GP-B T0082

Gravity Probe B – Testing General Relativity with Orbiting Gyroscopes

Int'l Workshop on *Precision Tests and Experimental Gravitation in Space*
Galileo Galilei Institute, Firenze, Italy; Sep 28-23, 2006

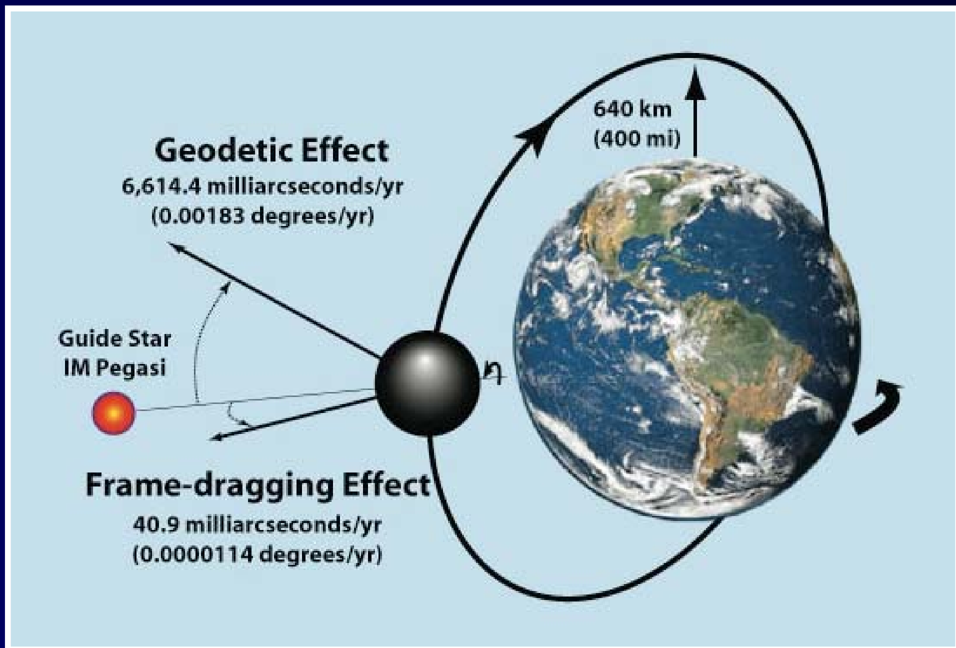
William Bencze, GP-B Program Manager
for the GP-B Team

NASA · Gravity ProBe · LOCKHEED MARTIN Missiles & Space · STANFORD UNIVERSITY

Outline

- Gravity Probe B
  - Description of the experimental concept
  - Difficult requirements and key enabling technologies.
  - Status of post-flight data analysis
- STEP Mission Update

Testing GR with Orbiting Gyroscopes



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

- Albert Einstein

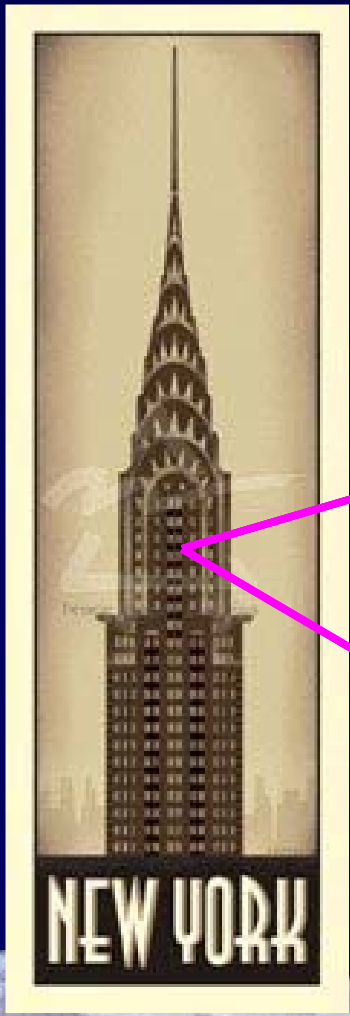
Leonard Schiff's relativistic precessions:

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

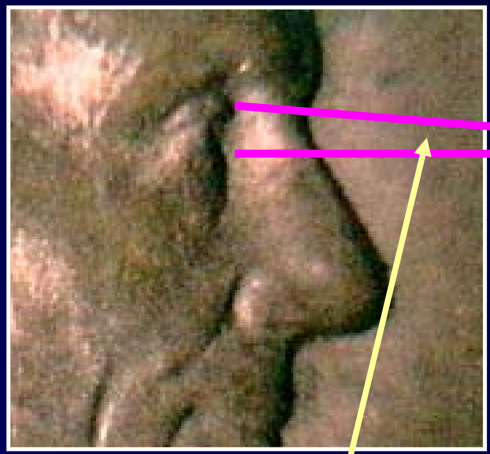
Geodetic, Ω_G Frame Dragging, Ω_{FD}

Spin axis orientation: $\frac{d\mathbf{s}}{dt} = \boldsymbol{\Omega}\times\mathbf{s}$

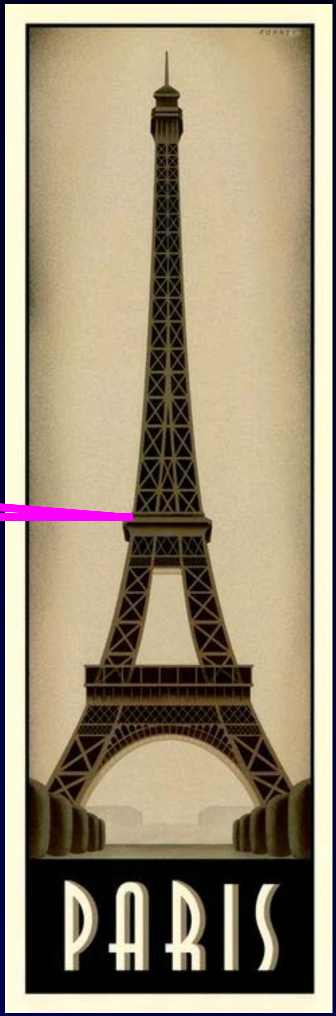
How Big is a 0.1 Milli-Arc-Second?



0.1 marc-sec = Angular width of Lincoln's eye in New York seen from Paris!



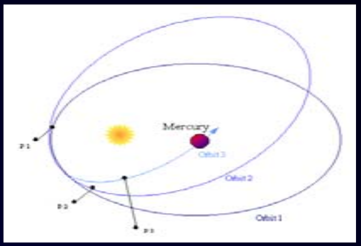
0.1 marc-sec



Einstein's 2 1/2 Tests

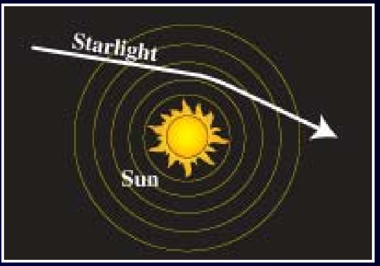
Perihelion Precession of Mercury

- GR resolved 43 arc-sec/century discrepancy.



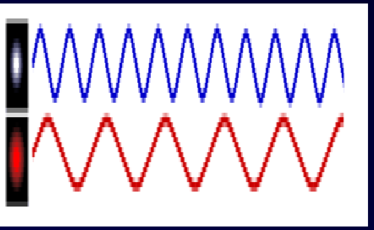
Deflection of light by the sun

- GR correctly predicted 1919 eclipse data.
- 1.75 arc-sec deflection: Present limit **10^{-3}**



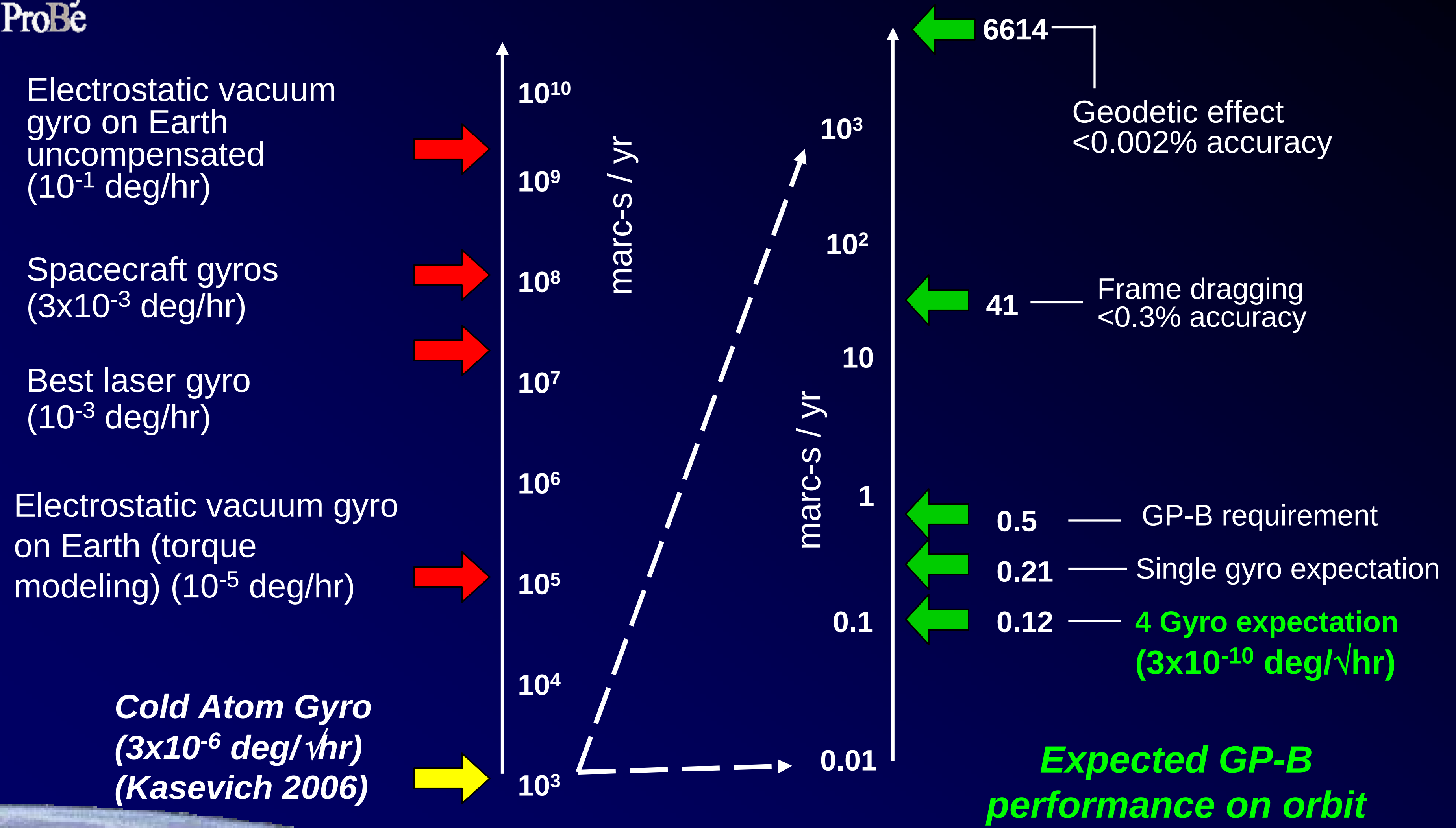
Gravitational Redshift: Equivalence Principle

- Einstein's "half test' – Equivalence principle only
- 1960 Pound-Rebka experiment (ground clocks)
- 1976 Vessot-Levine GP-A (orbiting clocks): **2×10^{-4}**



Tests of General Relativity to date rely on astronomical measurements, not a laboratory experiment under scientist's control.

