Institut Henri Poincaré

The Gravity Probe B Relativity Mission

John Mester
Stanford University

GP-B Collaboration

• Marshall Space Flight Center *Tony Lyons PM, Rex Geveden*	NASA Center Management
• 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, Satellite, Flight Software
• 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 Bartell*	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

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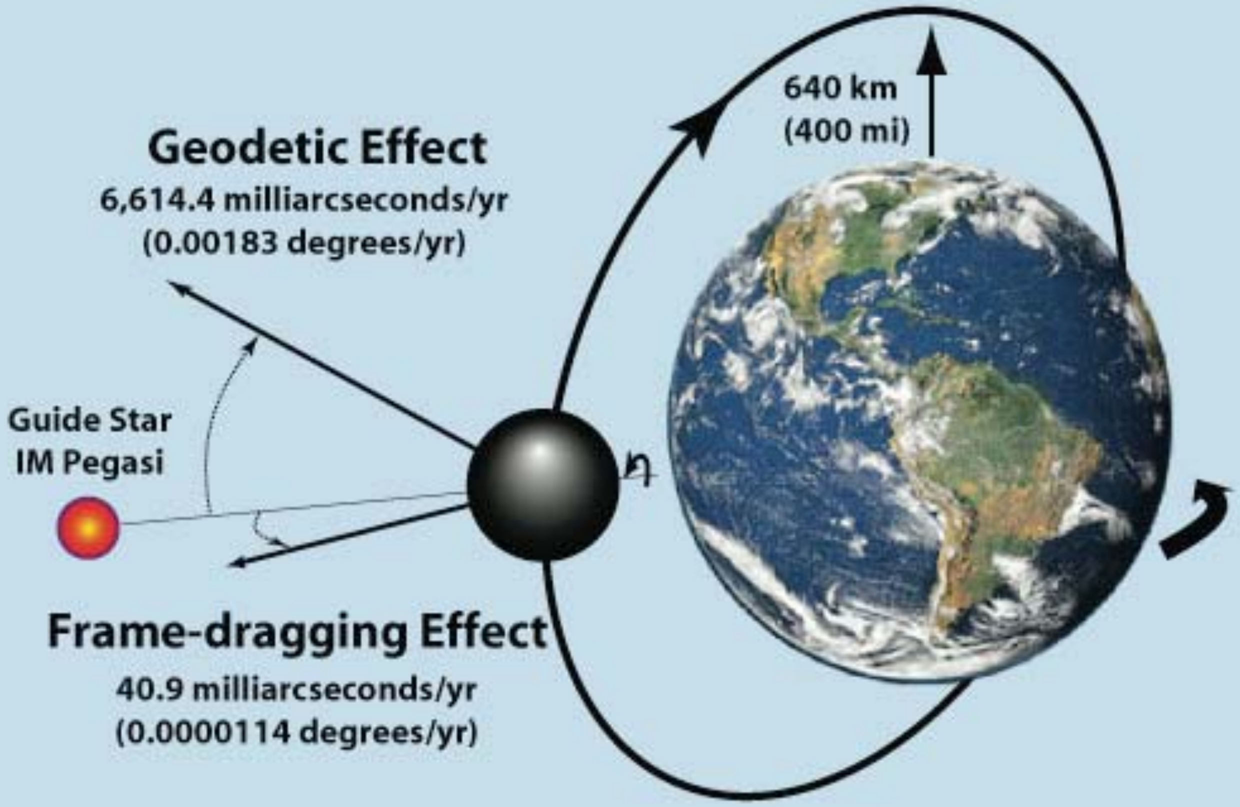
The Relativity Mission Concept



$$\overline{\Omega}_G = \left(\gamma + \frac{1}{2}\right)\frac{GM}{c^2R^3}\left(\overline{R}\times\overline{v}\right)$$

$$\overline{\Omega}_{FD} = \left(\gamma + 1 + \frac{\alpha_1}{4}\right)\frac{GI}{2c^2R^3}\left[\frac{3\overline{R}}{R^2}\cdot\left(\overline{\omega}_e\cdot\overline{R}\right) - \overline{\omega}_e\right]$$

