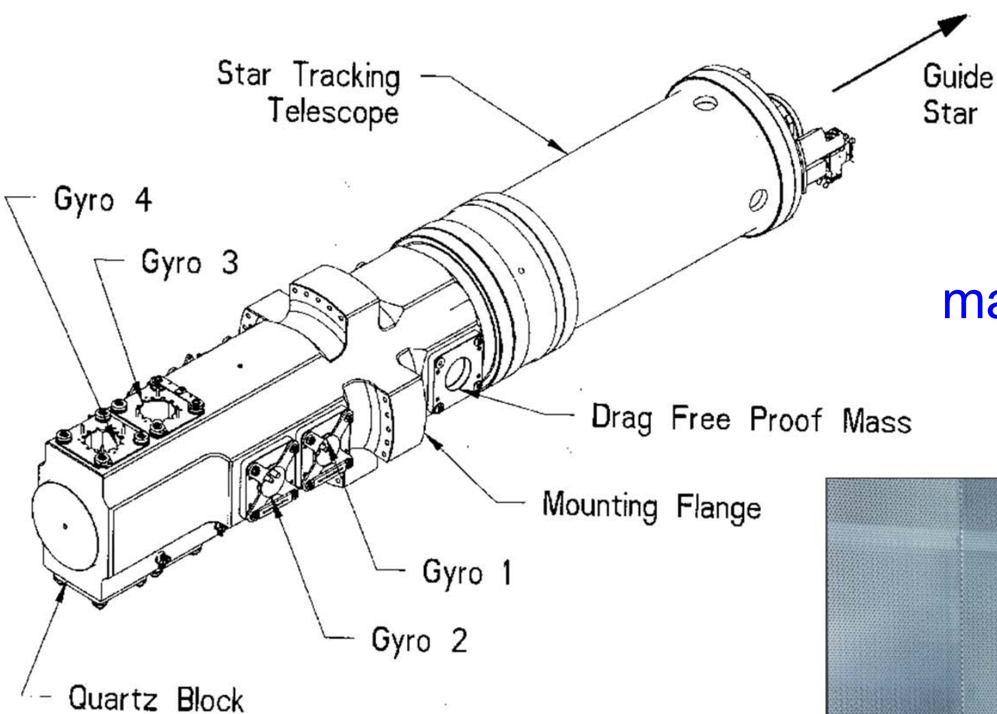




4 Requirements/Goals:

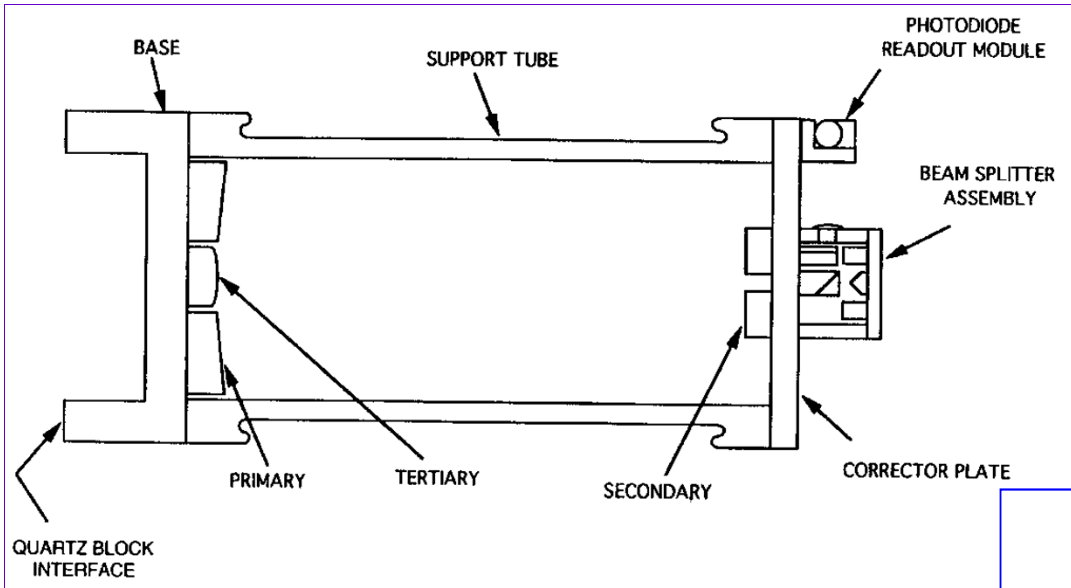
- SQUID noise 190 marc-s/√H
- Centering stability < 50 nm
- DC trapped flux < 5 ×10^{-6} gauss
- AC shielding > 5 ×10^{11}

Quartz Block/Telescope Structure



	Room T	2.8K
thermal expansion coeff.	5.5×10^{-7}	2×10^{-9}
max. allowed transverse heat flux	<0.01 mW	30mW

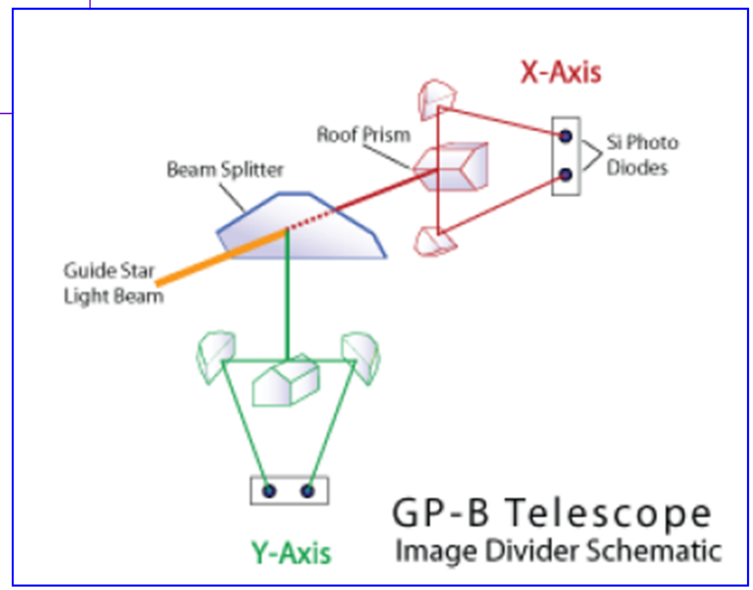
Telescope Concept: Sub-milliarc-s Star Tracker



Some dimensions

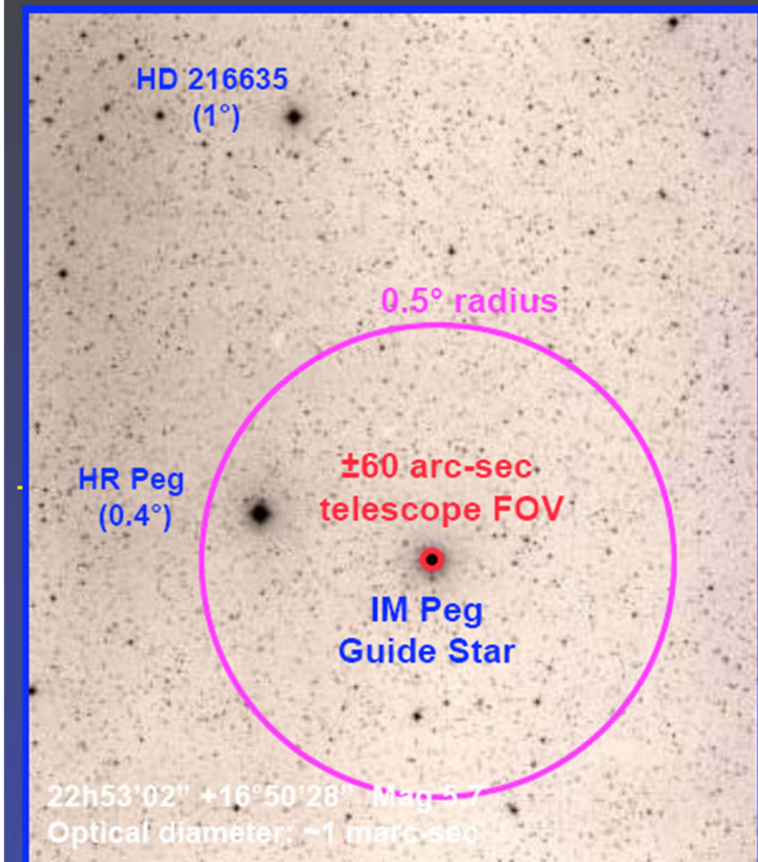
Physical length	0.33 m
Focal length	3.81 m
Aperture	0.14 m
<u>At focal plane</u>	
Image dia.	50 µm
0.1 marc-s	0.18 nm

Beam splitter assembly (detail)



Guide Star Selection

Palomar star map



Criteria:

- **Sufficiently close to equatorial plane for maximum frame dragging signal**
- **Optically bright enough to meet the pointing requirement.**
- **Be a radio star to allow VLBI proper motion measurement**

Star-Tracking Telescope

Detector Package

- Field of View: **±60 arc-sec.**
- Measurement noise: **~ 34 marc-s/√ Hz**

- **All-quartz construction.**
- **Cryogenic temperatures make a very stable mechanical system.**

Physical length	0.33 m	At focal plane:	
Focal length	3.81 m	Image diameter	50 μm
Aperture	0.14 m	0.1 marc-s =	0.18 nm

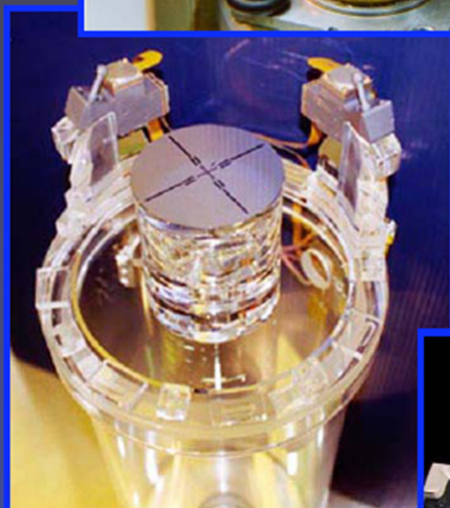
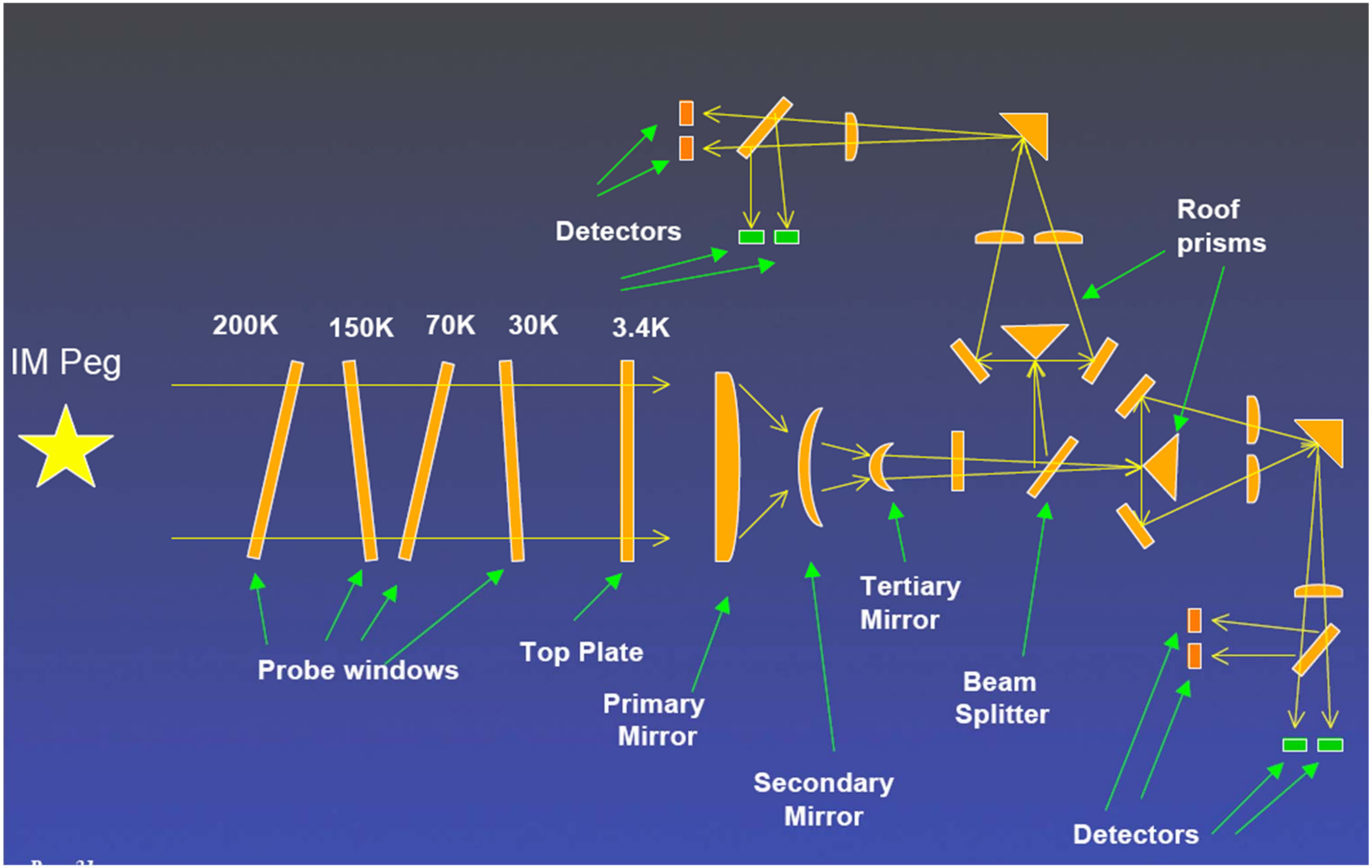