Why a Space-based Experiment?



Operation in 1g environment degrades mechanical gyro performance
Laser gyroscopes and other technologies fidelity too low for GP-B

The "simplest experiment"

"No mission could be simpler than Gravity Probe B. It's just a star, a telescope, and a spinning sphere."

- William Fairbank, GP-B PI (ca. 1964)

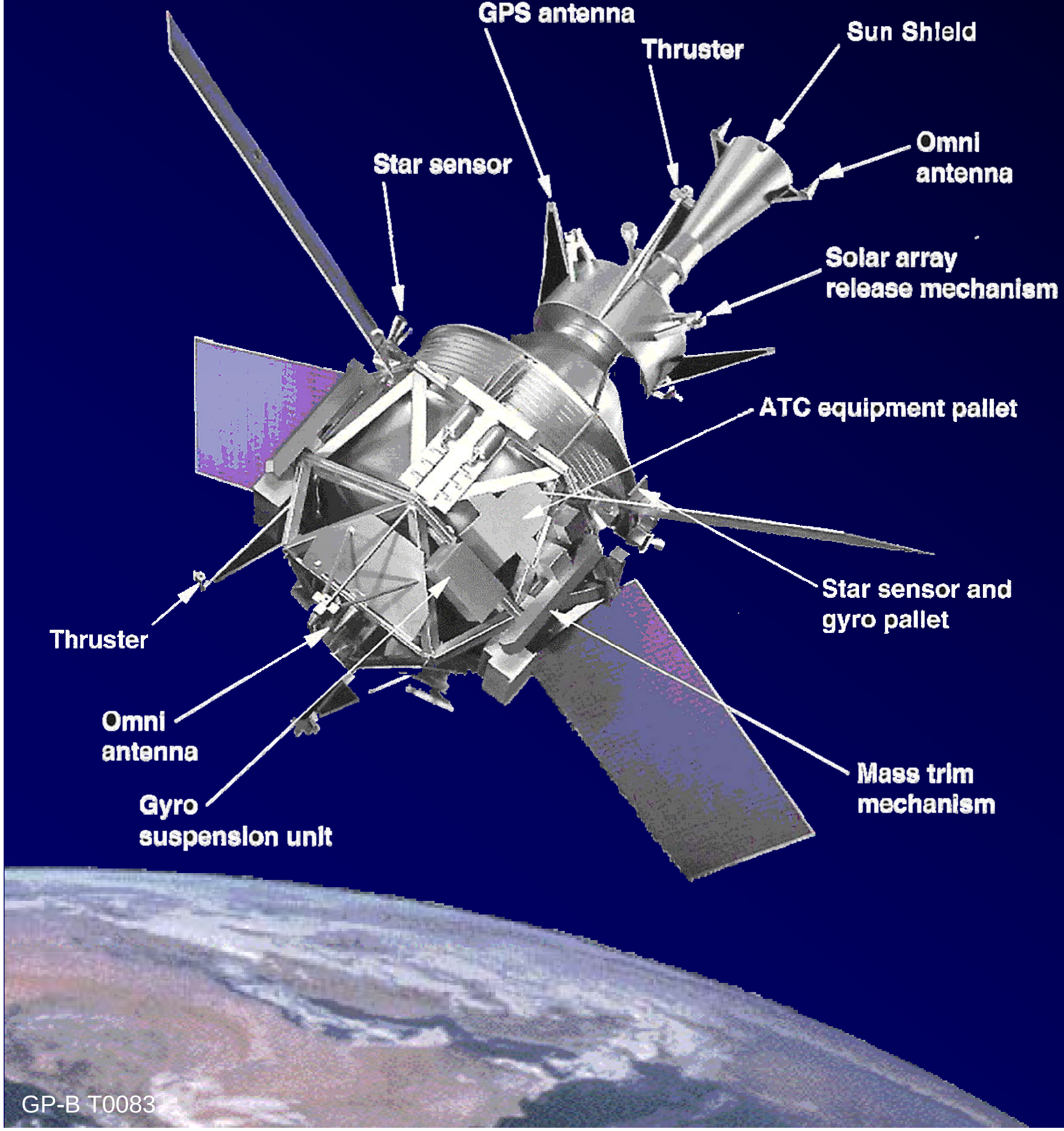
1. "Spinning Sphere" Perfect Gyros	**Drift < 0.1 marc-sec/yr**
– Perfect mass balance	< 20 nm mass unbalance
– Roundest spheres	< 20 nm p-v
– Gentle gyroscope suspension	200 mV
– Gyroscope centering control	~ 1 nm
– Precise initial gyro orientation	< 10 arc-sec
– Cross axis force control	~ 10^{-12} g cross-axis "drag free"
– Spin down torques (gas drag)	< 10^{-9} Pa
– Rotor electrical charge	< 15 mV
– Orientation readout: low noise SQUIDS	~ 200 marc-sec/√Hz
– Magnetic Shielding	240 dB shielding
– Cryogenics, superfluid He dewar	2500 liter @ 1.8K

The "simplest experiment" 2

2. Telescope – Accurate pointing	**< 0.1 marc-sec/yr**
– Precision vehicle pointing	~5 marc-sec
– Low measurement noise	~ 34 marc-sec/√Hz
– Mechanically "rock solid"	Cryogenic quartz fabrication
– Precise orbit	Orbit trim with GPS monitoring
3. Guide Star – Inertial Reference	**< 0.1 marc-sec/yr**
– Optically "bright"	6 magnitude
– Maximize frame dragging effects	Near equator
– Precise proper motion measurement	VLBI – good radio source
– Near extra-galactic radio source	Quasar – distant inertial frame

A "simple" experiment …
Indeed!

The Overall Space Vehicle



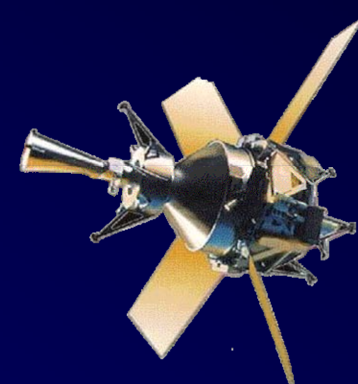
- ★ Redundant spacecraft processors, transponders.
- ★ 16 Helium gas thrusters, 0-10 mN ea, for fine 6 DOF control.
- ★ Roll star sensors for fine pointing.
- ★ Magnetometers for coarse attitude determination.
- ★ Tertiary sun sensors for very coarse attitude determination.
- ★ Magnetic torque rods for coarse orientation control.
- ★ Mass trim to tune moments of inertia.
- ★ Dual transponders for TDRSS and ground station communications.
- ★ Stanford-modified GPS receiver for precise orbit information.
- ★ 70 A-Hr batteries, solar arrays operating perfectly.

GP-B Launch - 20 April 2004

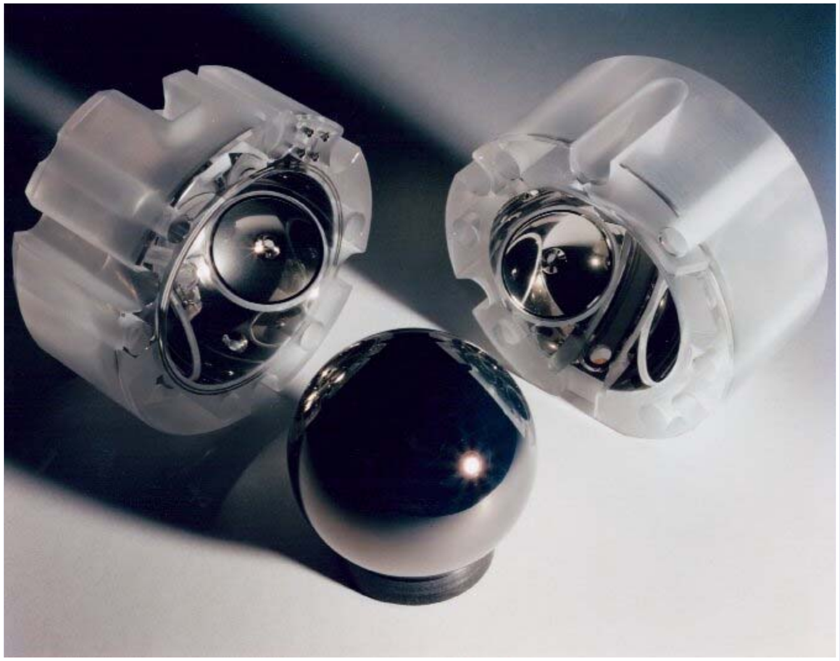
Fairing Installation

Launch!

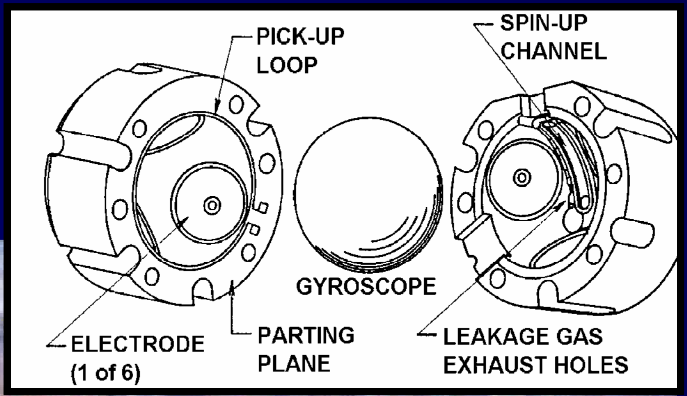
Release from launch vehicle



The Science Gyroscopes



Gyroscope rotor and housing halves

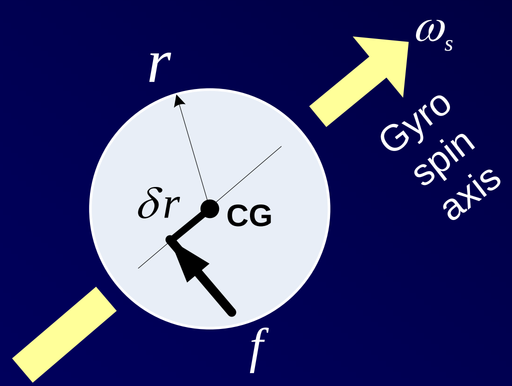


- ★ Material: Fused quartz, homogeneous to a few parts in 10^7
- ★ Overcoated with niobium.
- ★ Diameter: 38 mm.
- ★ Electrostatically suspended.
- ★ Spherical to 10 nm – minimizes suspension torques.
- ★ Mass unbalance: 10 nm – minimizes forcing torques.
- ★ All four units operational on orbit.