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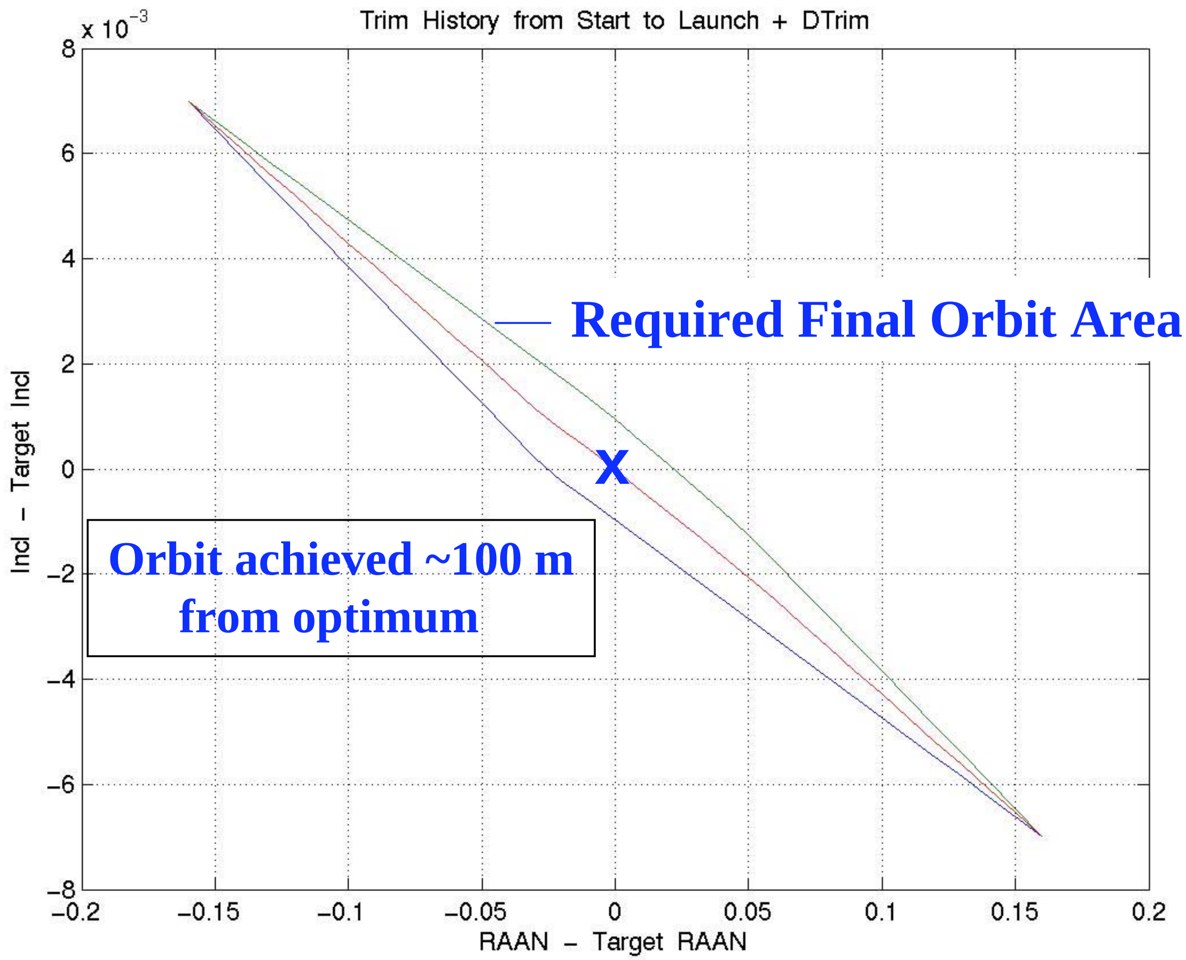
Launch: April 20, 2004 – 09:57:24