Image divider

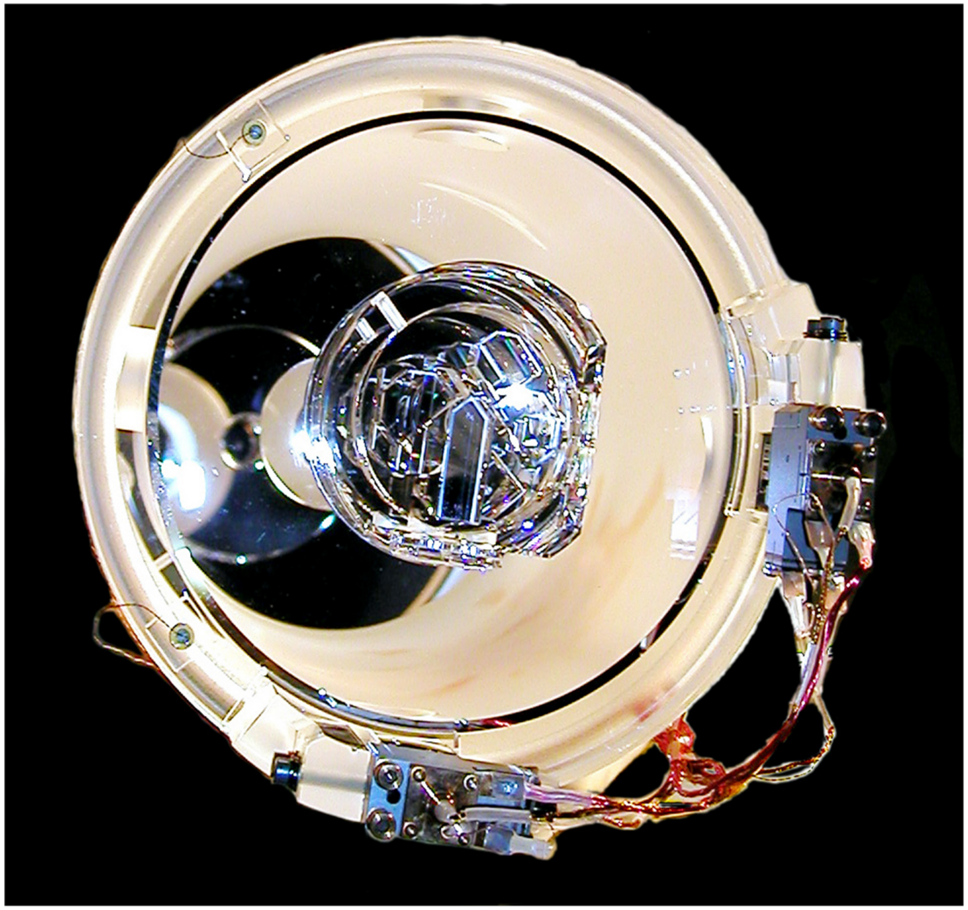
Integrated Telescope

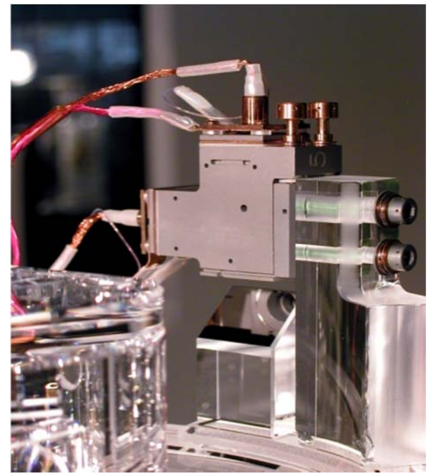
Telescope in Probe

Star-Tracking Telescope Optical Path

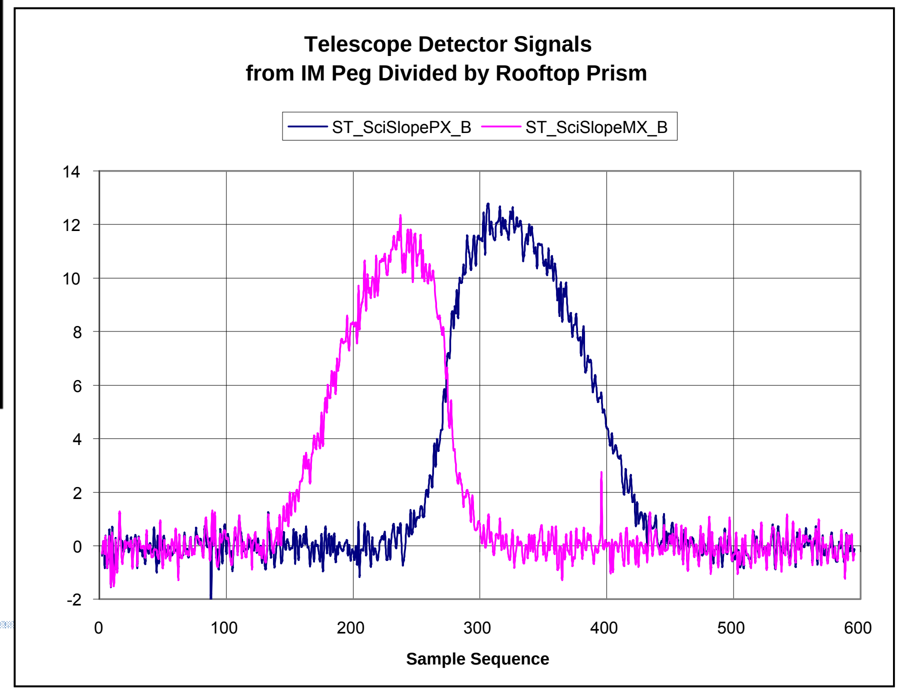


Telescope II

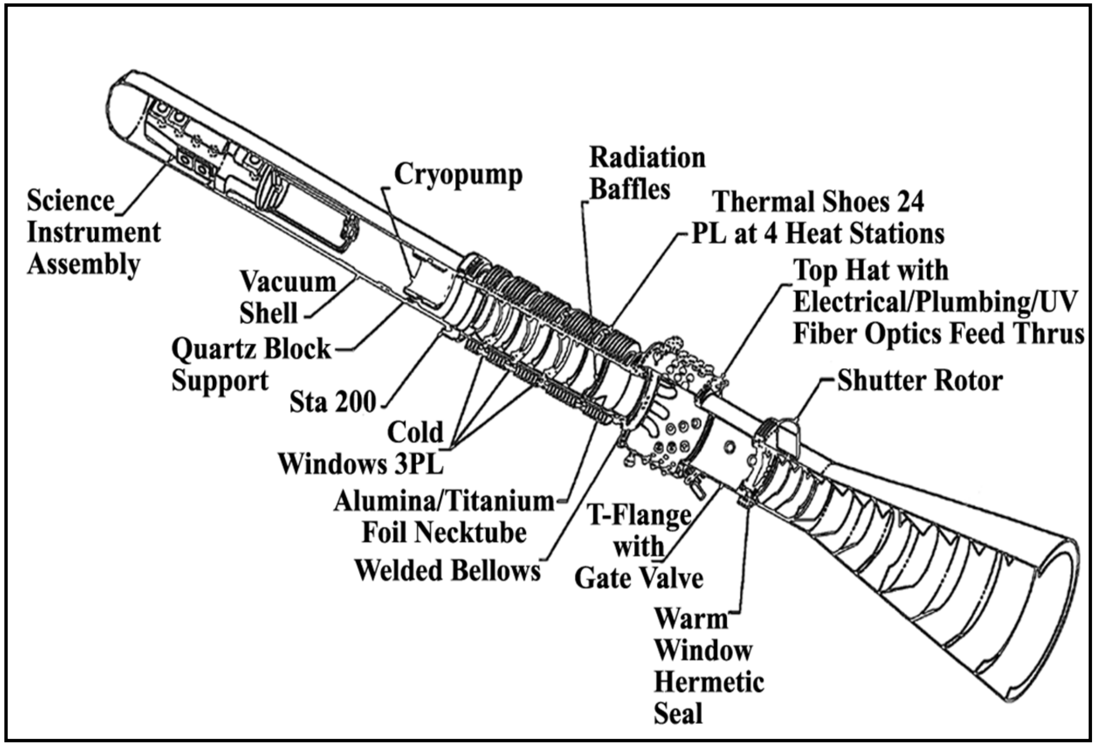




Detector Package

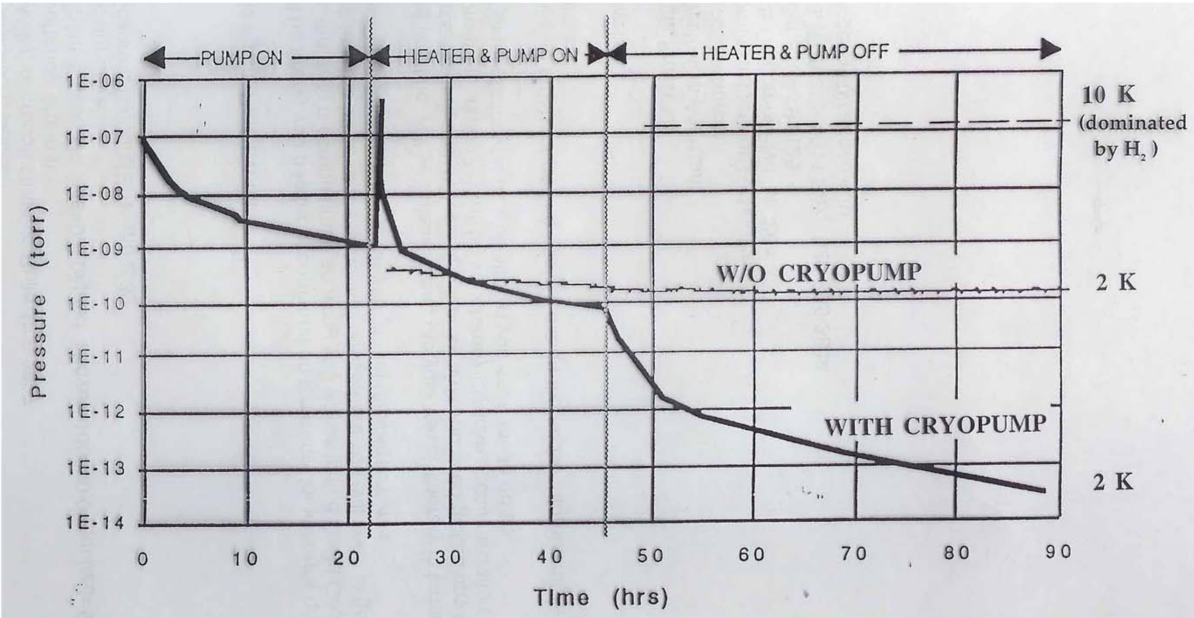


The GP-B Flight Probe



Ultra-low Pressure

Low Temperature Bakeout (ground demonstration)



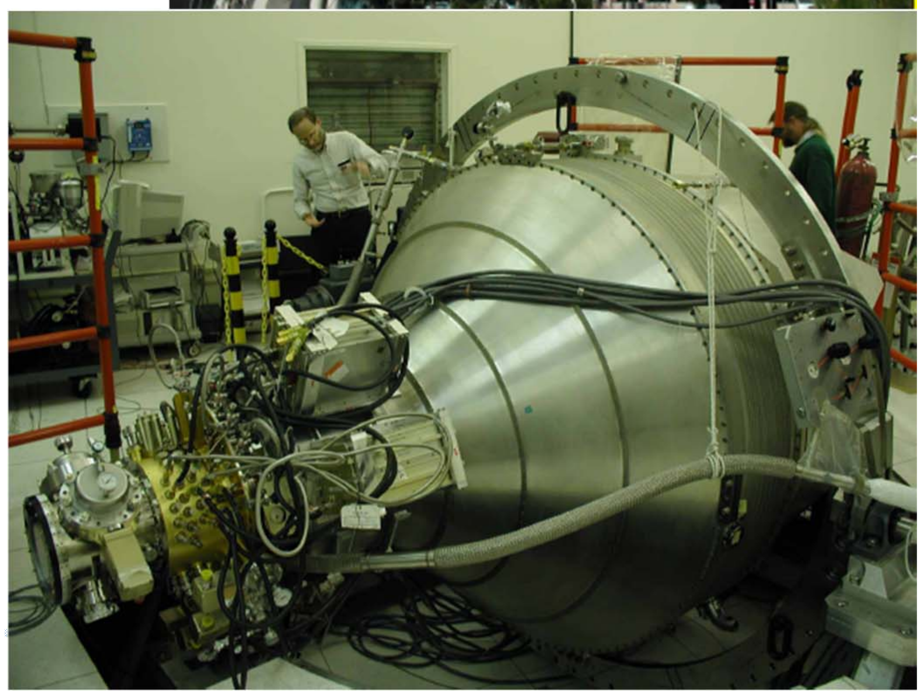
Gyro spindown periods on-orbit (years)

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

Sintered Titanium Cryopump

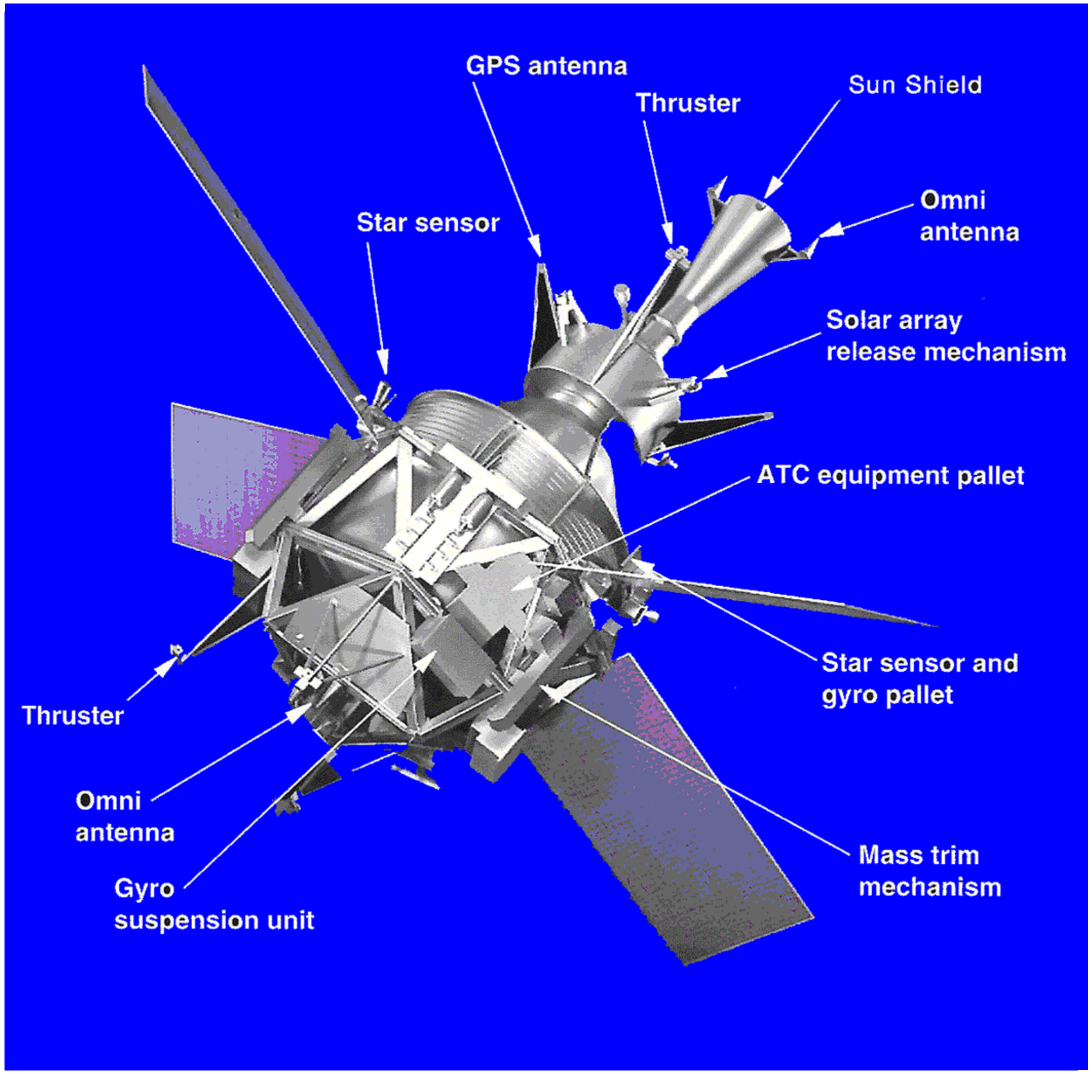
- Demonstrates pressure less than ~1.5 x 10^{-11} torr
- Additional evidence indicates pressure < 10^{-13} torr

The GP-B Cryogenic Payload



Payload in ground testing at Stanford, Aug. 2002

Spacecraft



- 16 Helium gas thrusters, 0-10 mN ea, for fine 6 DOF control.
- Mass trim to tune moments of inertia.
- Roll star sensors for fine pointing.
- Dual transponders for TDRSS and ground station communications.
- Modified GPS receiver for precise positioning and timing information.
- Laser ranging corner cube is a backup and cross-check for orbit determination.