Demonstrated performance:

- Spin speed: 60 – 80 Hz.
- 20,000 year spin-down time.

"Perfect" Mass Balance Needed!



External forces acting through center of force, different than CM

Drag-free eliminates mass-unbalance torque and key to understanding of other support torques

Mass Balance Requirements:

On Earth (f = 1 g) $\quad \frac{\delta r}{r} < 5.8 \times 10^{-18}$

(ridiculous – 10^{-4} of a proton!)

Standard satellite ($f \sim 10^{-8}$ g) $\quad \frac{\delta r}{r} < 5.8 \times 10^{-10}$

(unlikely – 0.1 of H atom diameter)

GP-B drag-free ($f \sim 10^{-12}$ g cross- track average) $\quad \frac{\delta r}{r} < 5.8 \text{ X } 10^{-6}$

(straightforward – 100 nm)

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

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

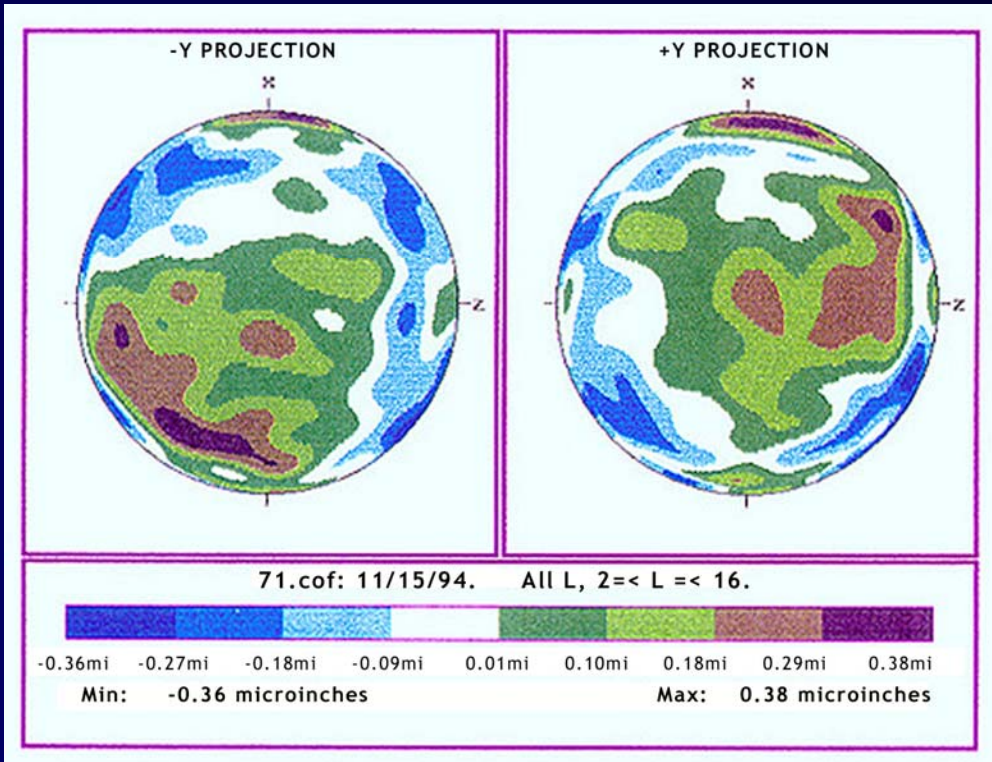
$$\frac{\delta r}{r} < \frac{2}{5}\frac{r\omega_s}{f}\Omega_0$$

Drift-rate: $\Omega = \tau / I\omega_s$

Torque: $\tau = mf\,\delta r$

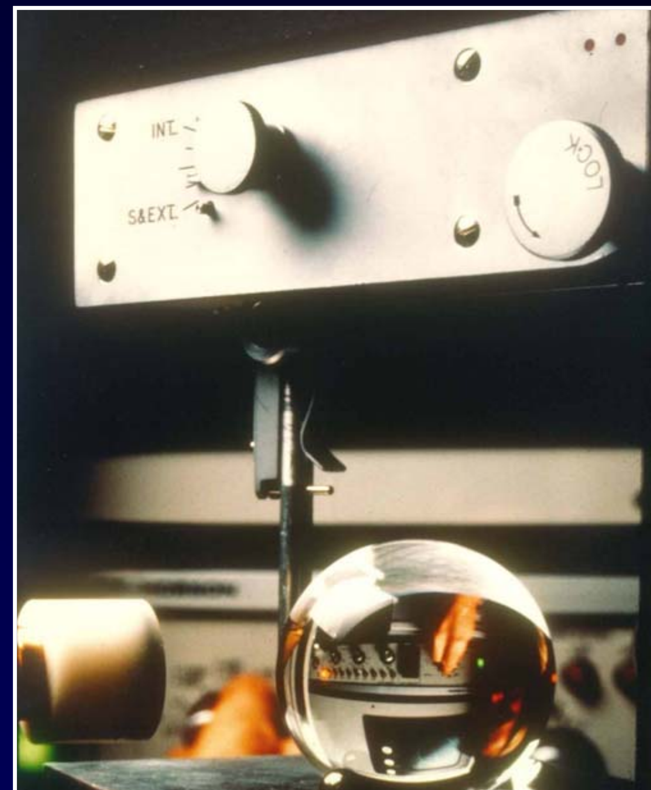
Moment of Inertia: $I = (2/5)\,mr^2$

Sphericity Measurement



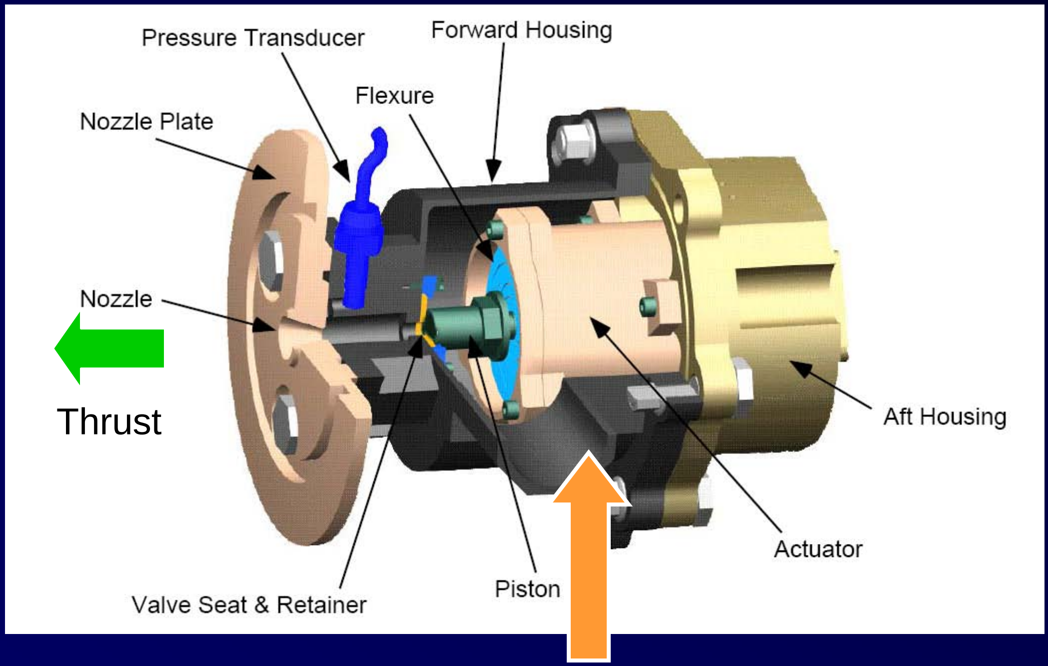
Typical measured rotor topology; peak-valley = 19 nm

Talyrond sphericity measurements to ~1 nm



If a GP-B rotor was scaled to the size of the Earth, the largest peak-to-valley elevation change would be only 6 feet!