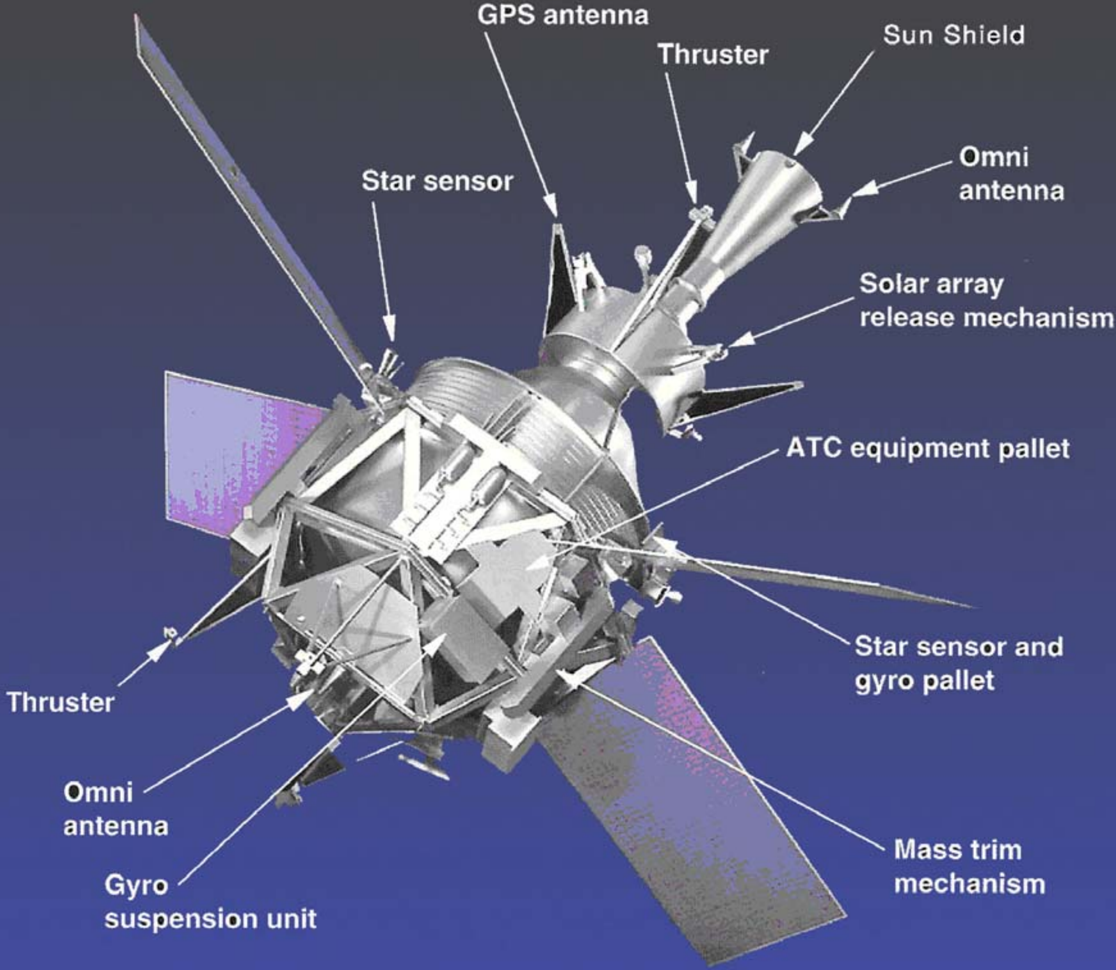
Boeing & Luck -- A Near Perfect Orbit



Delta II Nominal Accuracy

One Month of orbit trim operations planned, none needed

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.

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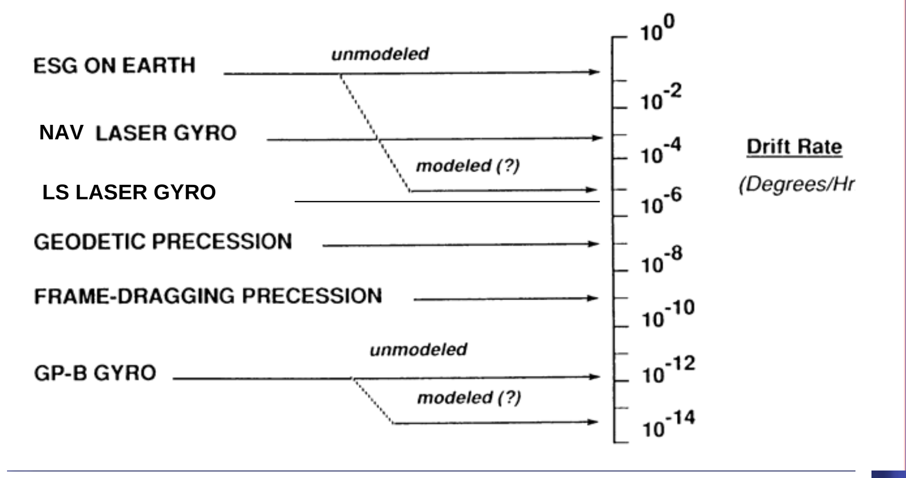
Fundamental GP-B Requirement

Gyro Newtonian Drift Rates ≤ GR Effects Under Test

==> GR effects manifest w/o modeling or subtraction of Gyro Newtonian effects

Achieved by controlling "near zeros" {
1) rotor inhomogeneities
2) "drag-free"
3) rotor asphericity
4) magnetic field
5) pressure
6) electric charge

Why go to space?



Anticipated leading error sources

- **Gyroscope drift**
- **Readout error effect**
- **Guide star proper motion uncertainty**