Attitude and Translation Control: Acquiring Star

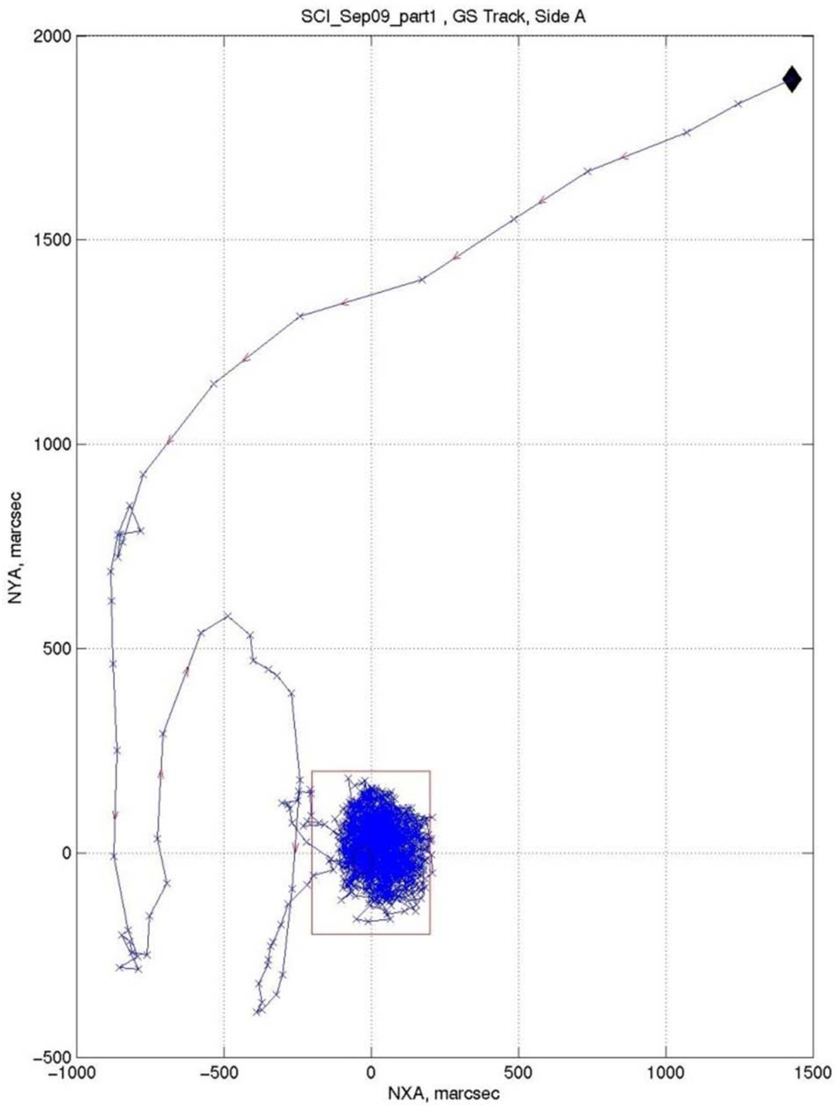
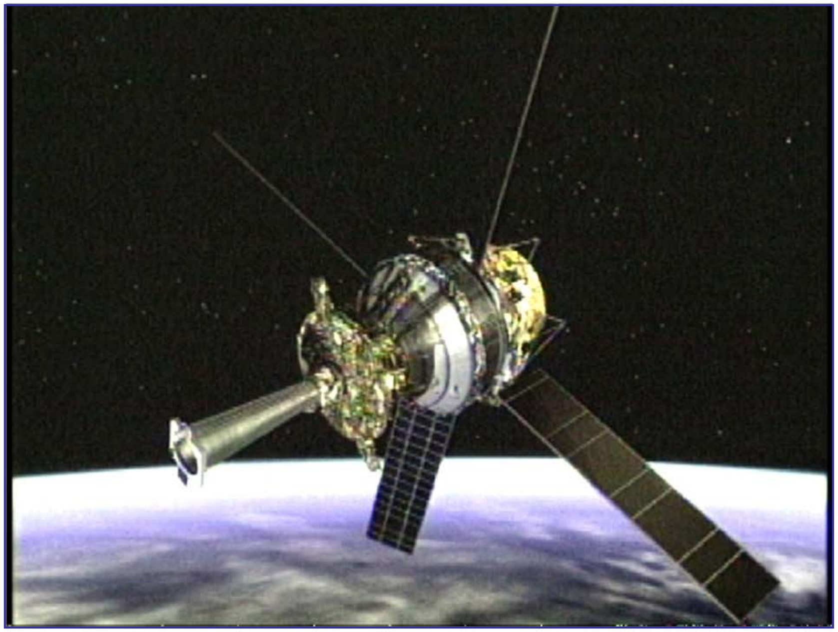


Fig. 705. SCI_Sep09_part1-L2 . GS Track (during GS Valid), Side A Start time: 148031616 sec. Total: 54.0 min

Acquisition time ~ 110 s

RMS pointing ~ 200 marcsec



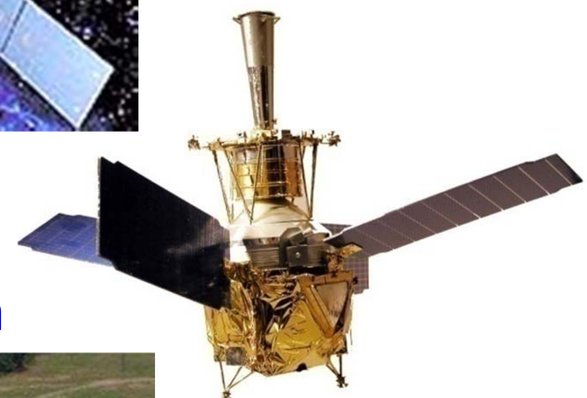
Communication, Commands, and Telemetry

- TDRSS Satellite
  - (Tracking and Data Relay Satellite System)
  - 10 contacts per day (depending on priority)
  - Contact time 20 -25 min
  - Transfer of data stored at 1 or 2 Kbits/sec

- Ground Station
  - 4 contacts/day
  - 10-12 minutes/pass
  - Transfer of data stored at 32 Kbits/sec

TDRSS Satellite

GP-B Satellite



Ground Station

Summary

- Low Acceleration Environment Offers Unprecedented Opportunity for Gravitational Experiments

- To Take Full Advantage of This Opportunity, a Number of Technologies have Been Developed and Successfully Tested In Space

- For Future Missions, Additional Attention Must Be Paid to Operational Plans

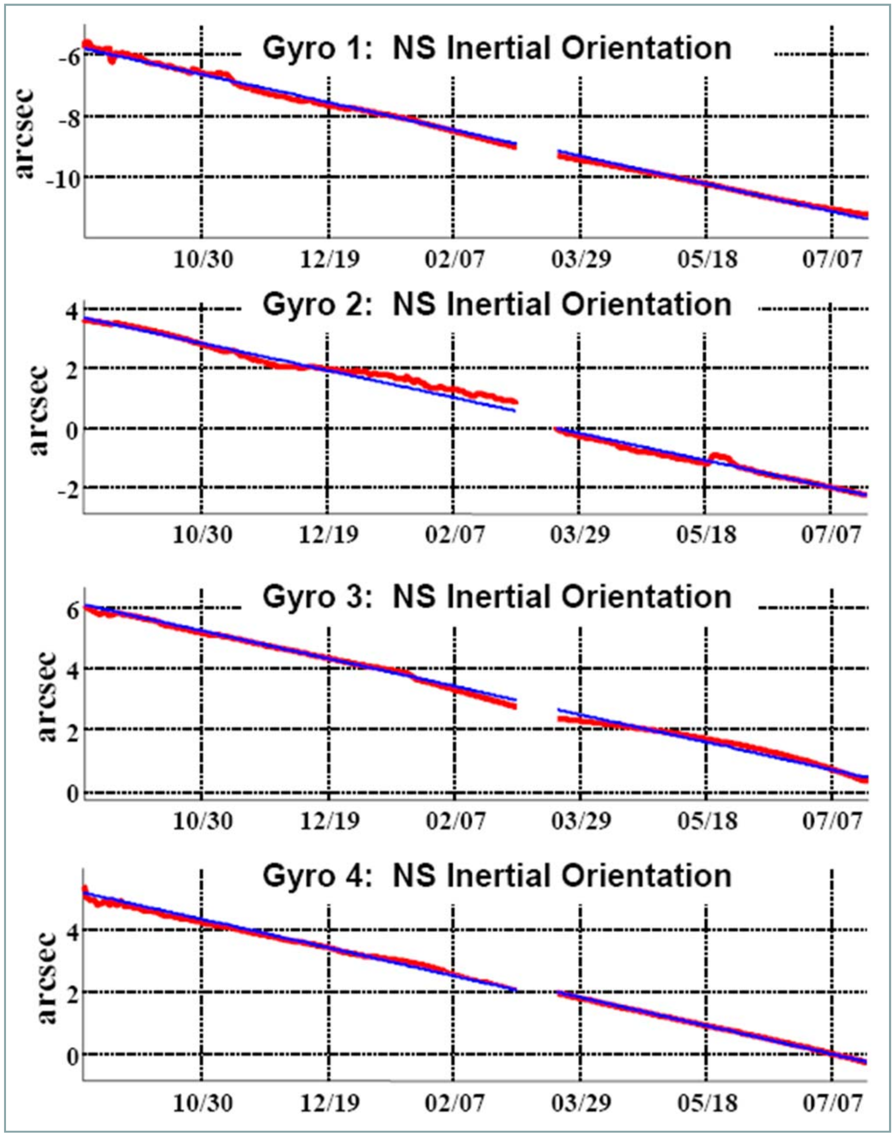
- Gravity Probe B Status:
  - Nov. 1961 ... The project began…
  - April 20, 2004 Launch
  - August 28, 2004 Completion of Initialization Phase, Start of Science Data Collection
  - August 15, 2005 Start of Calibration Phase
  - Sept. 29, 2005 Liquid Helium Depleted
  - April 20, 2007 Release of Data and Results
  - April, 2008 … Data and results still not available

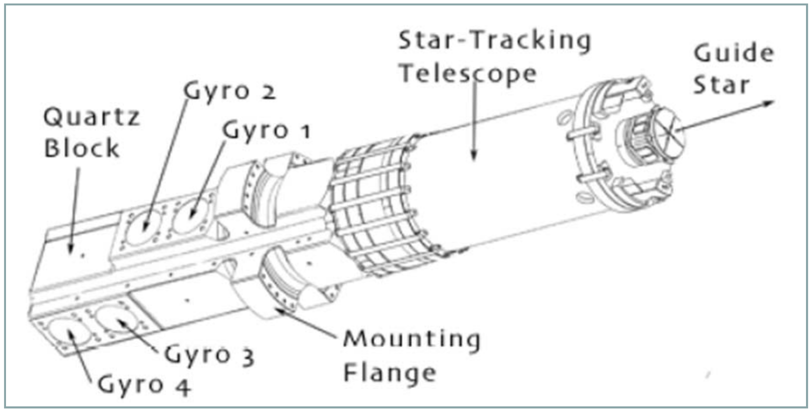
Gravity Probe B – Flight Hardware and Operations

- Stanford U, Lockheed-Martin, and NASA Marshall Space Flight Center

43 years, $870M, and 114 PhD later… [proposed in 1961 at a cost of $35M..]

Seeing General Relativity Directly



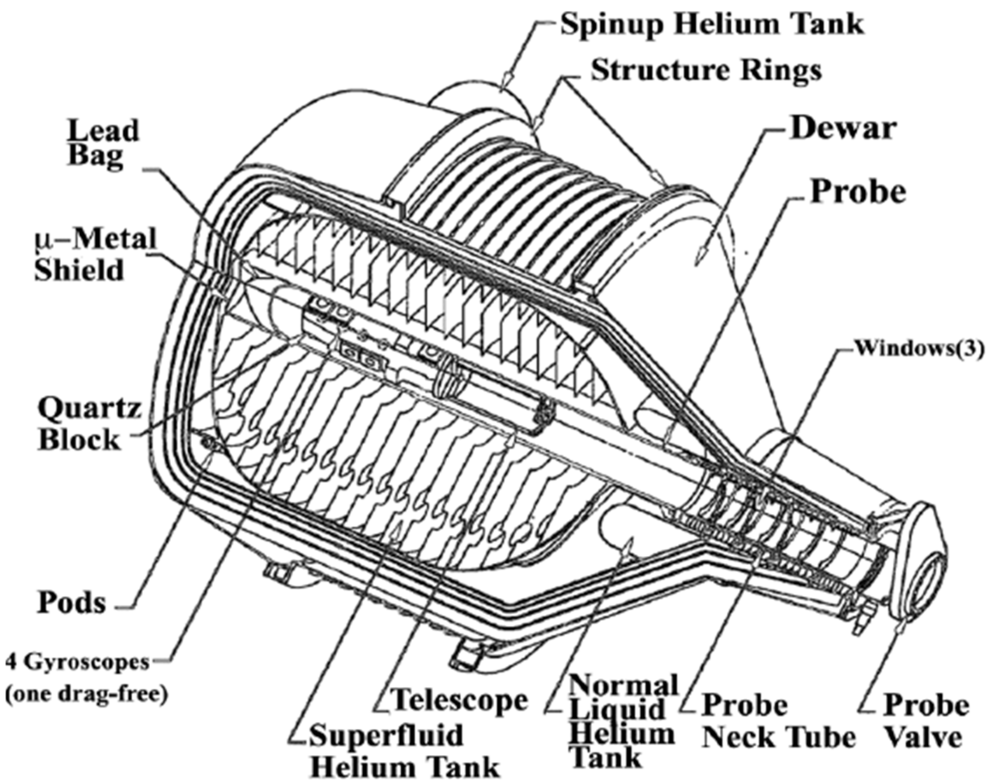


Red: Unprocessed flight data

Blue: After self-checking misalignment torque correction

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
- Modeling (if any): must be intrinsic, not ad hoc