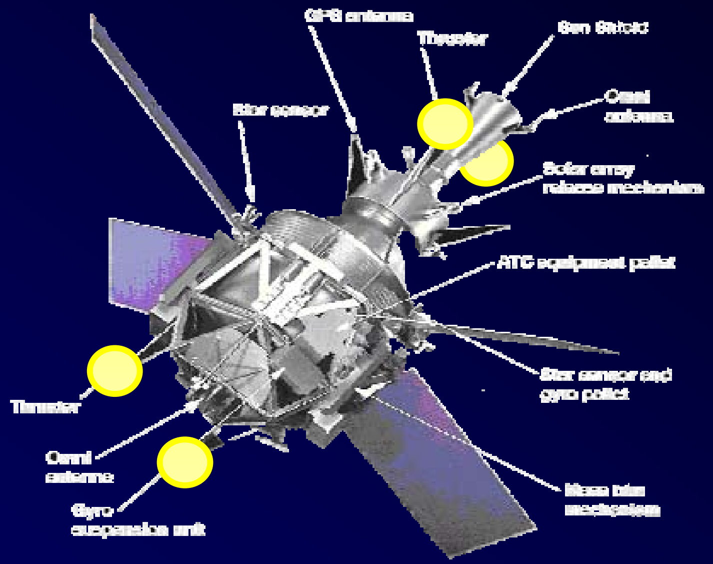
Flight Proportional Thruster Design



Thrust: 0 – 10 mN
I_{SP}: 130 sec
Mdot: 6-7 mg·s^{-1}
Noise: 25 μN·Hz$^{-1/2}$

Propellant: Helium Dewar Boiloff
Supply: 5 to 17.5 torr

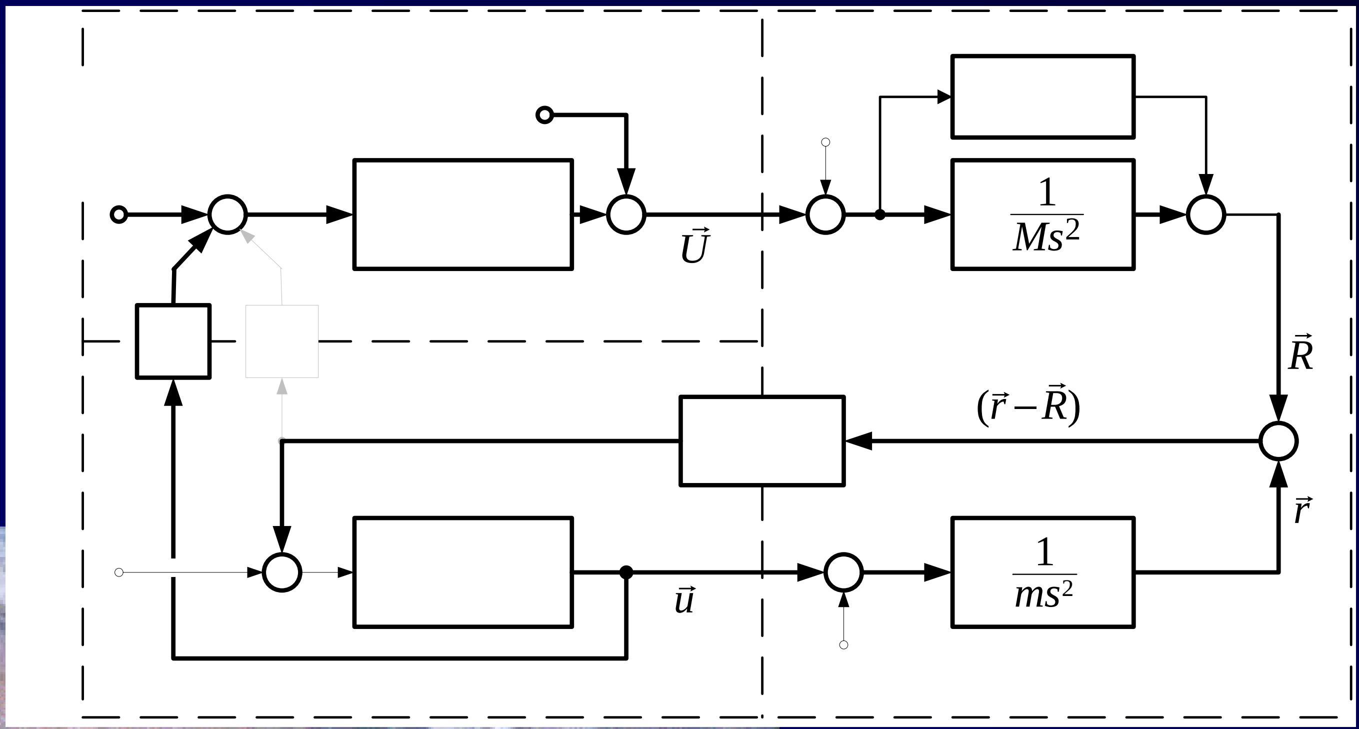
- Cold gas (no FEEP!) proportional thruster; 16 units on space vehicle.
- Operates under choked flow conditions
- Pressure feedback makes thrust independent of temperature



Location of thrusters on Space Vehicle

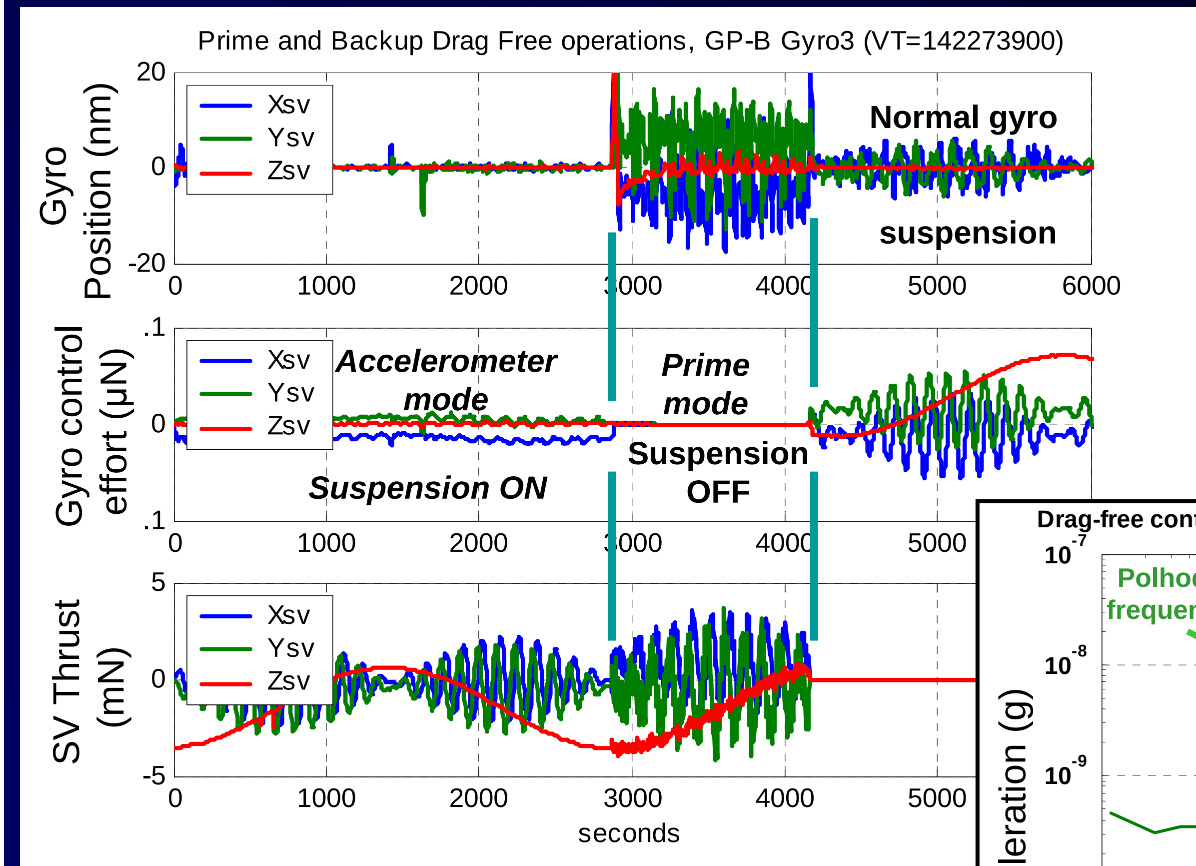
Drag-free Operational Modes

- Suspended "accelerometer" mode
  - Measured gyro control effort nulled by space vehicle thrust.
  - Used during most of mission due to robustness, gyro safety.
- Unsuspended "free float" mode
  - SV chases gyro; nulls position signal.



Translation Control

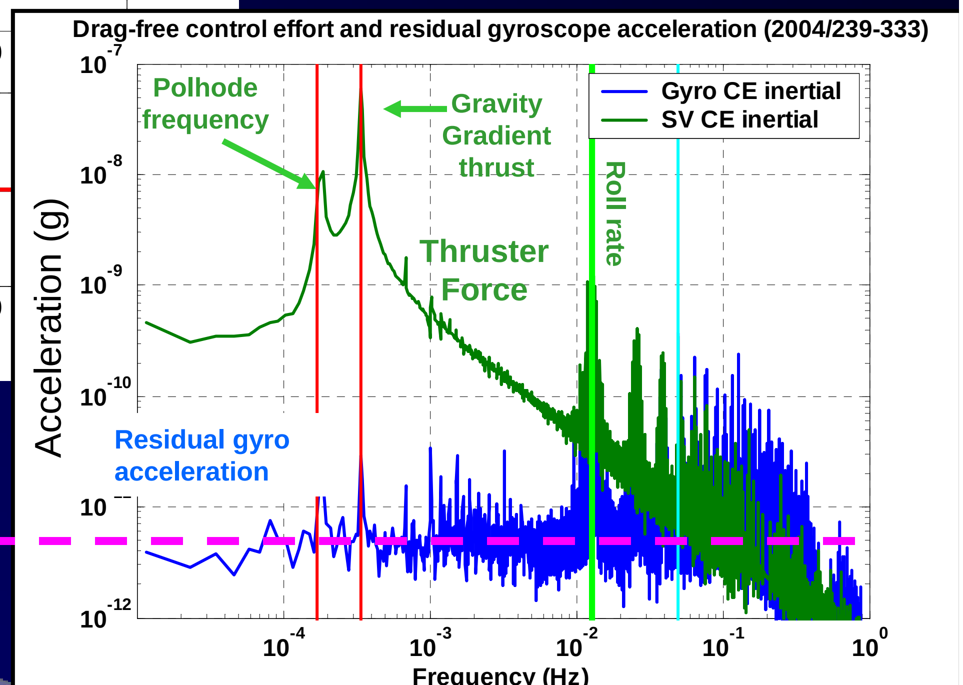
Drag Free Control for a Perfect Orbit



Drag free modes in operation

Demonstrated performance better than 10^{-11} g residual acceleration on drag free gyroscope in measurement band (12.9mHz ± 0.2mHz) Rejection ~ 10,000x

Inertial space – Frequency domain



5×10^{-12} g in band

~1.5×10^{-8} $(m/s^2)/\sqrt{Hz}$ 0.02mHz – 80 mHz

Superconducting SQUID Readout

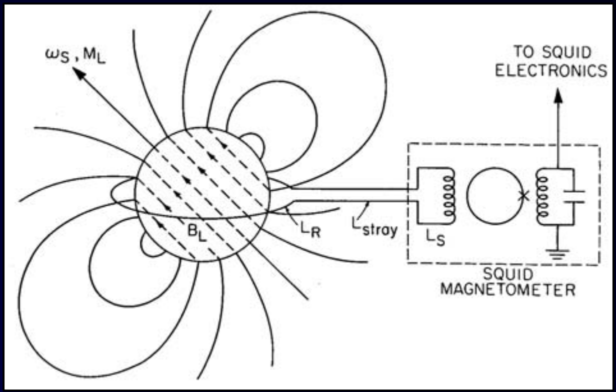
The Conundrum:

How to measure with extreme accuracy the direction of spin of perfectly round, perfectly uniform, sphere with no marks on it?

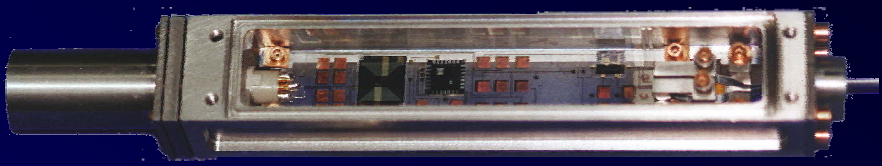
The Solution:

London Moment Readout**.** A spinning superconductor develops a magnetic “pointer” aligned with its spin axis.

Magnetic field sensed by a SQUID, a quantum limited, DC coupled magnetic sensor.