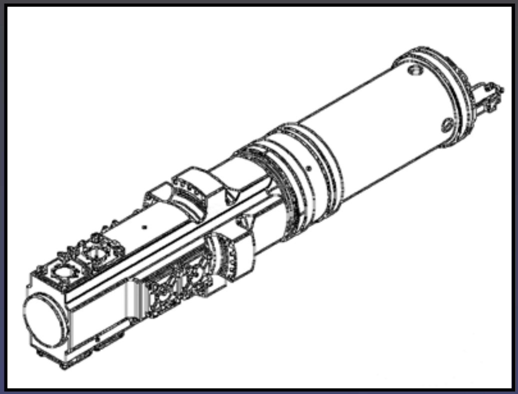
1 marcsec/yr = 3.2 × 10^{-11} deg/hr

1 marcsec ~
width of a human hair seen from 10 miles

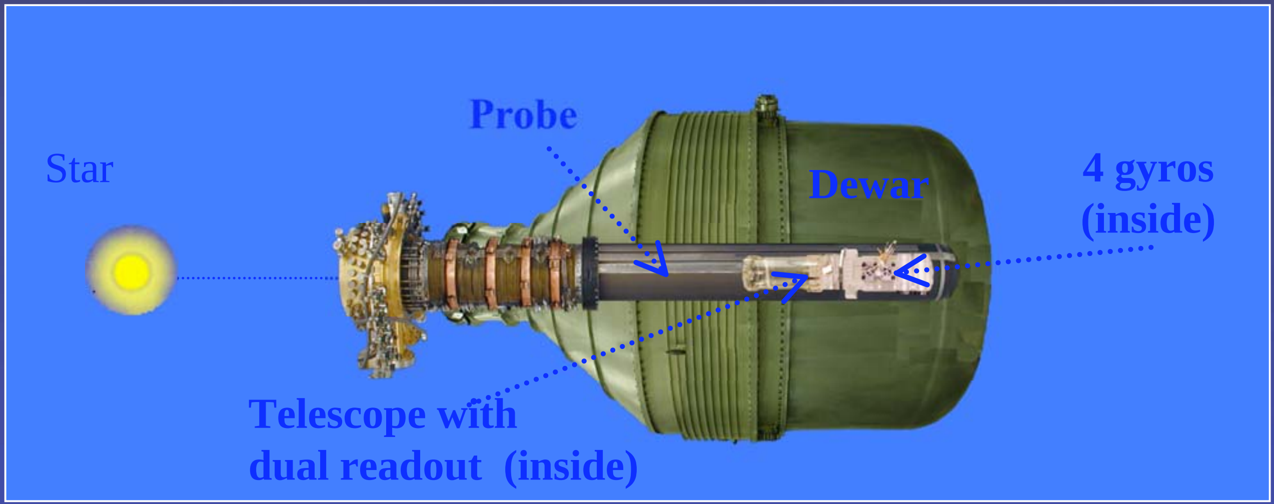
GP-B: The Main Systems

Gyroscope

Telescope

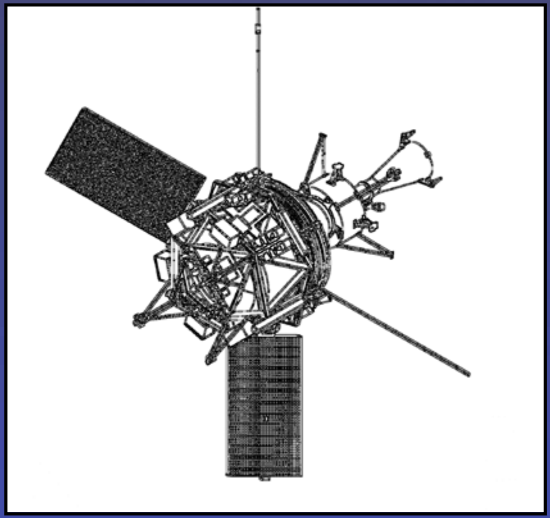


Science Instrument



Cryogenic Probe

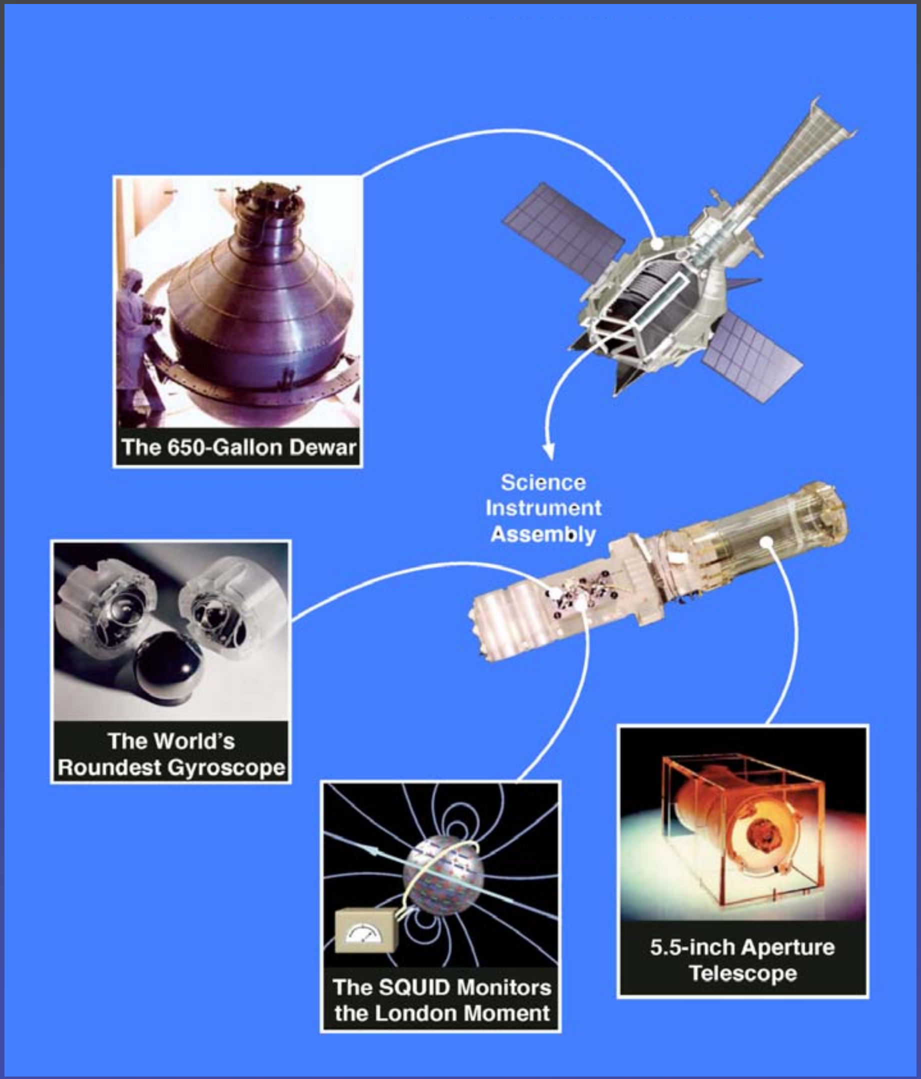
Payload



Space Vehicle

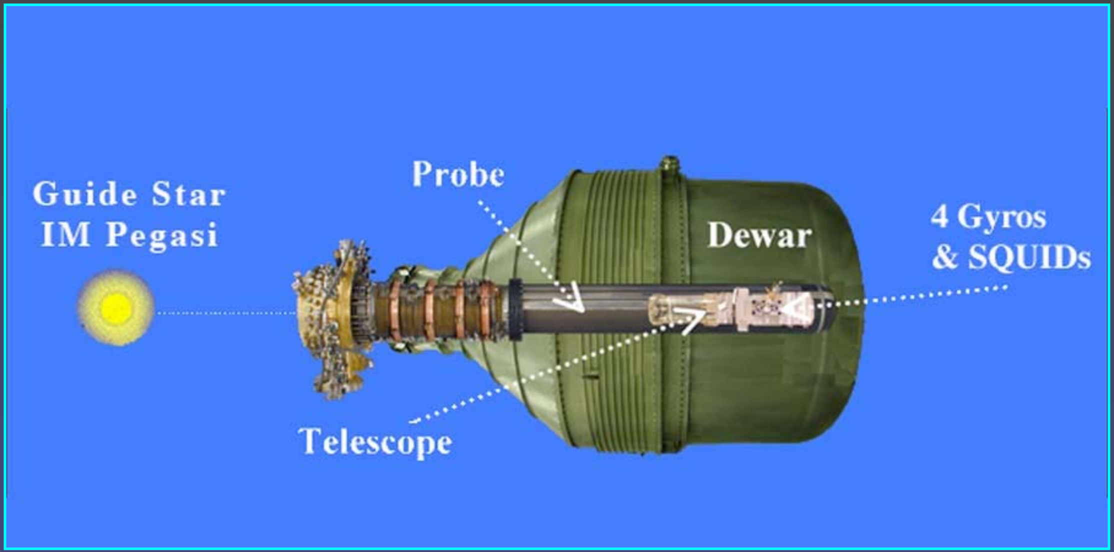
GP-B Experimental Design I

- Gyro suspension system keeps the gyro at the center of the housing by servo-controlled electrostatic forces applied to a set of 6 electrodes
- Gyro is spun up to ~80 Hz with helium gas
- London magnetic moment is aligned with gyro spin axis and measured by superconducting quantum interference device
- Science instrument assembly is placed in a non-magnetic vacuum probe, which is then placed in a dewar filled with superfluid helium



GP-B Experimental Design II

- Spin axes of four gyros are initially aligned with a guide star, IM Pegasi — a reference in inertial space
- A telescope keeps tracking the guide star



- Long term drift in the spin axis orientation of the gyros is measured relative to inertial space
- GP-B spacecraft rolls at a period of 77.5 s and runs in a near-polar, near-circular orbit at an altitude of ~640 km