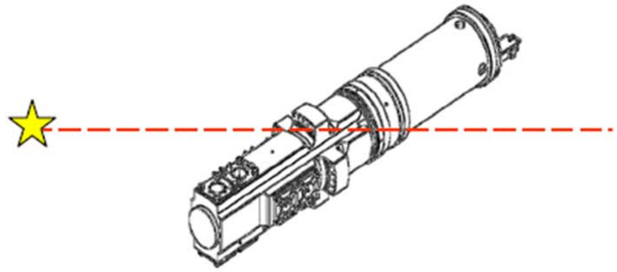


- Space:
  "Drag-free", separation of effects, elimination of "seeing“
- Cryogenics:
  Readout, mechanical stability, low magnetic field, UHV technology

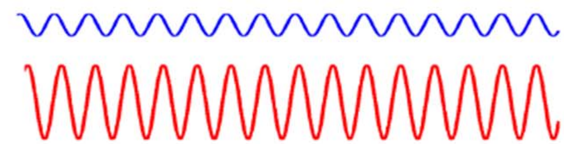
GRAVITY PROBE B

Dither & Aberration: Two Secrets of GP-B

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

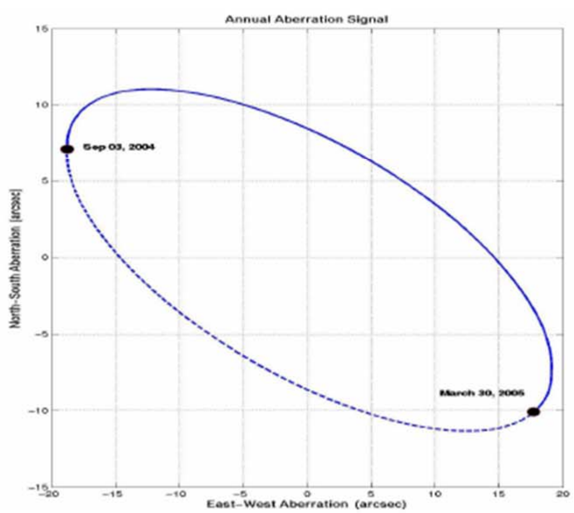


{ gyro output
telescope output



→ *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

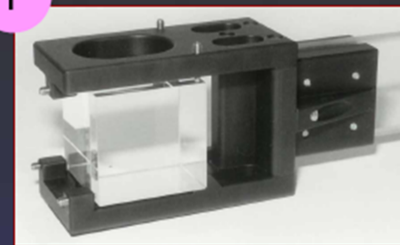
→ Continuous accurate calibration of GP-B experiment

Near Zeros & Their Technologies

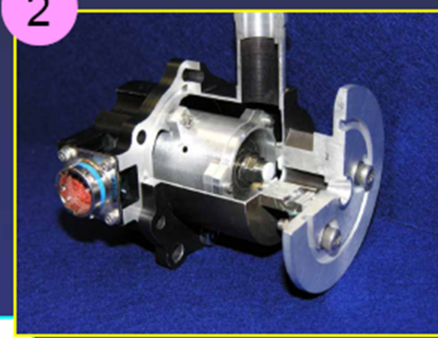
Seven Near Zeros

1) Rotor inhomogeneities	$< 10^{-6}$	met
2) "Drag-free" (cross track)	$< 10^{-11}$ g	met
3) Rotor asphericity	< 10 nm	met
4) Magnetic field	$< 10^{-6}$ gauss	met
5) Pressure	$< 10^{-12}$ torr	met
6) Electric charge	$< 10^{8}$ electrons	met
7) Electric dipole moment	0.1 V-m	issue

1

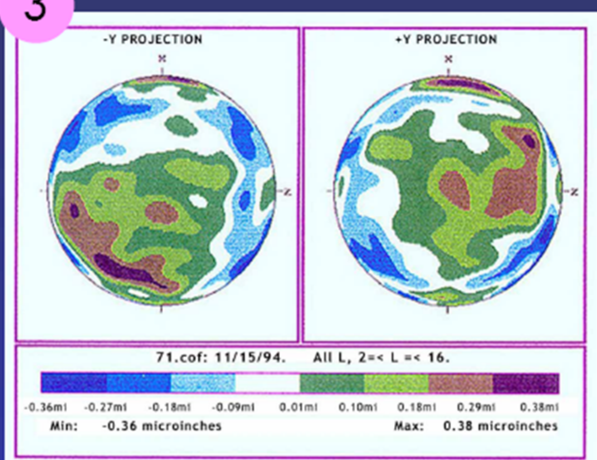


2



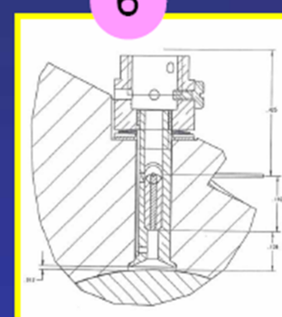
4

3

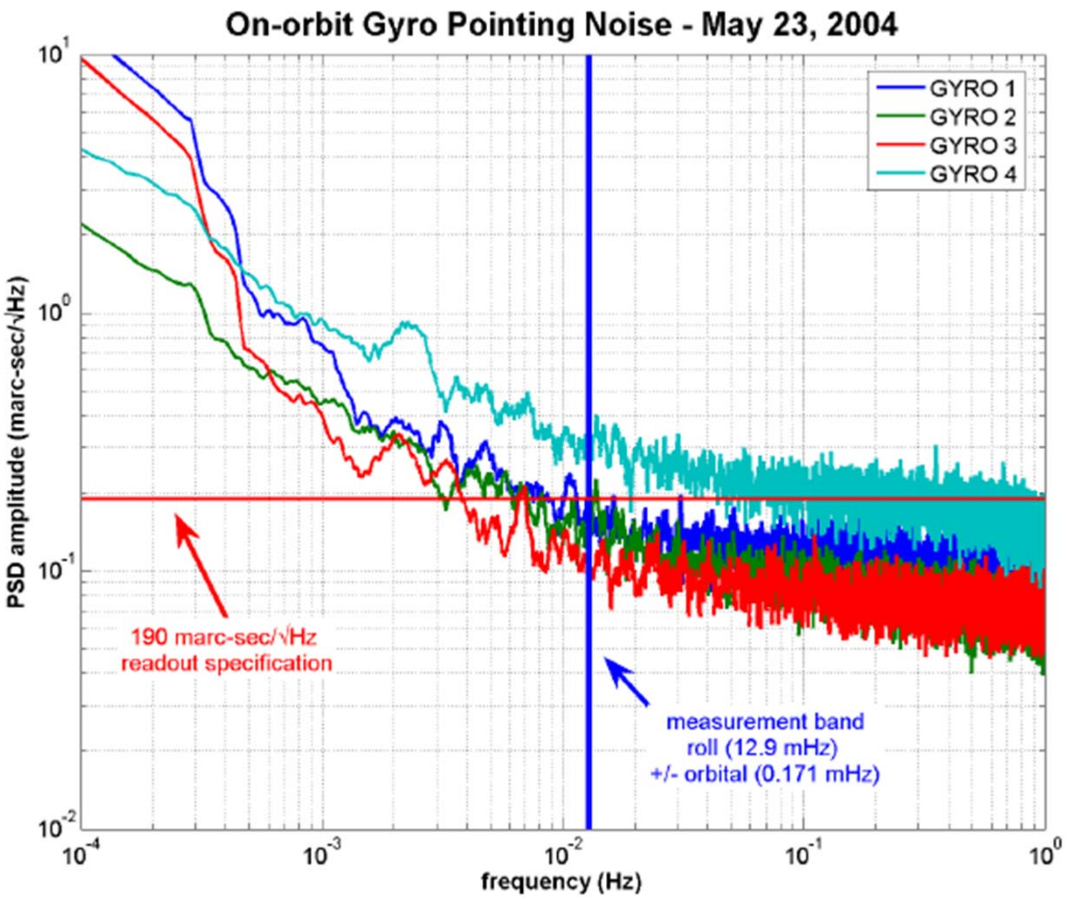


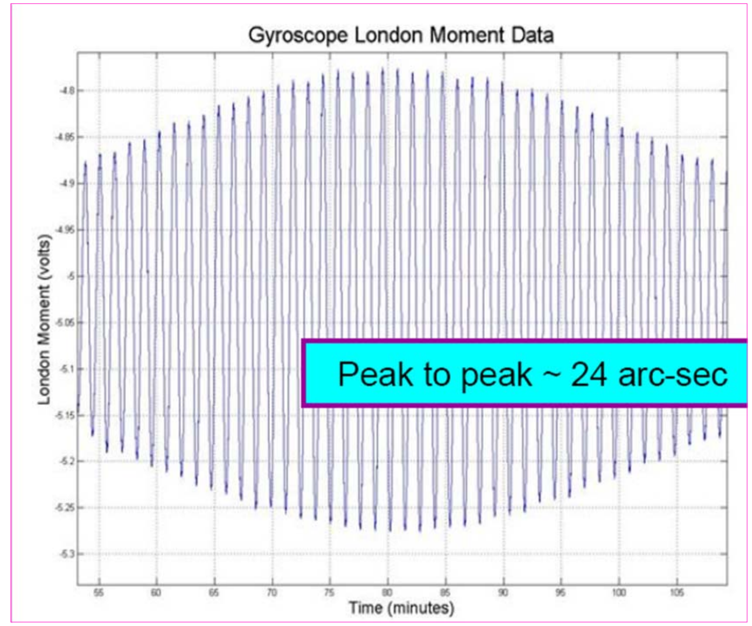
5

6



Gyro Readout Performance On-Orbit

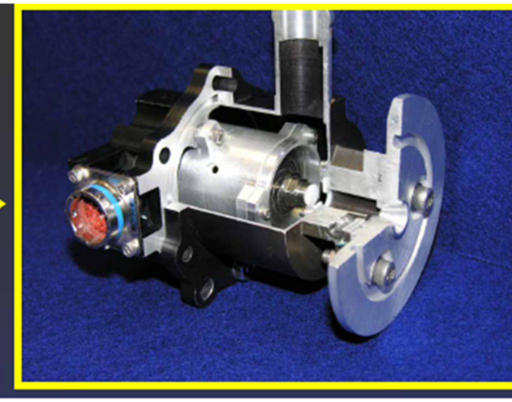


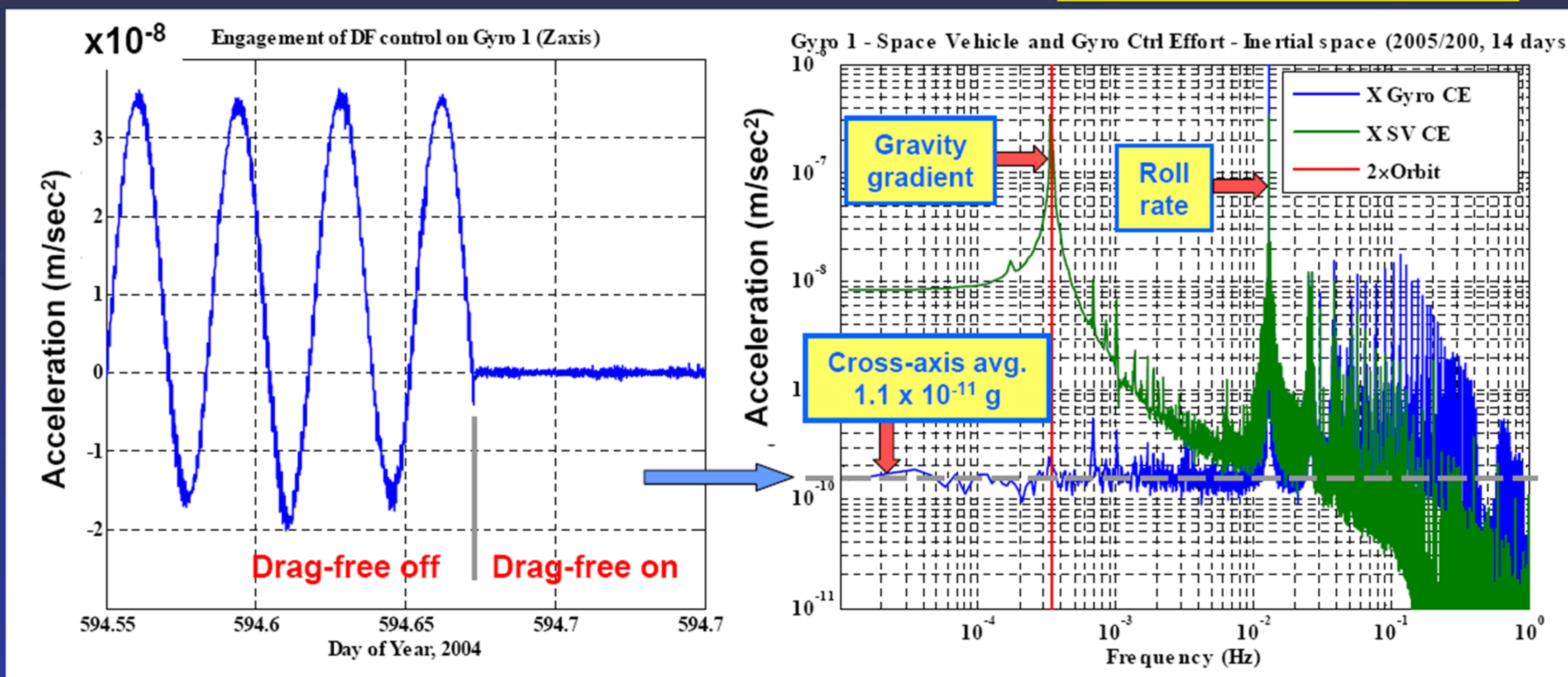


Gyro	Experiment Duration (days)	SQUID Readout Limit (marc-s/yr)
1	353	0.198
2	353	0.176
3	353	0.144
4	340	0.348

Drag-Free: 2ndNear Zero

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





In-flight Verification, 3 Phases Observation

A. Initial Orbit Checkout - 128 days

- re-verification of all ground calibrations [scale factors, tempco's etc.]
- disturbance measurements on gyros at low spin speed

B. Science Phase - 353 days

- exploiting the built-in checks [Nature's helpful variations]

C. Post-experiment tests - 46 days

- refined calibrations through deliberate enhancement of disturbances, etc. [...learning the lesson from Cavendish]