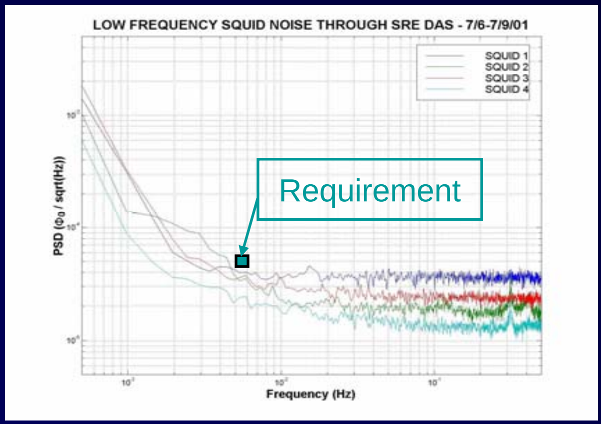


$$M_L = -\frac{2mc}{e}\omega_s = -1.14\times10^{-7}\,\omega_s \quad \text{(Gauss)}$$



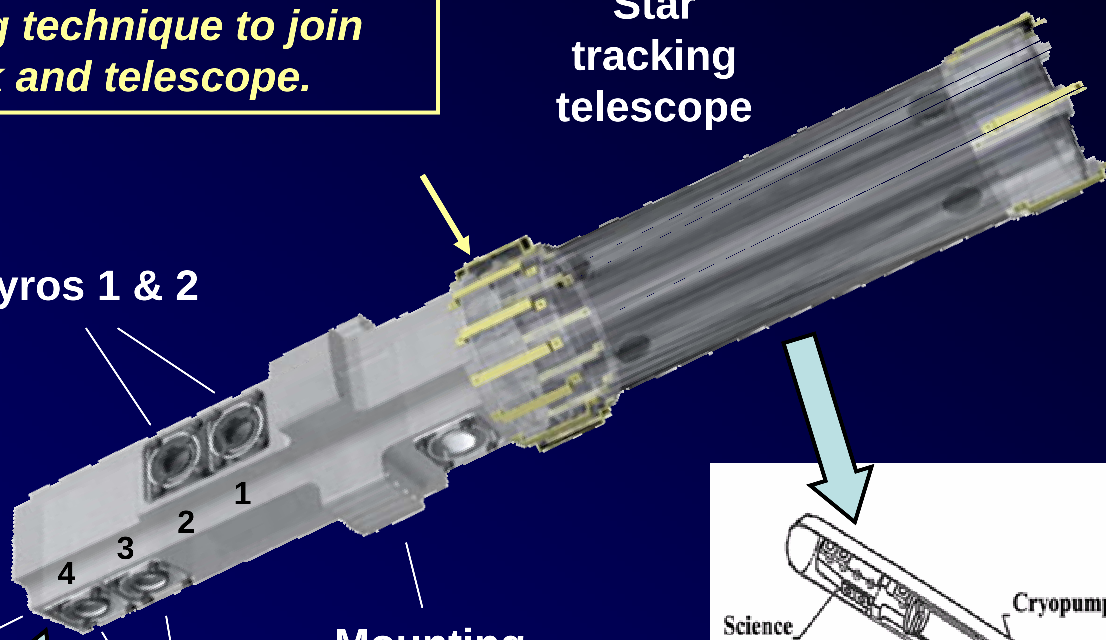
SQUID electronics in Niobium carrier

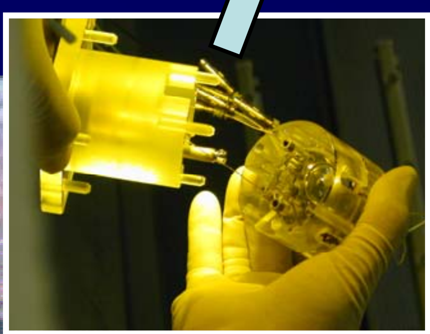
Performance: measurement better than 200 marc-s/√Hz

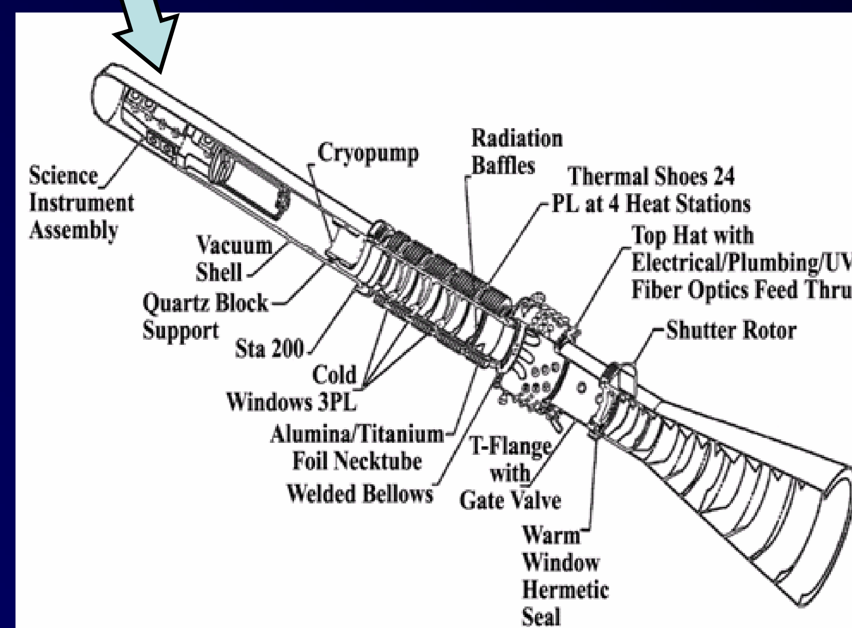


Science Instrument Assembly

Stanford-developed silicate bonding technique to join block and telescope.







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

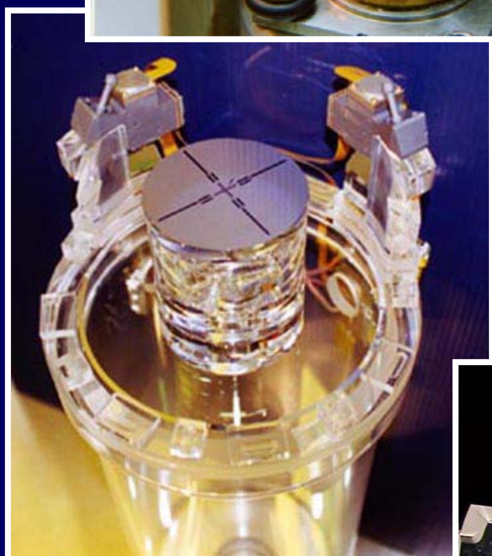


Image divider

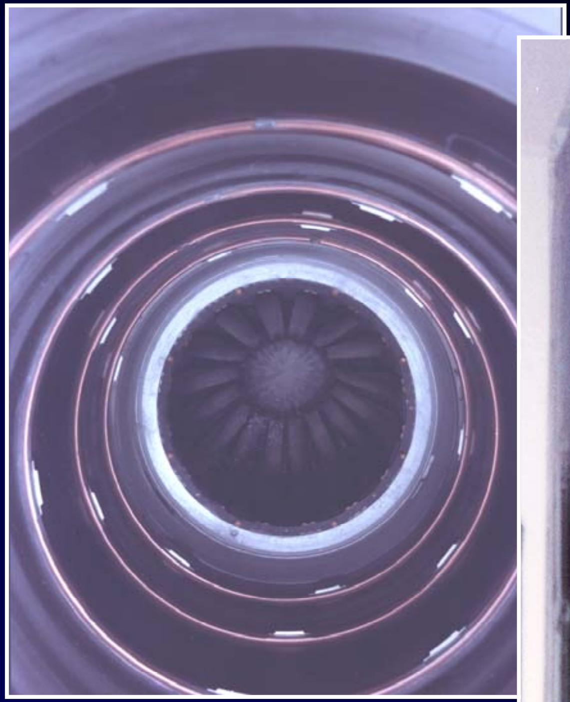
Integrated Telescope

Telescope in Probe

Ultra-low Magnetic Field

- Magnetic fields are kept from gyroscopes and SQUIDs using a superconducting lead (Pb) bag
  - Mag flux = field x area.
  - Successive expansions of four folded superconducting bags give stable field levels at ~ 10^{-7} G.
- AC shielding at 10^{-12} [=240 dB!] from a combination of cryoperm, lead bag, local superconducting shields & symmetry.

Enables the readout system to function to its stringent requirements



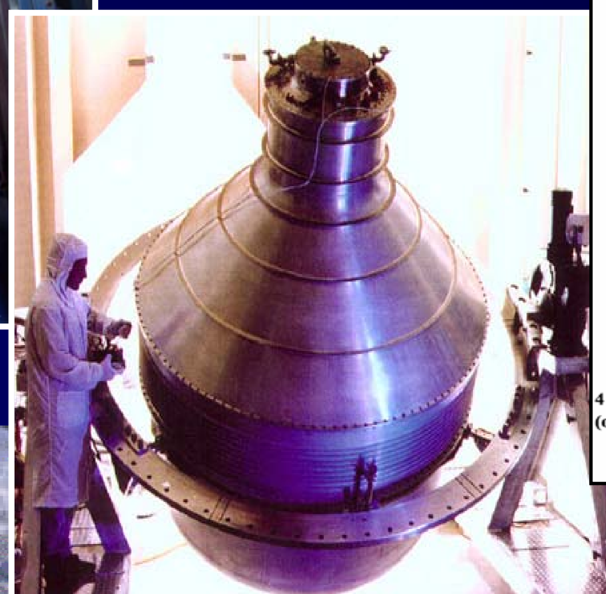
Lead bag in Dewar

Expanded lead bag

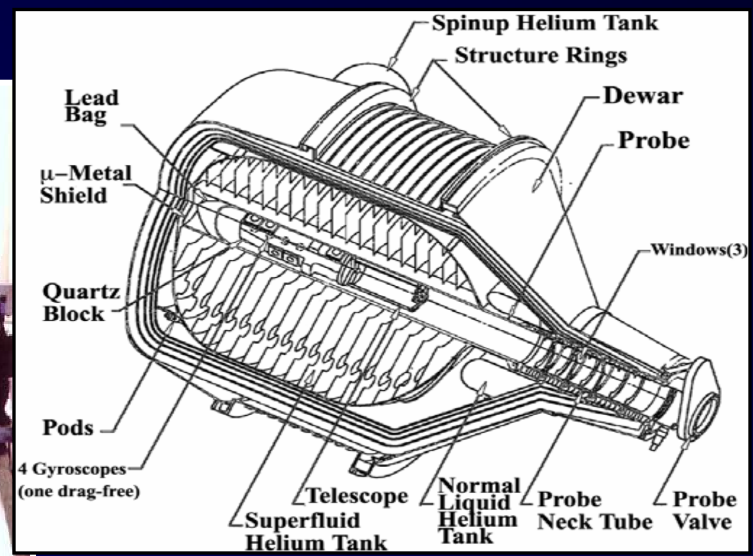
Cryogenic Dewar and Probe

Probe during assembly

- 2524 liter superfluid helium (1.82K dewar)
- Porous plug phase separator.
- Lifetime 17.3 months – longest lived dewar in space.
- Dewar boil-off gas used for attitude and translation control of vehicle