Dewar and Probe

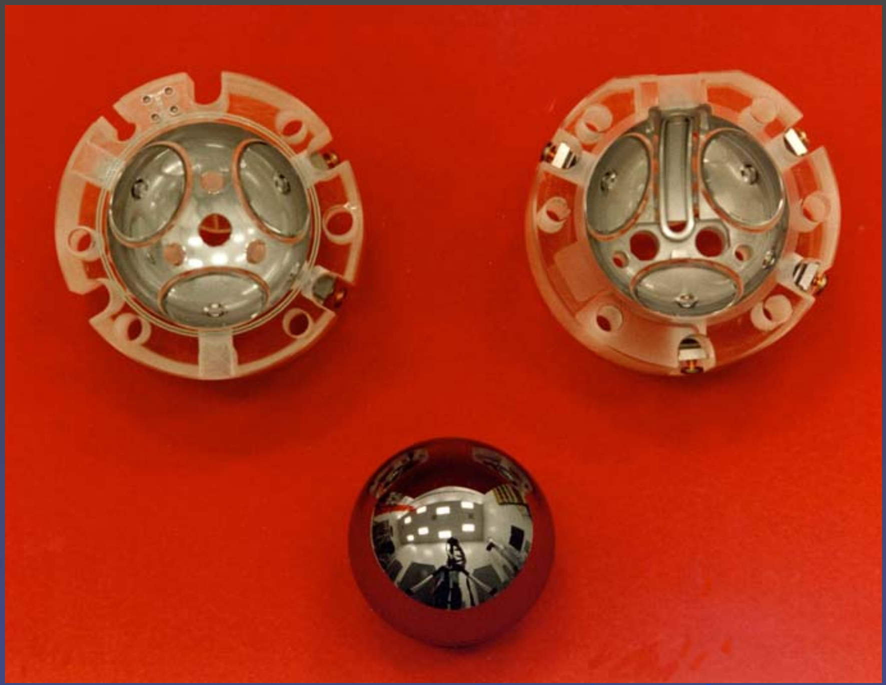
Probe during assembly

- **Dewar boiloff gas used for attitude and translation control of vehicle**
  - ATC back pressure controls dewar temperature.
  - Porous plus phase separator allows Helium gas to flow from dewar.
- **Dewar temperature of 1.82 K keeps science instrument temperature stable.**
- **Lifetime 17.3 months,** 16 month requirement

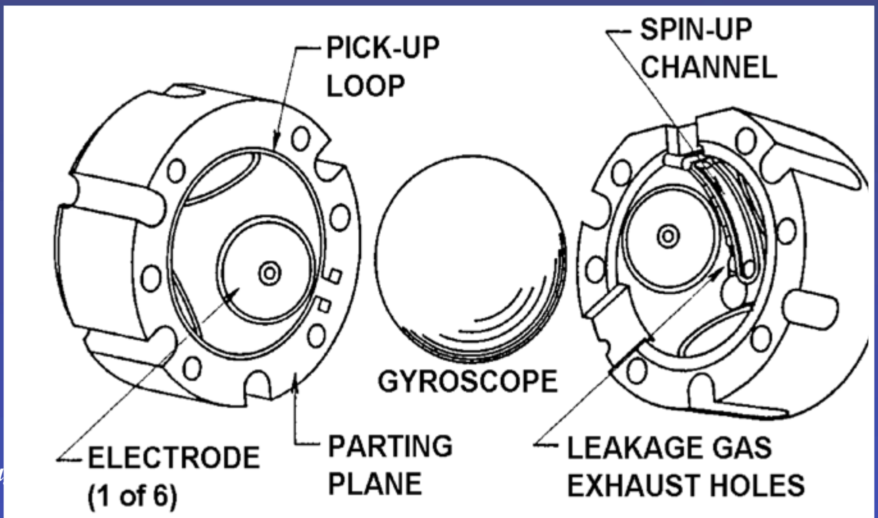

Dewar

- Largest flight dewar: 2524 liters.

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.