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

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

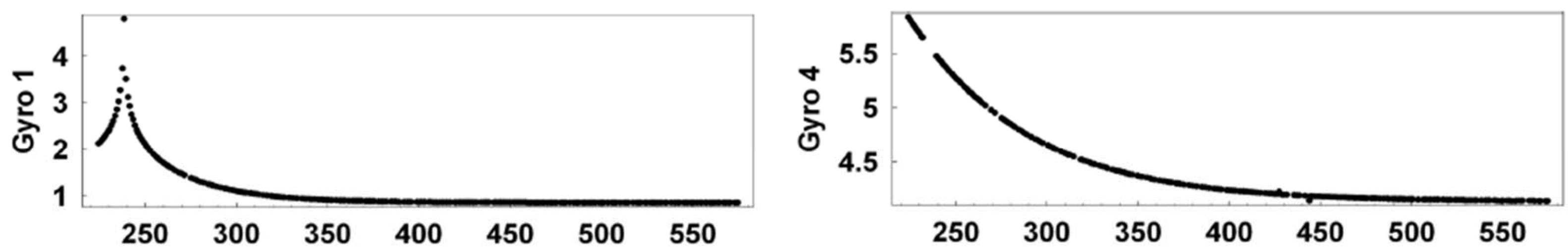
Discovery 1 (Phase A, B) – Polhode-rate variations ⇒ affect C_g determinations

Discovery 2 (Phase B, C) – Larger-than-expected misalignment torques

Discovery 1: Polhoding& Cg

- **Issue:** *C_g better than 10^{-4} ⟹ linking data from 6 or more orbits*
- **The actual 'London moment' readout:**
  - M_L + dipole component of trapped flux along spin axis M_T ~ 1% M_L
  - Total trapped flux fixed in rotor but M_T modulated by polhoding
  - Orbit-to-orbit fit ⟹ complicated by varying polhode rate

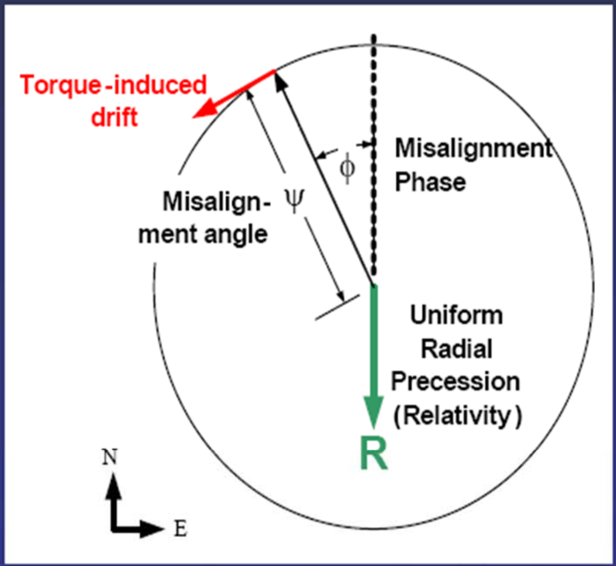
Polhode Period (hours) vs Elapsed Time (days) since January 1, 2004



- **Current:** Fit 4 to 6 polhode harmonics to get mean M_T
- **Refinement:** Utilize Trapped Flux Mapping data

Discovery 2: Misalignment Torques

- Torque & misalignment angle ϕ, ψ ⟹ 0.1 to 1.0 arc-s/yr drift rates
- Probable cause – Electrostatic 'patch effect' on rotor *and* housing
- Relativity
  - Fixed direction in inertial frame
- Misalignment Torque/Drift
  - Torque $\propto$ to ψ
  - Drift $\perp$ misalignment vector

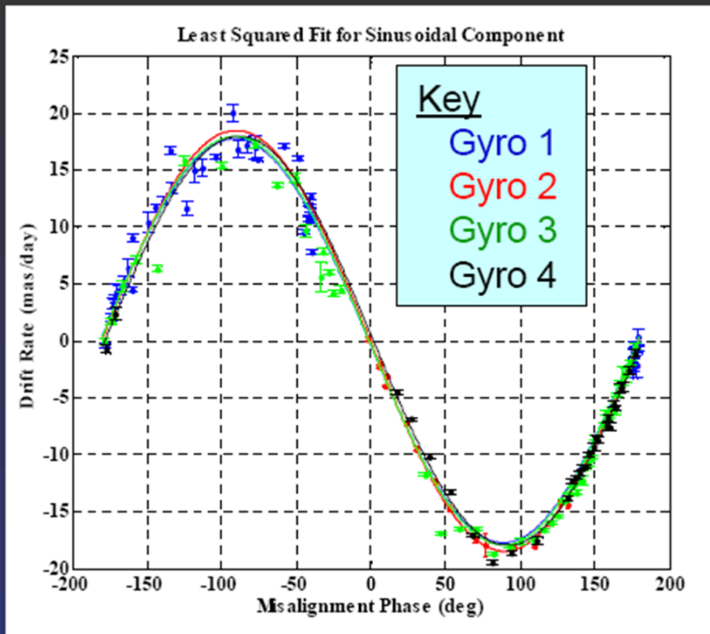


- M. Keiser observation
  - Component of R $\parallel$ ϕ free of misalignment torques
  - ϕ modulated over year by annual aberration

Eliminating Misalignment Drift

- Two Complementary Approaches, 'Geometric' & 'Algebraic'
- 'Geometric', rate-based
  - (i) Torque-free component of R determined from e.g. 5-day batch-averaging
  - (ii) BONUS: torque-coefficient k found in separate measure of component $\perp$ to (i)
- 'Algebraic', orientation-based
  - (i) Also utilizes geometrical relationships, BUT with
  - (ii) Explicit torque models & continuous estimation & filtering
- Complementarity
  - e.g., separate k-profile determinations from the two methods can be cross-checked against each other

Geometric Method Results



- Original Mission Concept
  - $\delta\Omega = Lt^{-3/2}$, t ~ mission length
- Simple Geometric Approach
  - $\delta\Omega_G = \sqrt{2}\, LT^{-1}t^{-1/2}$, T - batch length

SQUID Readout Limit (marc-s/yr)

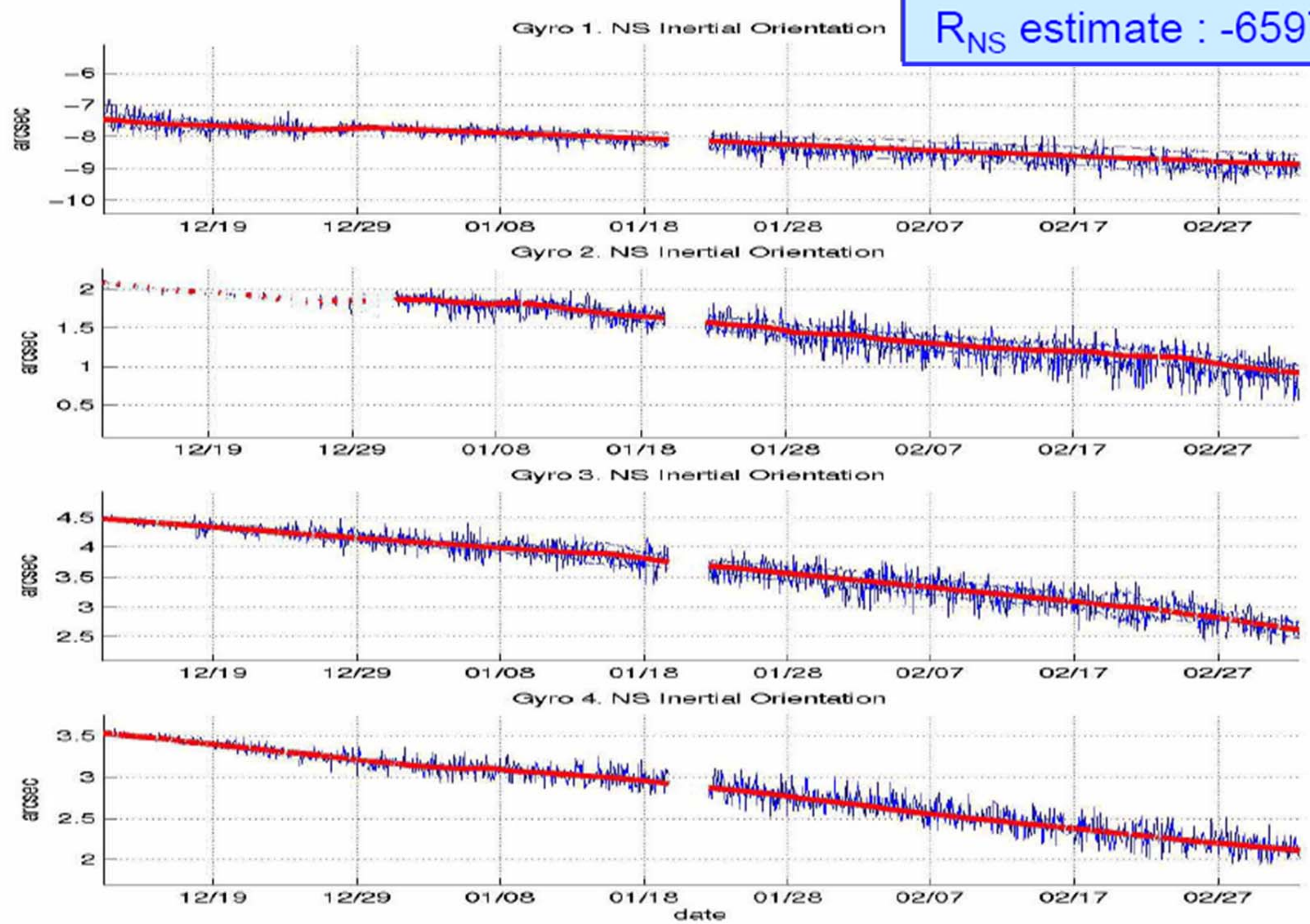
	Gyro 1	Gyro 2	Gyro 3	Gyro 4
Original	0.198	0.176	0.144	0.348
Simple Geometric (5-day batch)	19.8	17.6	14.4	33.5

- Power of Geometric Approach
  - Clear proof of relativity separation
  - Diagnostic tool for other potential disturbances
- Requirement for Final GP-B Result
  - Recover $t^{-3/2}$ dependence by Algebraic or Enhanced Geometric Method

Algebraic Method Example

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

R_{NS} estimate : -6597 ± 20 marc-s/yr



2nd floor analysis from December 2006

Initial Geodetic Effect Results

	'Geometric'	'Algebraic'			
		glimpse 1	glimpse 2	glimpse 3	glimpse 4
	Full Year	158 days	85 days	82 days	41 days
1σ statistical error only	-6638 ± 11	-6584 ± 52	-6597 ± 20	-6595 ± 10	-6604 ± 7

Separate gyro, ~ 5-day batches

Combined gyro processing, continuous filtering

Progress in modeling with algebraic approach evident

SQUID noise limit

Net expected

-6571 ± 1 *

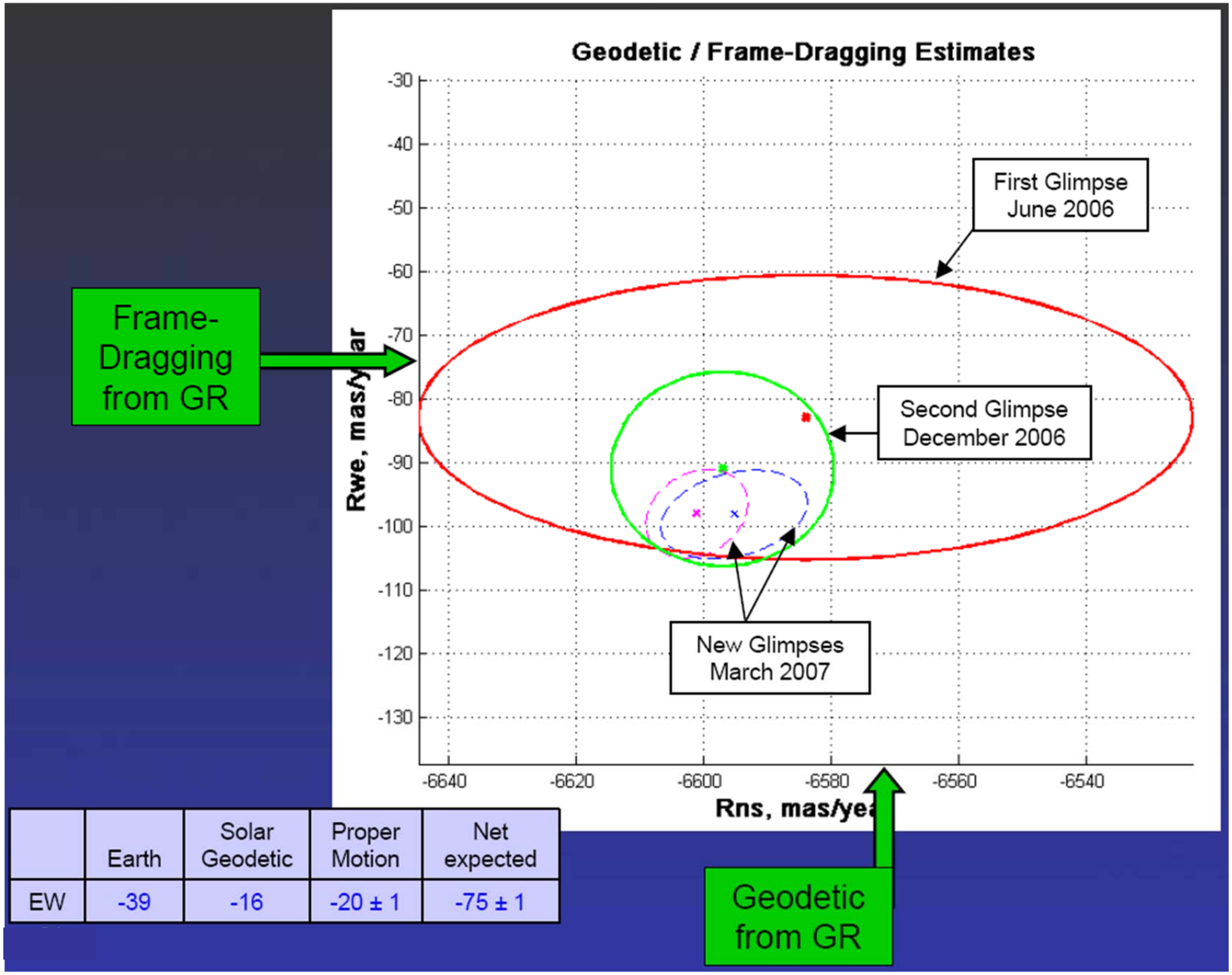
[marc-s/yr]