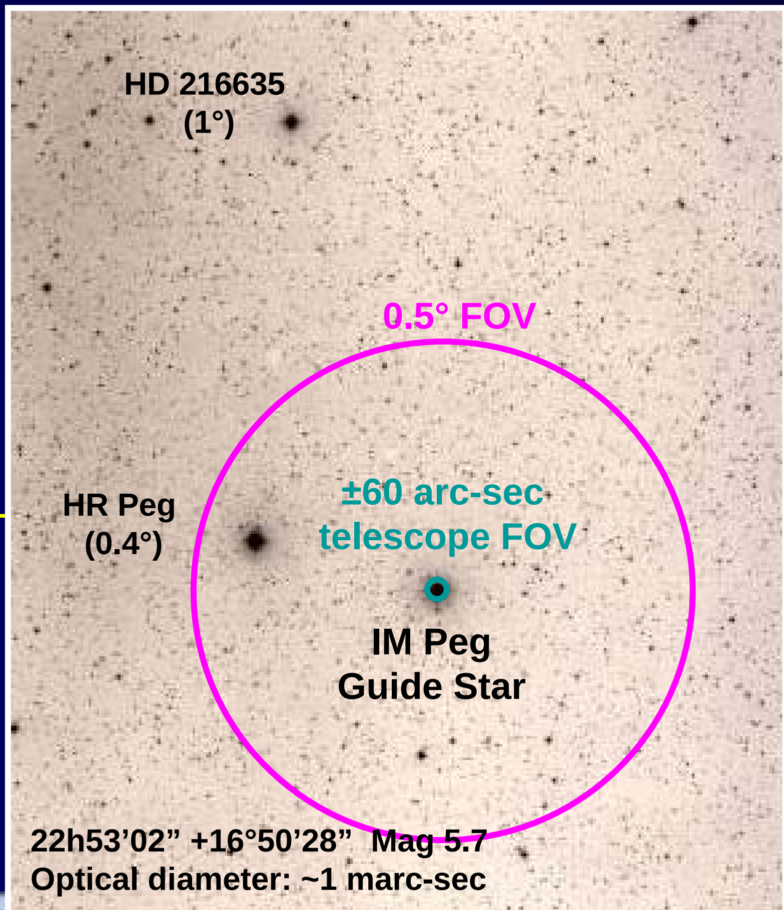


Dewar



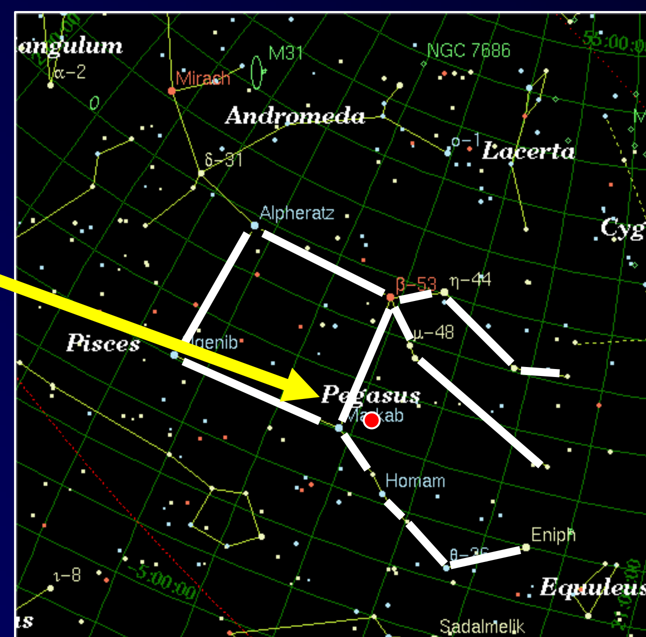
Guide Star Selection

Palomar star map



Criteria:

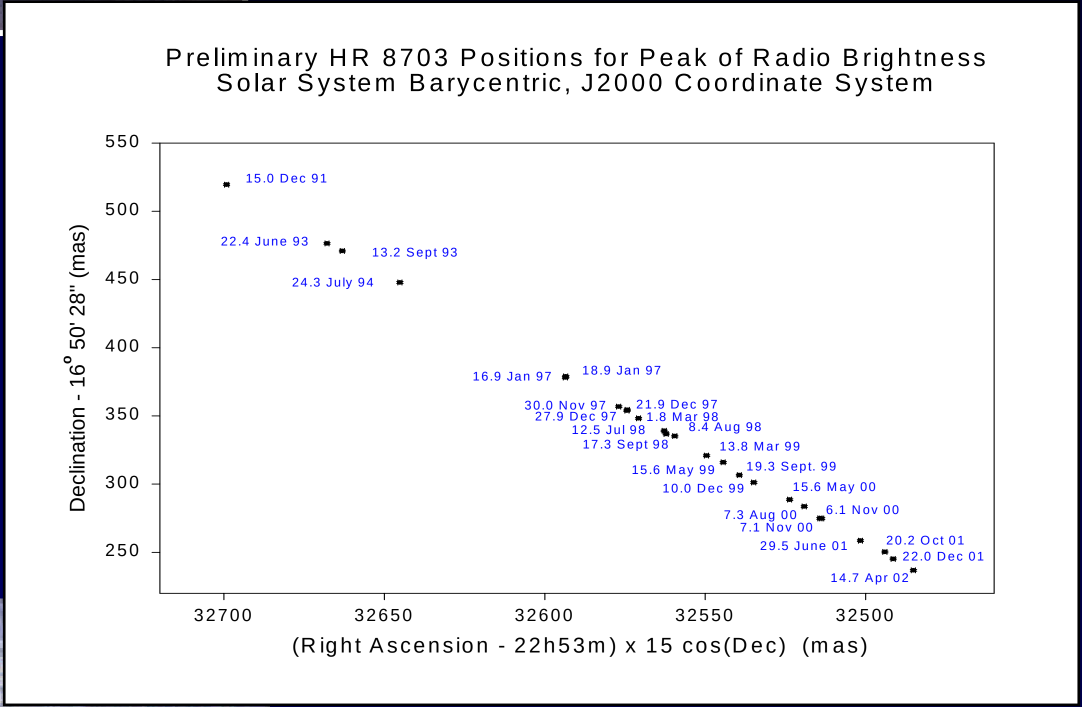
- Sufficiently close to equatorial plane for maximum frame dragging signal
- Optically bright enough to meet the pointing requirement.
- Be a radio star to allow VLBI proper motion measurement



Proper Motion Measurement via VLBI

- SAO measuring position of IM Peg via VLBI.
- Calibrated against extra-galatic objects
- Defines a very precise distant inertial frame.

History of IM Peg position since Dec 1991



3 Stages of In-flight Verification

A. Initial orbit checkout (121 days)

- Re-verification of all ground calibrations.
- Scale factors, thermal sensitivities, etc.
- Disturbance measurements on gyros at low spin speed.

B. Science Phase (~ 11 months)

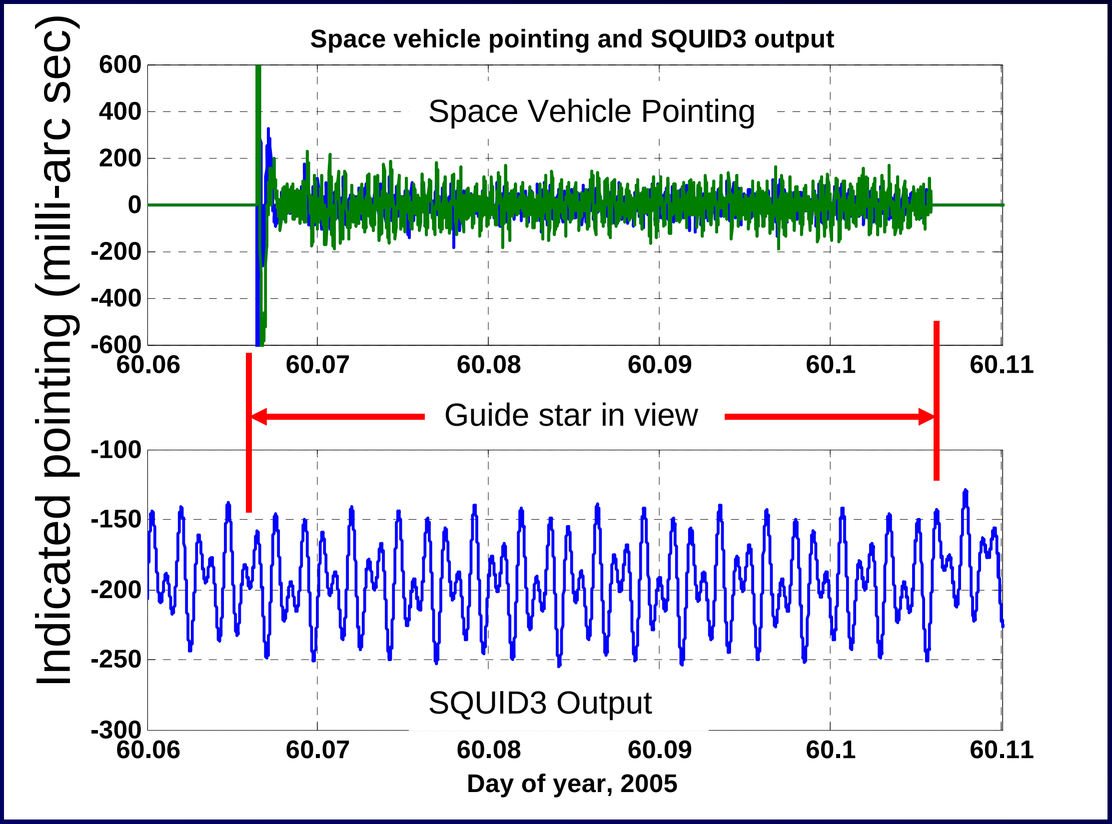
- Exploiting the built-in checks (i.e. Nature's helpful variations).

C. Post-experiment tests (~ 1 month starting Aug 2005)

- Refined calibrations through careful and deliberate enhancement of disturbances, etc.

Mission Operations Center (MOC) at Stanford University

One Orbit of Science Data



Repeat every 97 minutes for a year......

Data processing:

- Remove known (calibrate-able) signals from SQUID signal to get at gyro precession.