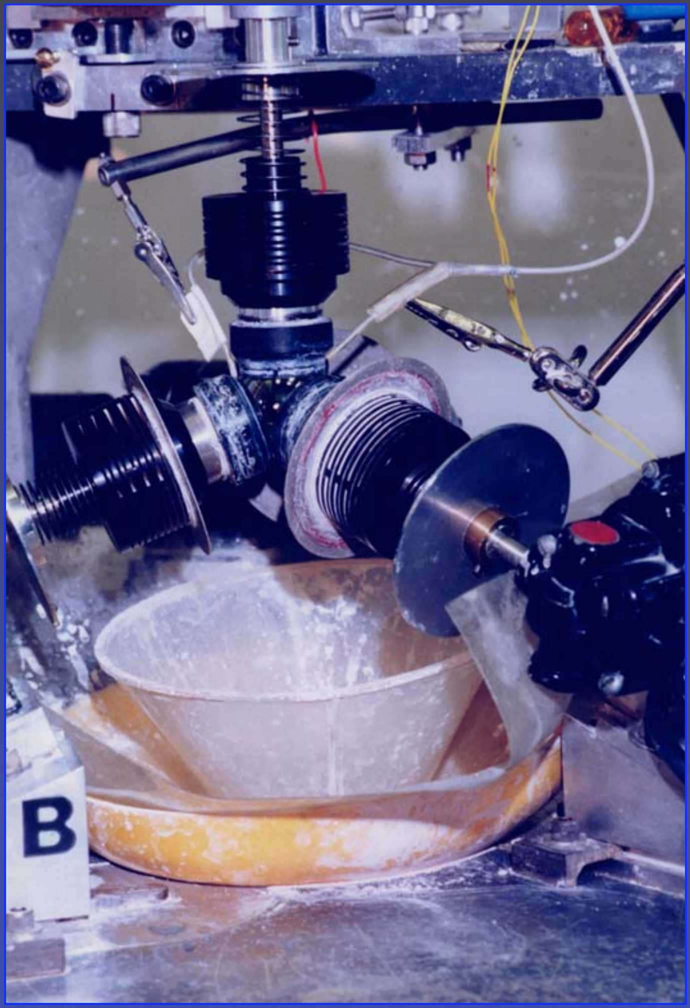
Demonstrated performance:

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

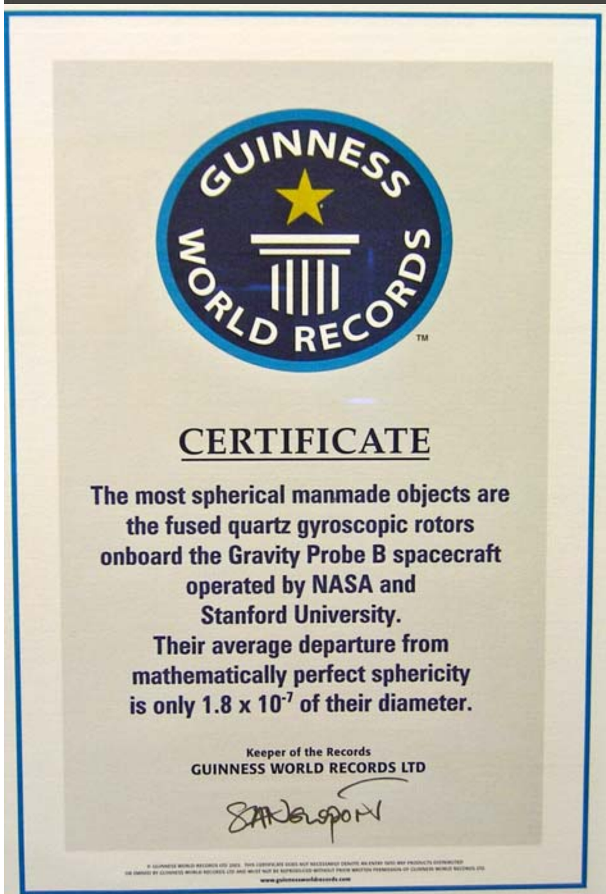
If a GP-B rotor was scaled to the size of the Earth, the largest peak-to-valley elevation change would be only 2 meters!