-6638 ± 97

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

* Earth -6606, solar geodetic +7, proper motion +28 ± 1 ⇒ net expected -6571 ± 1

Glimpses of Frame-Dragging



	Earth	Solar Geodetic	Proper Motion	Net expected
EW	-39	-16	-20 ± 1	-75 ± 1

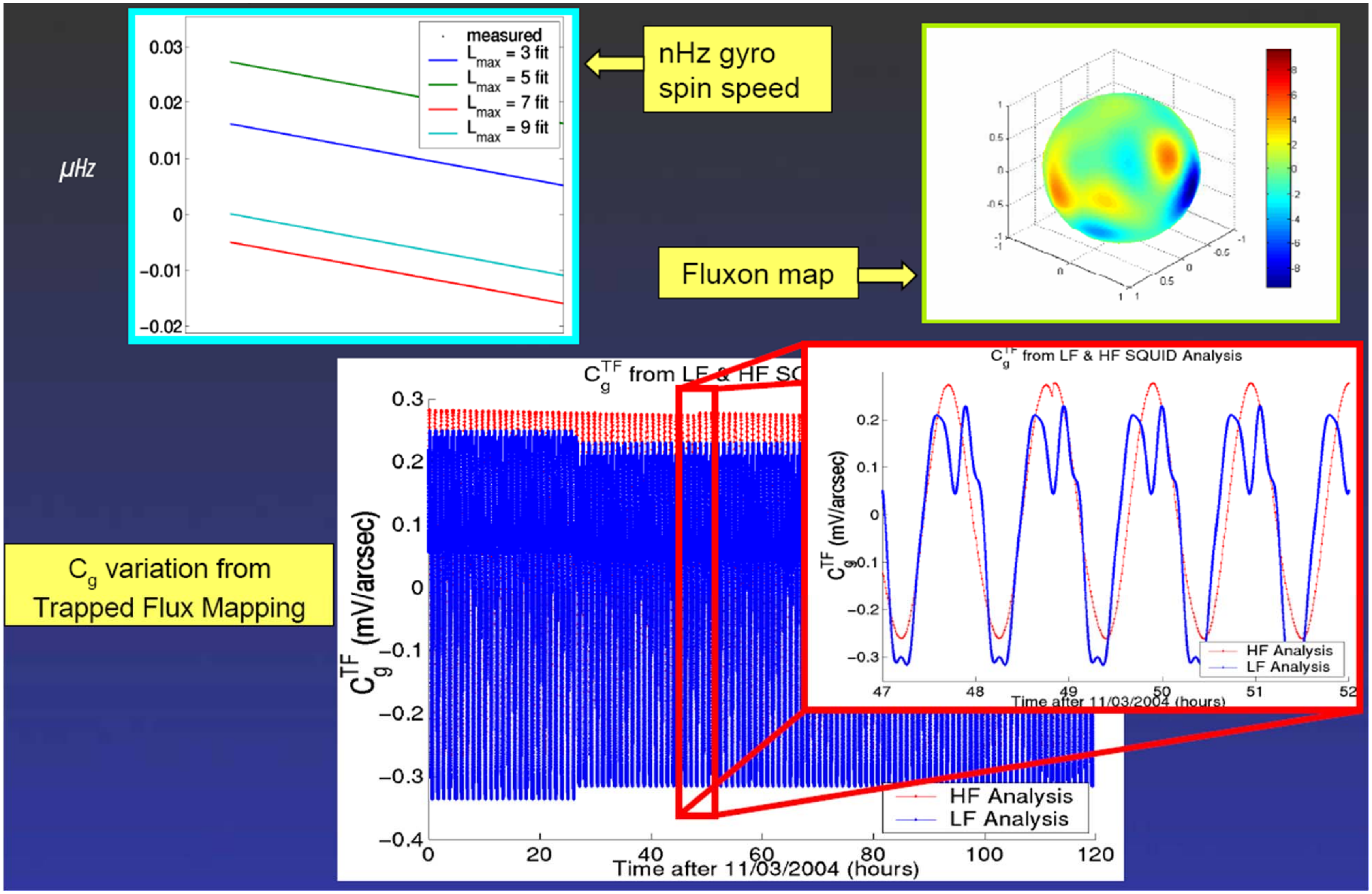
Assessment of 4 Frame-Dragging Glimpses

- Modeling of scale factor & torques improved substantially since June 2006
- Filtering technique more robust; can estimate many more parameters
- CAVEATS
  - Excessive sensitivity to modeling of torque coefficients ⇒ occasional worrying outliers
  - Inconsistencies between 4 gyros are real ⇒ long-term modeling with detailed torque coefficient history in work
  - Combined gyro processing eliminates some error sources ⇒ may miss others
- Requires cross-checking with geometric method essential to understand physical processes

The Story So Far

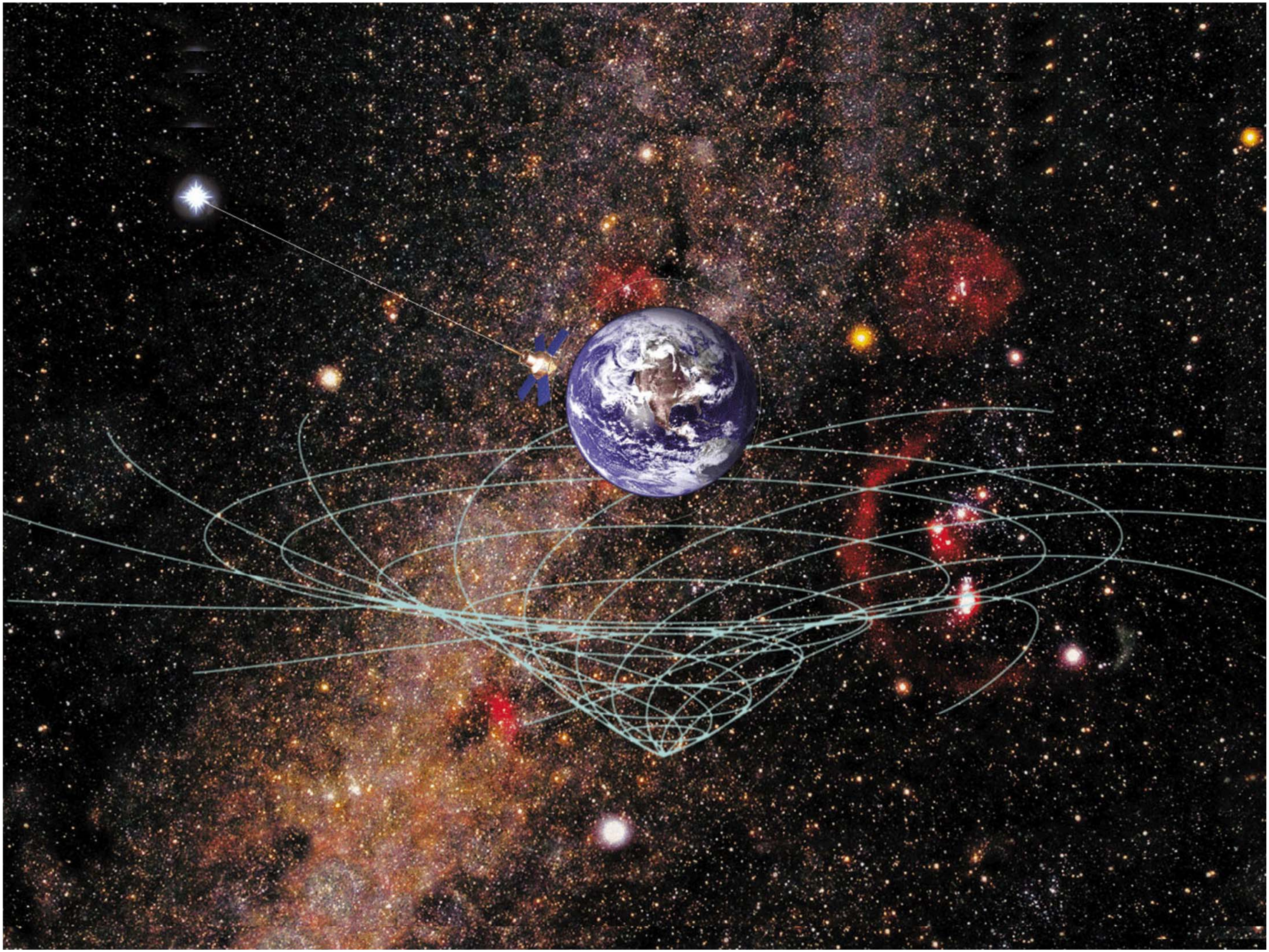
- Geodetic effect clearly seen in unprocessed science data
- Gyro orientation data have reached SQUID readout limit in each gyro
- Results of In-Flight Verification/Calibration process
  - Most pre-launch estimates confirmed, eliminating many potential error sources
  - Discovery 1: polhode damping & its effect on Cg [this needs to be completely separated in final analysis]
  - Discovery 2: 'patch effect' misalignment torques
- Complementary 'geometric' & 'algebraic' approaches to misalignment torques
  - Encouraging agreement between torque-coefficient determination
- 'Glimpses' of Frame-Dragging effect
  - Probably authentic but strong caveat needed due to outliers which reveal model sensitivity

Cg & Trapped Flux Mapping



The Way Forward

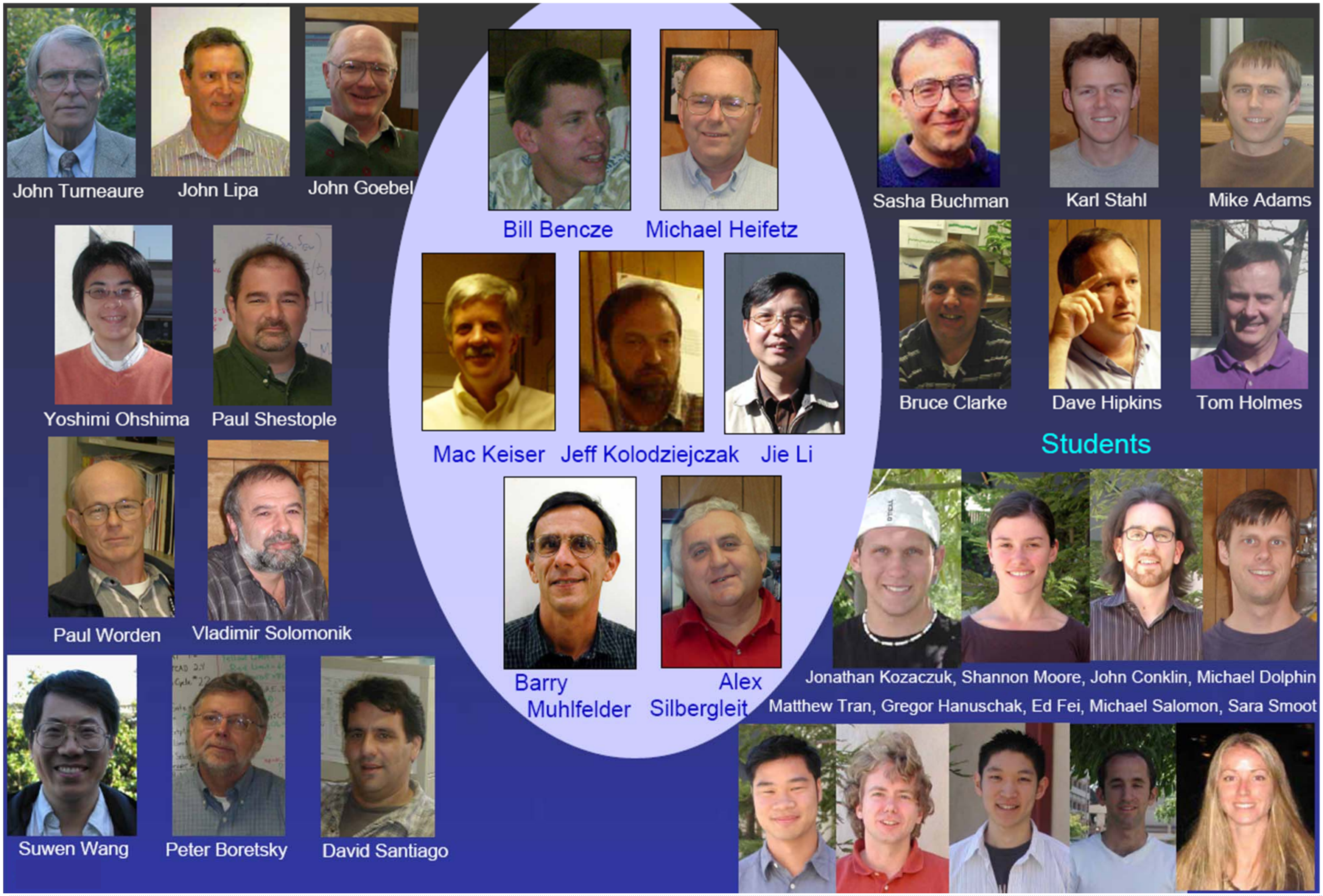
1. Many issues completely solved, meet full accuracy
2. Elimination of Cg Scale Factor Issue by Trapped Flux Mapping Data
3. Completing of Misalignment Torque Modeling & Exploration of Other Potential Torque effects
4. Limit & Goal of Final Analysis through December 2007
   - SQUID readout limit 0.144 to 0.343 marc-s/yr depending on gyro
   - segmented data raises these limits to ~ 0.5 to 1 marc-s/yr (Duhamel effect)
5. Final 'Double Blind' Comparison with HR8703 Proper Motion Data



Testing General Relativity

- GM/c^2R & the annoying successfulness of Newton
  - Sun ~ 2 x 10^{-6}; Earth ~ 7 x 10^{-10}; 1 m diameter tungsten sphere ~ 10^{-21}
- Einstein's 2½ tests–Perihelion of Mercury, light deflection, redshift(½ test)
- Kinds of test enabled by new technologies since 1960
  - Clocks, electromagnetic waves, massive bodies
  - Observations vs controlled physics experiments
- New non-null tests
  - Shapiro time delay
  - Binary pulsar, especially gravitational wave damping
  - Geodetic (de Sitter) effect in Earth-Moon motion about Sun
- The Eddington PPN formalism & new null tests
  - Lunar ranging, Nordtvedt effect restricts scalar-tensor theories
  - Earth tides, Will effect eliminates Whitehead's preferred frame theory
- On to gravitational wave astronomy [50 years since J. Weber detector]

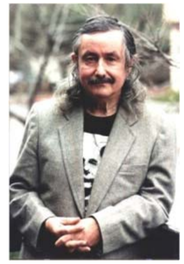
The GP-B Data Analysis Team




NASA
STANFORD
UNIVERSITY
LOCKHEED MARTIN

GRAVITY PROBE B

Stanford Investigators



Francis Everitt
Principal Investigator (PI)