Remove effects of:

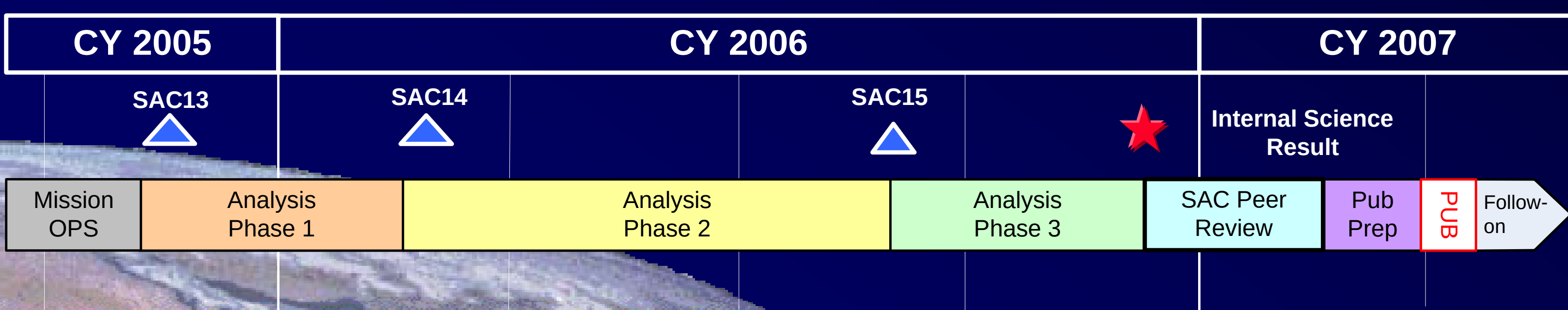
- Motional aberration of starlight.
- Parallax.
- Pointing errors; roll phase errors.
- Telescope/SQUID scale factors.
- Pointing dither.
- SQUID calibration signal.
- Scale factor variation with gyro polhode (trapped flux).
- Other systemic effects.

Data Analysis: An Incremental Approach

- **Phase 1 – Day-by-day. (thru March 2006)**
  - Full year data grading; Instrument calibration.
  - Treatment of known features (e.g. aberration, pointing errors).
  - Result: first-cut "orientation of the day" per gyroscope.

- **Phase 2 – Month-to-Month. (thru September 2006)**
  - Identify and remove systematic effects.
  - Improve instrument calibrations through long-term trending.
  - Result: second-cut: "trend of the month" per gyroscope.

- **Phase 3 – 1 Year Perspective. (thru April 2007)**
  - Combine and cross-check data from all 4 gyroscopes
  - Incorporate measured guide star proper motion.
  - Result: Experimental results compared with predicted GR effects.



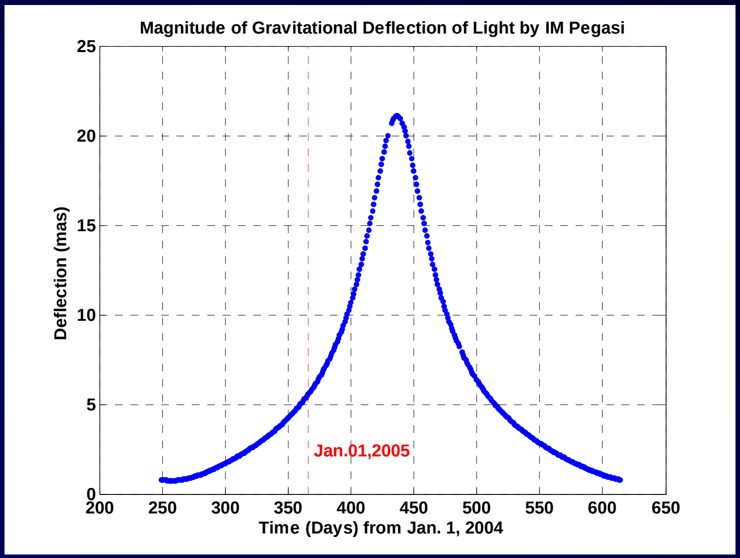
Built-In Checks Assure Accurate Result

- **Structure of Data**
  - Predicted GR results: **6614.4 marc-sec Geodetic**
    40.9 marc-sec Frame-dragging
  - Orbital aberration: **5185.6 marc-sec**
  - Annual aberration: **20495.8 marc-sec**
  - Gravitational deflection of light: **21.12 marc-sec peak (11 Mar 2005)**
  - Parallax: **~ 10 marc-sec**

- **Scaling Verifications**
  - **Magnitudes & planar relations of effects known**

- **Robustness further confirmed by agreement with**
  - **Multiple data analysis approaches.**
  - **Gyro-to-gyro direct comparisons.**

Gravitational deflection of starlight



Redundancy – with Variation

- **4 gyros & SQUIDs with distinct characteristics**
  - Different rotor & housing shapes, mass distributions, surface finish.
  - Different spin directions - 2 clockwise, 2 counterclockwise
  - Different spin speeds & polhode rates
  - Different acceleration environments (distances from drag-free point)
  - Different magnetic fields & pressures

- **Optical reference**
  - Guide telescope – 2 separate optical images & detector assemblies
  - Roll reference – 2 roll axis star telescopes

4 gyros agreeing amid all these variations → ***A POWERFUL VERIFICATION***

What's Taking so Long, Anyway?

- Overall, the GP-B spacecraft operated very well on orbit.
- However, not perfectly:
  - Out-of-spec pointing
    - Requires more careful telescope calibration.
  - Polhode period damping – modelling
    - Modulates the gyro orientation angle readout scale factor. (systematic error source)
  - Interference from onboard electronics system (ECU)
  - "Segmented" data from spacecraft anomalies.
    - Knitting segments together requires care.
  - Need for "data grading" – 1 TB of science data!

All require time to understand, model, and remove…

…a lesson for other "simple" missions now in development

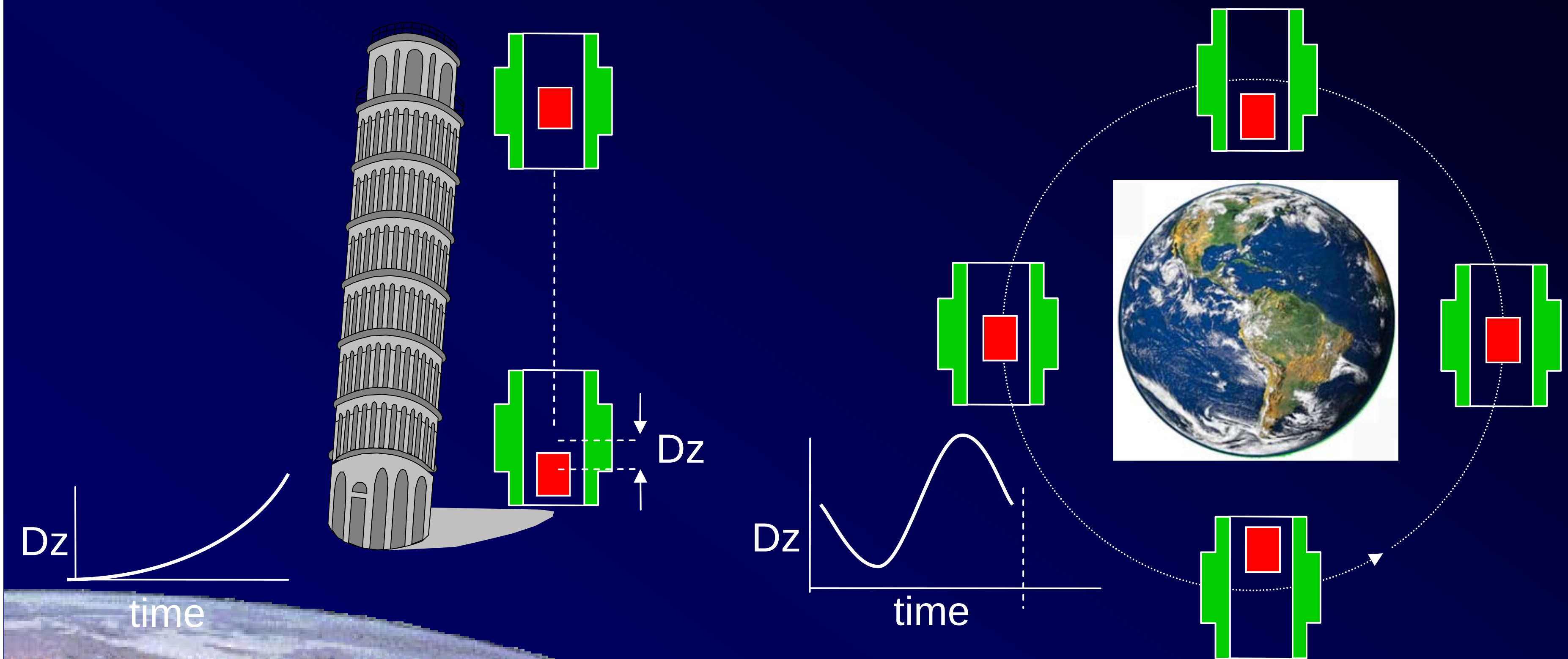
Satellite Test of the Equivalence Principle
"STEP"

Program Update

Satellite Test of the Equivalence Principle

Newton's Mystery {

- $F = ma$ — mass - the receptacle of inertia
- $F = GMm/r^2$ — mass - the source of gravitation