Brad Parkinson
Co-PI

Dan Debra
Co-PI

John Turneaure
Co-PI

Sasha Buchman
Co-Investigator

Mac Keiser
Co-Investigator

Jim Lockhart
Co-Investigator

Barry Muhlfelder
Co-Investigator

Mike Taber
Co-Investigator

Stanford Program Managers

Brad Parkinson
1984 - 1998

John Turneaure
1998-1999

Sasha Buchman
2000-2001

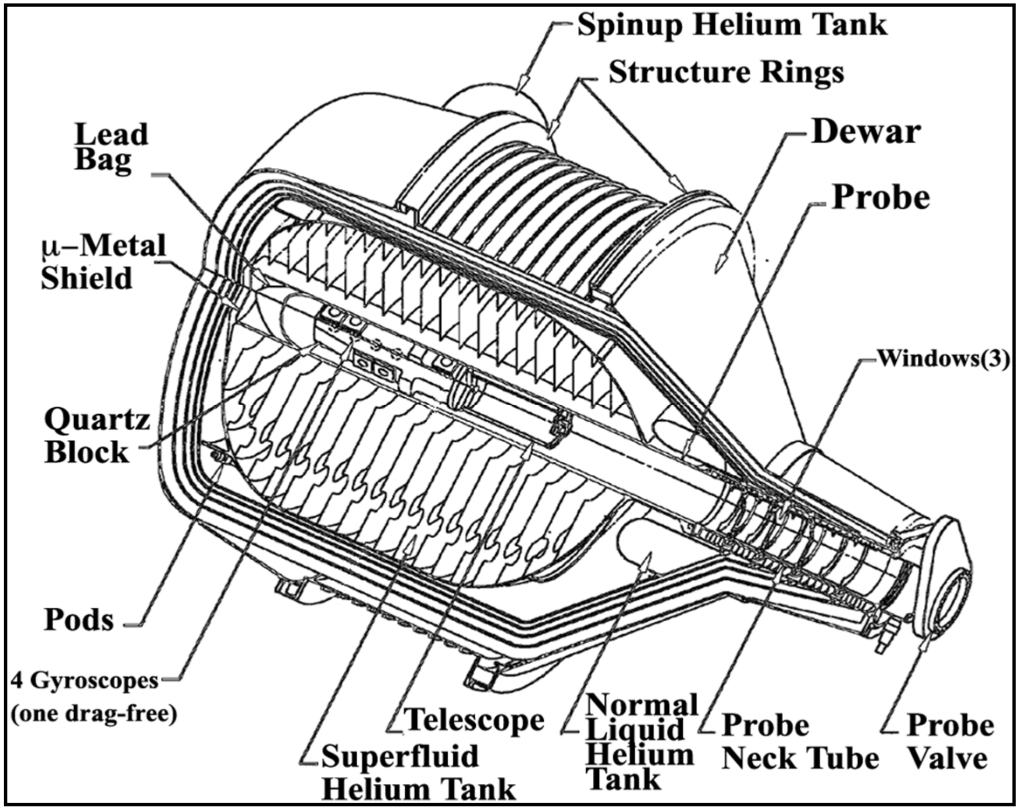
Ron Singley
2002

Gaylord Green
2003

Spacecraft Operations

- Initialization Phase
  - Gyroscope Levitation
  - Guide Star Acquisition
  - Preliminary Calibrations
  - Adjustment of Attitude and Translation Control
  - Gyroscope Spin Up
- Science Data Collection Phase
  - Science Data Collection with Gyroscopes At Full Spin Speed
- Calibration Phase
  - Deliberate Enhancement of Potential Systematic Errors

The GP-B Cryogenic Payload



Payload in ground testing at Stanford, August 2002

Predicted Lifetime: 16 months

Actual Lifetime: 17.3 months

Electrostatic Suspension System Functional Design

Functional Design

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**

Specific force: $10^{-7} m/s^2$, $10^{-5} m/s^2$, 10^{-2}

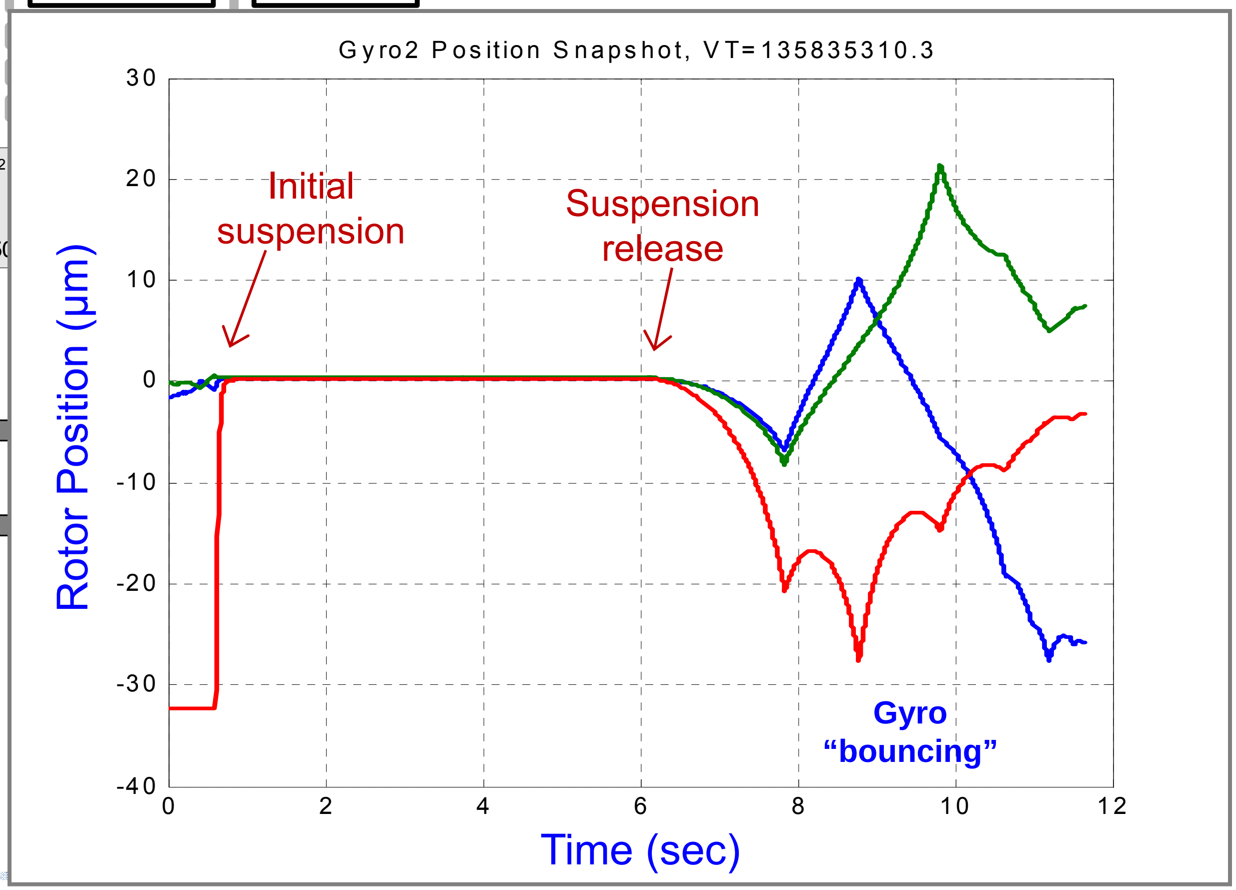
← *Low voltage drive*

Req'd voltage: 0.2V, 2V, 50

Primary Disturbances

Grav. gradient
ES torques
Rotor charge
Meteoriotes
Spin-up gas
Soft computer failures
1g field

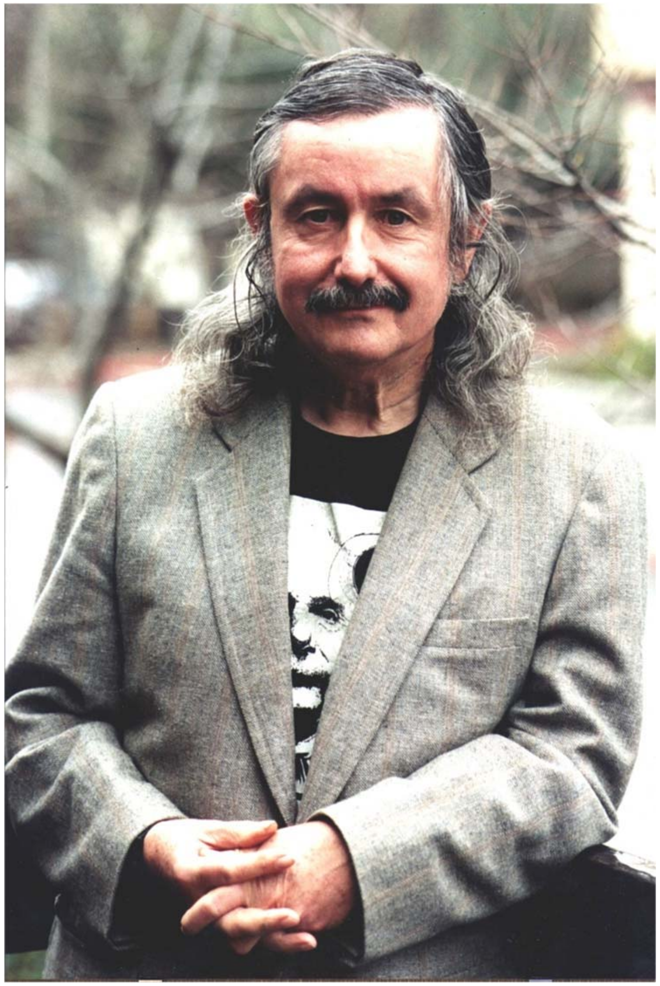
Initial Gyro Levitation and De-levitation using analog backup system



Francis Everitt: Principal Investigator

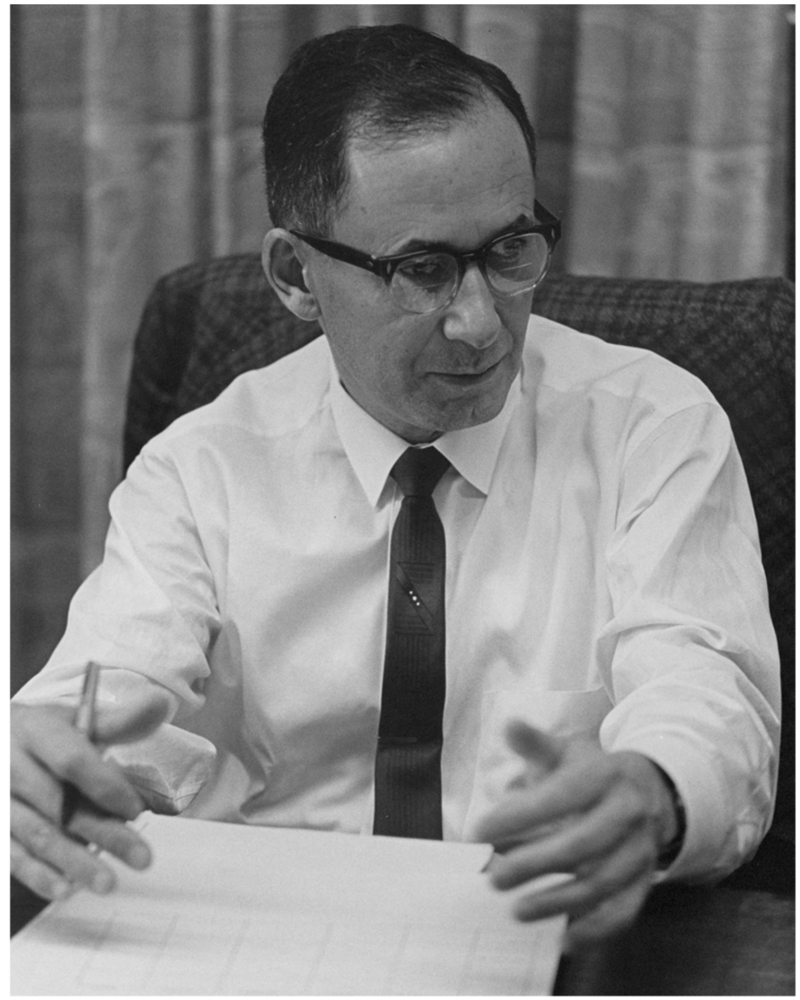
- Started on GP-B in 1962
- Ph.D from University of London (Imperial College) under P.M.S Blakett
- UPenn - Experimental discovery of LHe “Third Sound”
- Leading influence to GP-B experiment

P.M.S. Blackett
1948 Nobel Prize



Leonard Schiff: Co-Founder of GP-B

- Started college at 14
- Ph.D MIT at 22
- Worked at UC Berkeley under Robert Oppenheimer
- Acting Head, U Penn Physics Dept at 27
- At 1st Atomic Bomb test at 30
- Head, Stanford Physics Dept at 33
- Published “Quantum Mechanics” at 34



William Fairbank: Co-Founder of GP-B

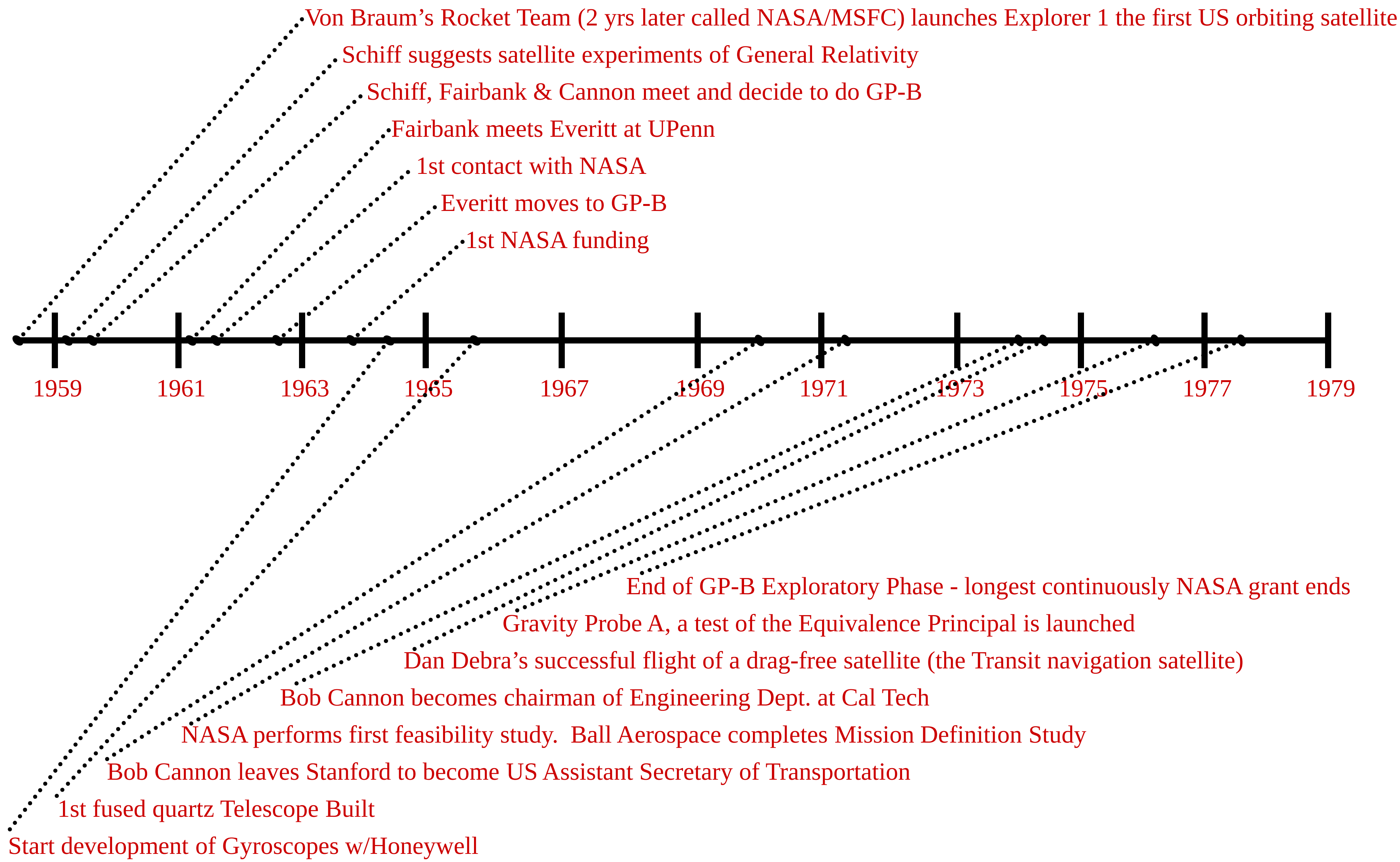
- Whitman College, Chemistry
- Radiation Lab, MIT
- Ph.D Yale - 1st university doing work in Low Temp Physics
- Yale - Experimental discovery of LHe "Second Sound"
- Professor, Amherst & Duke
- Moved to Stanford in 1959
- Stanford - Renowned for his work in Low Temp Physics
- Quarks & Gravity Waves

Robert Cannon: Co-Founder of GP-B

- Doctorate MIT
- Moved to Stanford in 1959
- Established Stanford's Guidance and Control Laboratory
- U.S. Assistant Secretary of Transportation
- Chairman, Div. of Engineering, Cal Tech
- Chairman, Dept. of Aeronautics and Astronautics, Stanford University

GRAVITY PROBE B

Timeline (1959-79)



Timeline (1979-99)

Bob Cannon returns to Stanford as Chairman of Aero & Astro Dept.

NASA conducts major review of technology readiness.

NASA launches first Shuttle

NASA/MSFC studies determine the spacecraft would be too large (5300 lbs, 576W) and too $$

IRAS flight proves out feasibility of spaceflight dewar

Stanford restructures program, cuts weight in half, power by 2/3 (146W), and cost to $130M
launch planned for 1989 and science mission for 1991 (both on Shuttle)

Shuttle Flight phase endorsed by NASA, LM chosen as major subcontractor

1979 1981 1983 1985 1987 1989 1991 1993 1995 1997 1999

B Parkinson & T Langenstein
join as Project Manager team

Gyroscopes, Quartz Block, & Telescope complete

Probe Delivered to Stanford

Dewar goes cold & Stanford establishes magnetic shield in Dewar.

Science Dewar delivered to Stanford

NASA cancels Shuttle Test Unit and directs Stanford to go directly to flight

Dewar Starts Fabrication

First Flight Hardware in SM starts to be built

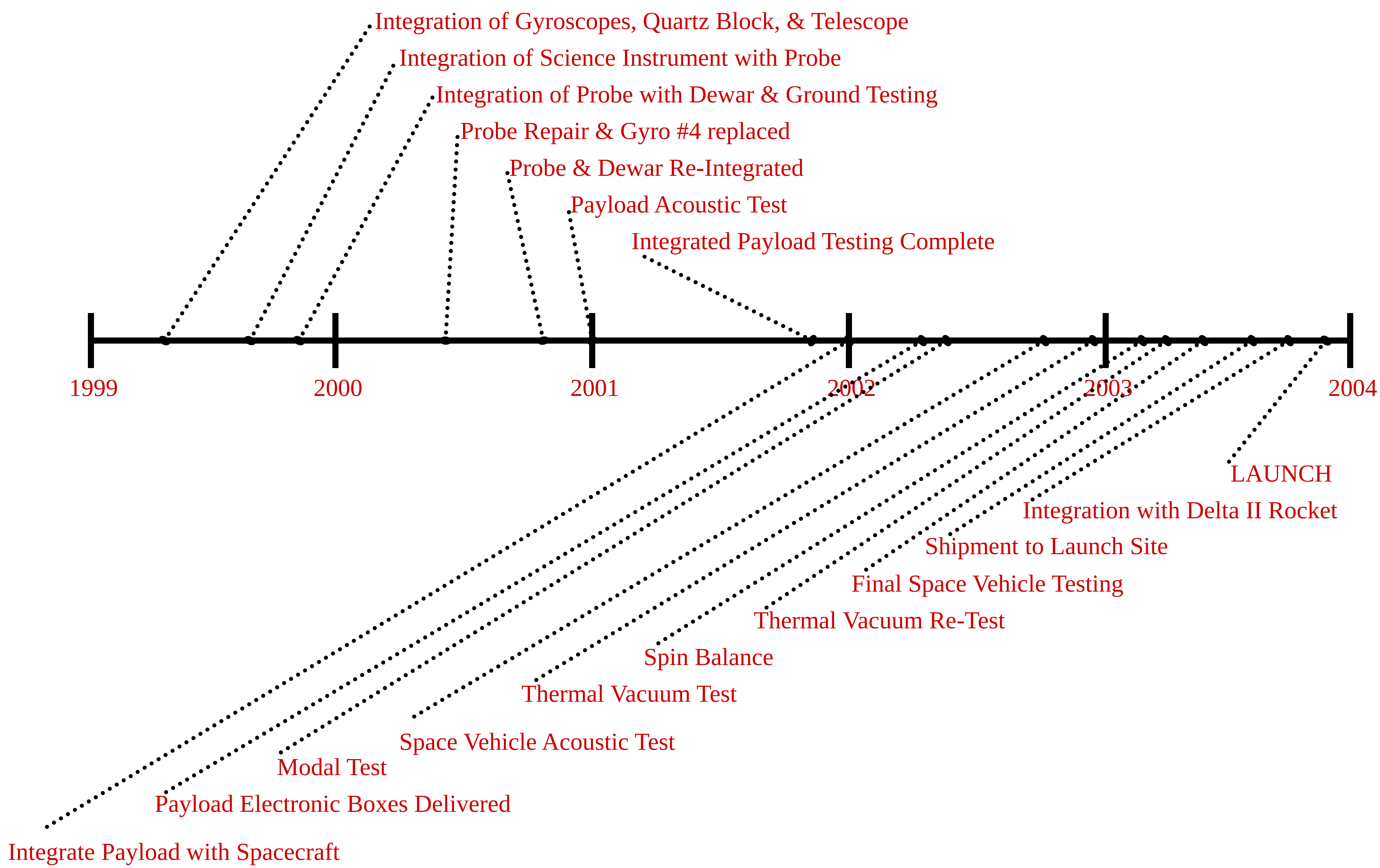
Stanford's 1st prolonged levitation of a quartz sphere.

Challenger Accident

Gyroscopes rotors focus on solid quartz

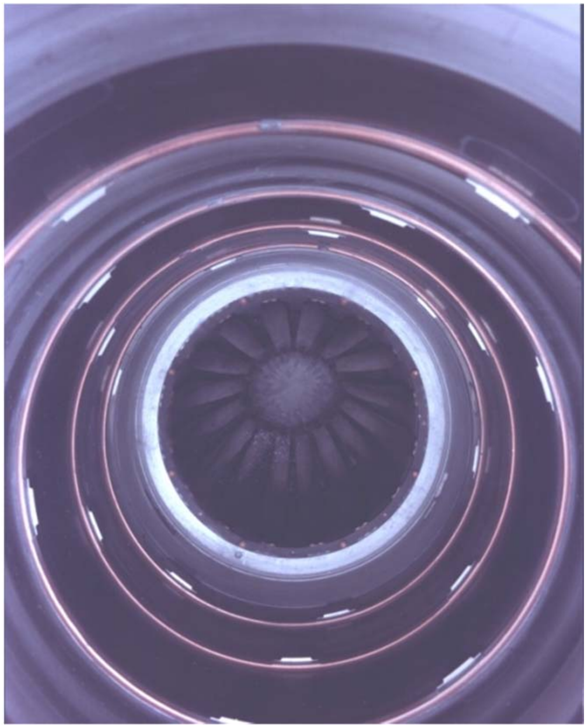
GRAVITY PROBE B

Timeline (1999-2004)



Ultra-low Magnetic Field

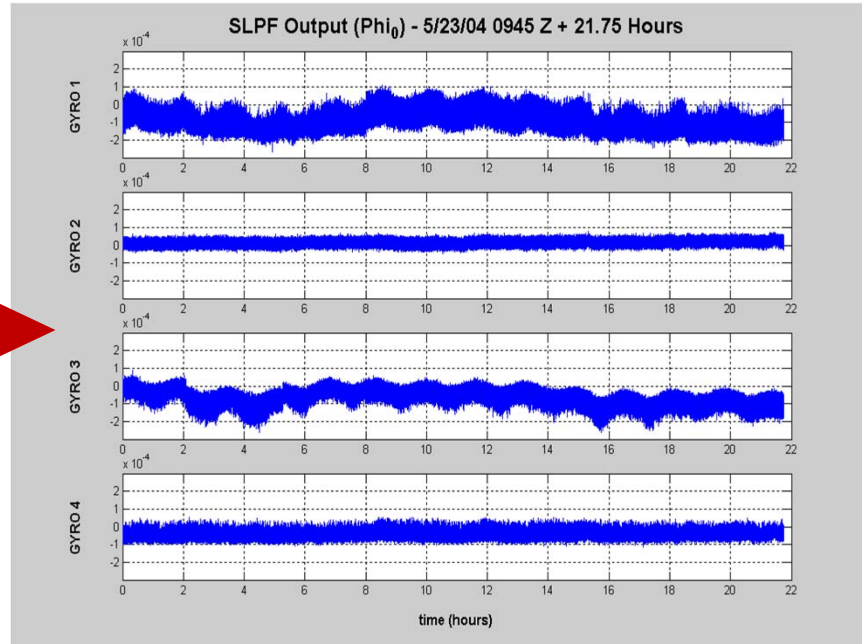
- Superconducting Lead Bag Technology
  - flux = field x area
  - successive expansions stable field levels ~ 10^{-7} gauss
  - 2 × 10^{-12} [~120 dB!] ac shielding through combination of cryoperm, lead bag, local superconducting shields & symmetry



GRAVITY PROBE B

Gyro Readout Performance On-Orbit

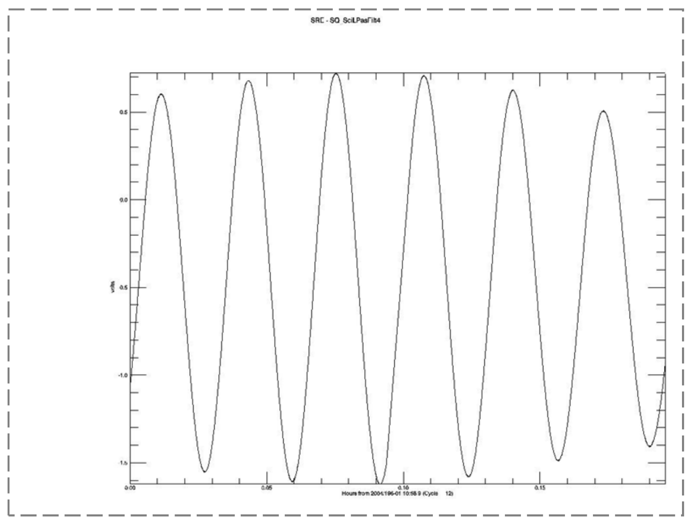
Output of SQUID low-pass filters for caged gyros over 22 hours



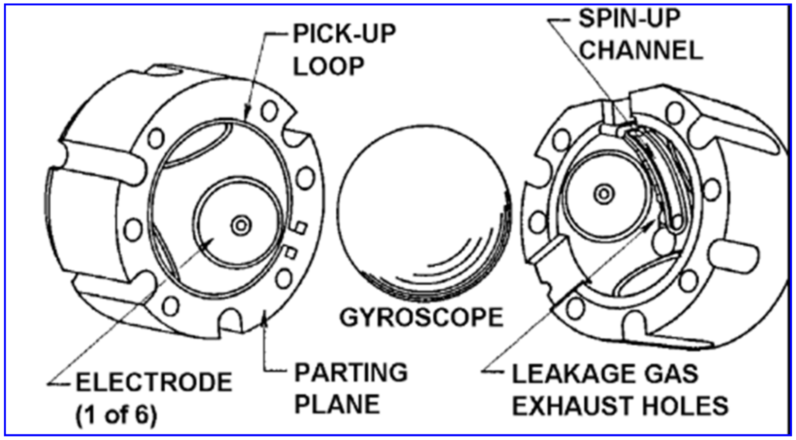
ISSUE:
Heating/cooling of gyros 1 & 3 external cable @ 97.5 min. orbit period

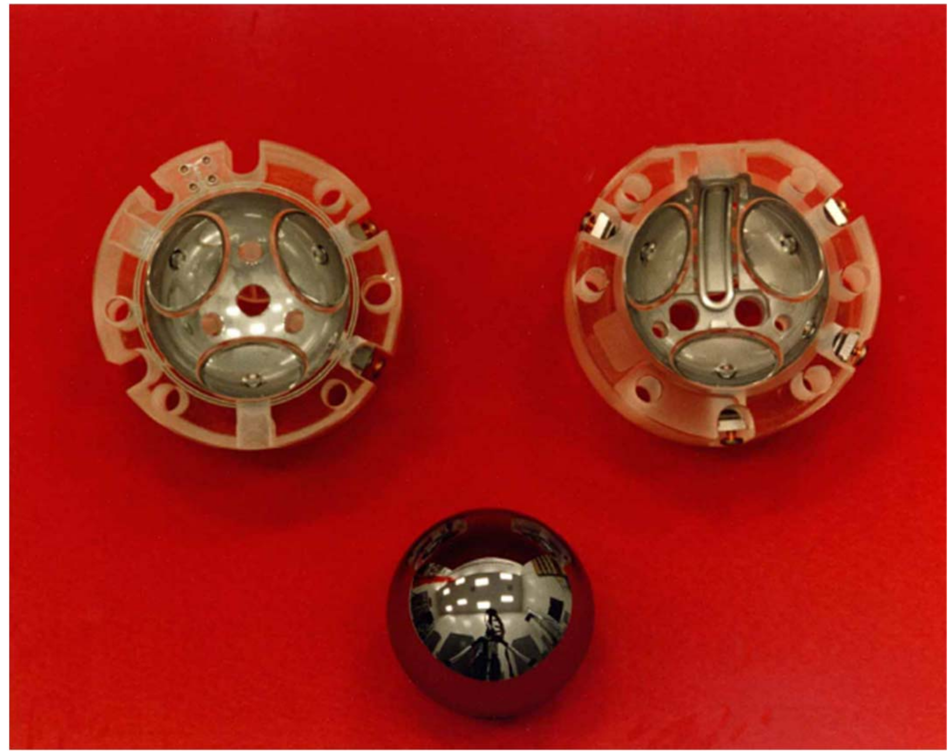
SOLUTION:
Raise S/V roll-rate to 77.5 sec. period. [scales ~ t^{-2}]

Roll Frequency Signal at Output of SQUID low-pass filter for spinning gyroscope



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