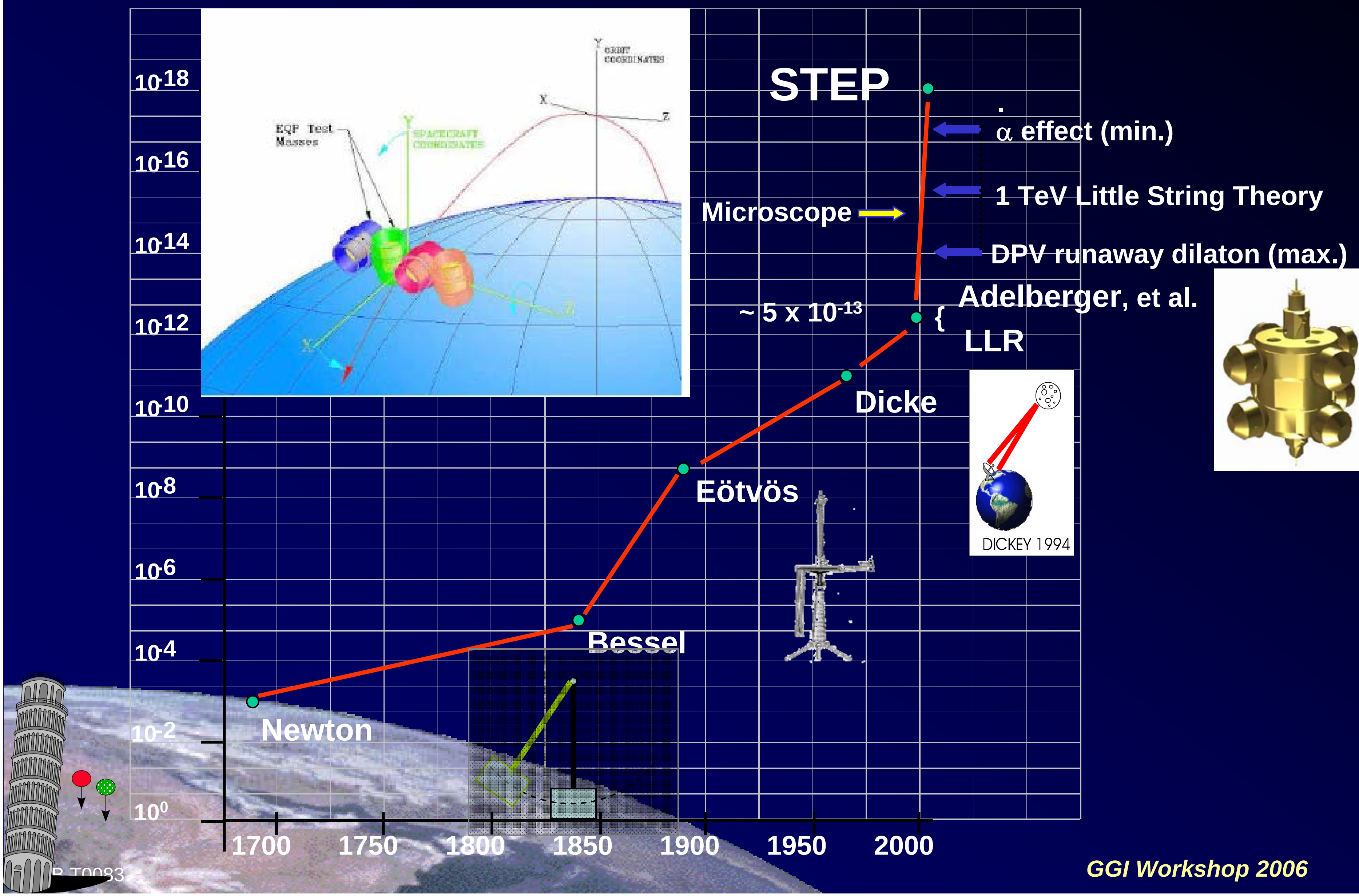


Orbiting drop tower experiment {

- * More time for separation to build
- * Periodic signal

Space: > 5 Orders of Magnitude Leap

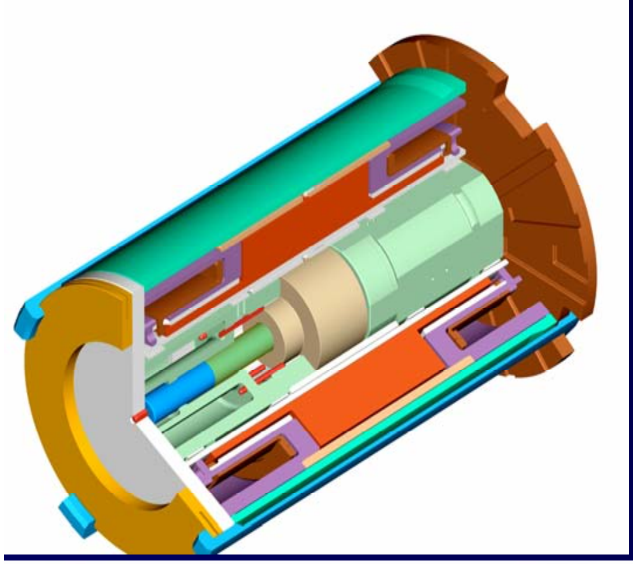
STEP Goal: 1 part in 10^{18}

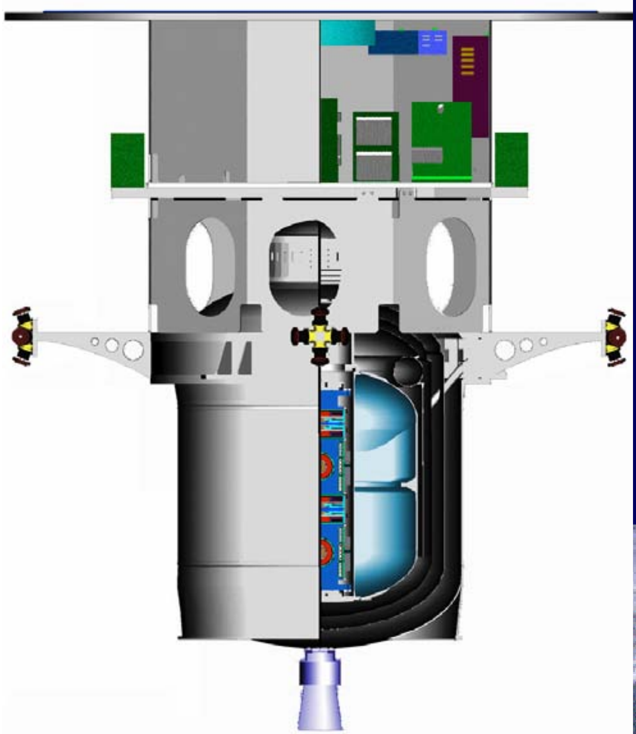


Proposed EP Tests in Space

Proposal	Institution	Accuracy Goal
SEE ***Satellite Energy Exchange***	**U. Tennessee**	**Unspecified**
Microscope	**ONERA, OCA** **CNES, ESA**	10^{-15}
Equivalence ***Balloon drop test of EP***	**Harvard SAO,** **IFSI Rome**	10^{-15}
GG ***Galileo Galilei***	**Università di Pisa**	10^{-17}
STEP ***Satellite test of EP***	**Stanford U., NASA/MSFC,** **European collaboration**	10^{-18}

STEP Mission Elements





6 Month Lifetime
- Sun synchronous orbit, I=97o
- 550 Km altitude
- Drag Free control w/ He Thrusters

Cryogenic Experiment
- Superfluid Helium Flight Dewar
- Aerogel He Confinement
- Superconducting Magnetic Shielding

4 Differential Accelerometers
- Test Mass pairs of different materials
- Micron tolerances
  Superconducting bearings
- DC SQUID acceleration sensors
- Electrostatic positioning system
- UV fiber-optic Charge Control

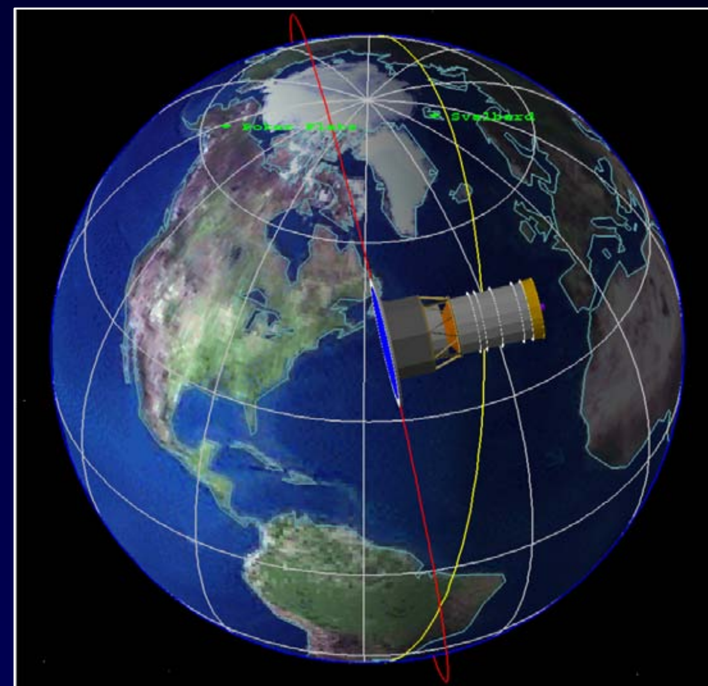
STEP Status

Beginning 2nd year of 3 year Technology Program under NASA MSFC

Technology Program Goals:

- Fabricate prototype flight instrument
  - Differential accelerometer
  - Cryogenic electronics
  - Quartz block mounting structure

- Transfer critical GP-B technologies
  - SQUID readout
  - Drag-free thrusters
  - Electrostatic positioning system

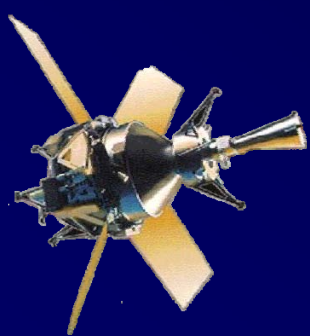


- Integrated ground test of prototype flight accelerometer

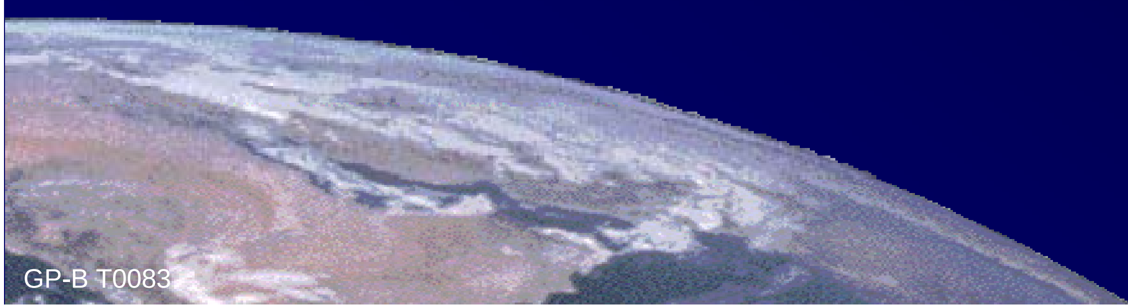
GP-B: Over the Horizon

- ★ Dewar was depleted on 29 Sep 2005 – superconducting electronics ceased to function.

- ★ Systematic effects will be characterized and compensated for in 2006, followed by detailed data review by external experts.



- ★ **Data analysis will continue to April 2007 when results will be published at the April APS meeting. (Jacksonville, Florida)**



GP-B – An International Collaboration

• **Stanford University** ***C.W.F. Everitt PI, GP-B team***	**Development, Science Instrument, Management** **Mission Operations, Data Analysis**
• **Lockheed Martin** ***GP-B team***	**Probe, Dewar, Spacecraft bus, Flight Software**

Research at Other Institutions

• **Science Advisory Committee** ***Clifford Will chair***	
• **Harvard Smithsonian** ***Irwin Shapiro***	**Guide Star and Star Proper Motion Studies**
• **JPL** ***John Anderson***	**Independent Science Analysis**
• **York University** ***Norbert Bartel***	**Guide Star and Star Proper Motion Studies**
• **Purdue University** ***Steve Collicot***	**Helium Ullage Behaviour**
• **San Francisco State** ***Jim Lockhart***	**Gyroscope Read-out Topics**
• **National University of Ireland** ***Susan M.P. McKenna-Lawlor***	**Proton Monitor**
• **University of Aberdeen** ***Mike Player***	**High Precision Homogeneity Measurement of Quartz**