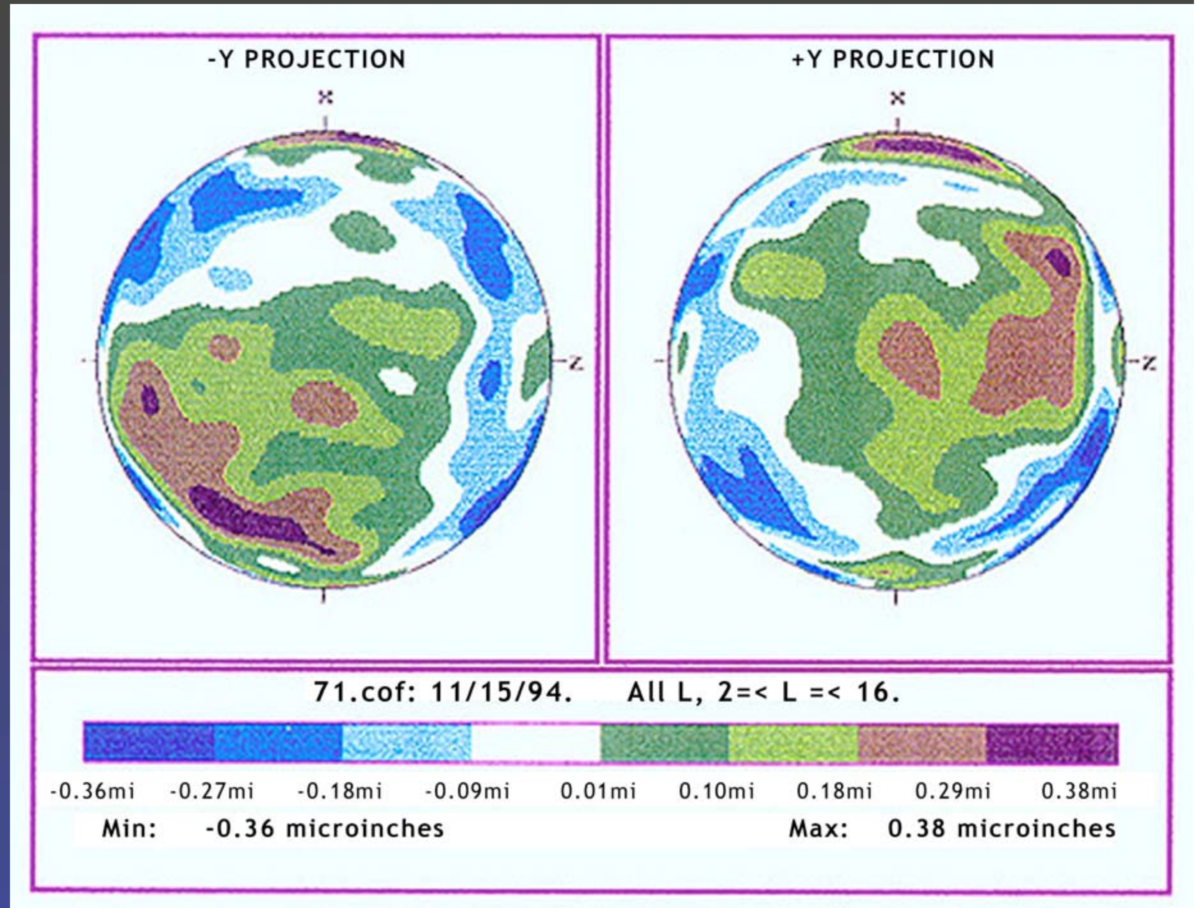
Asphericity: Near Zero – Making

- 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!

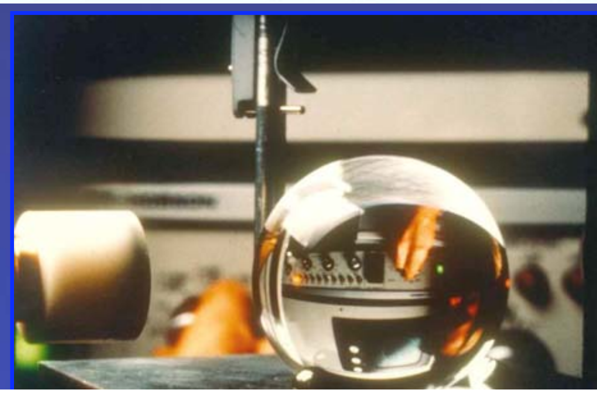


Gyro Asphericity Ground Verification

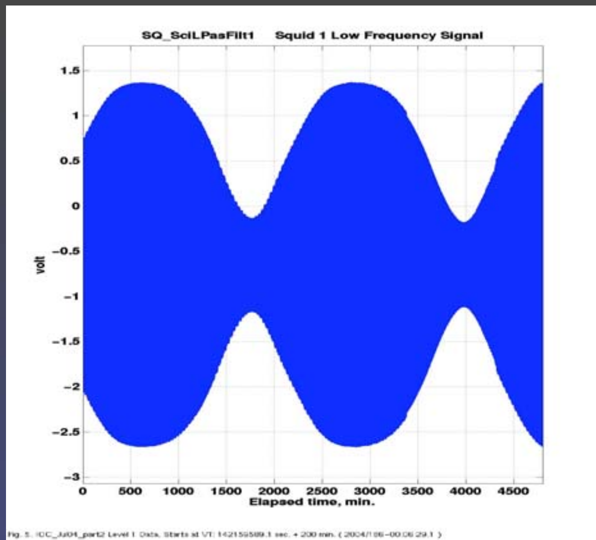




Talyrond sphericity measurement resolution ~1 nm



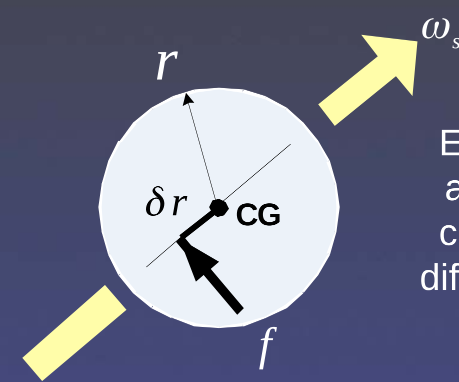
Near Zero: Mass Unbalance $\left(\&\frac{\Delta I}{I}\right)$



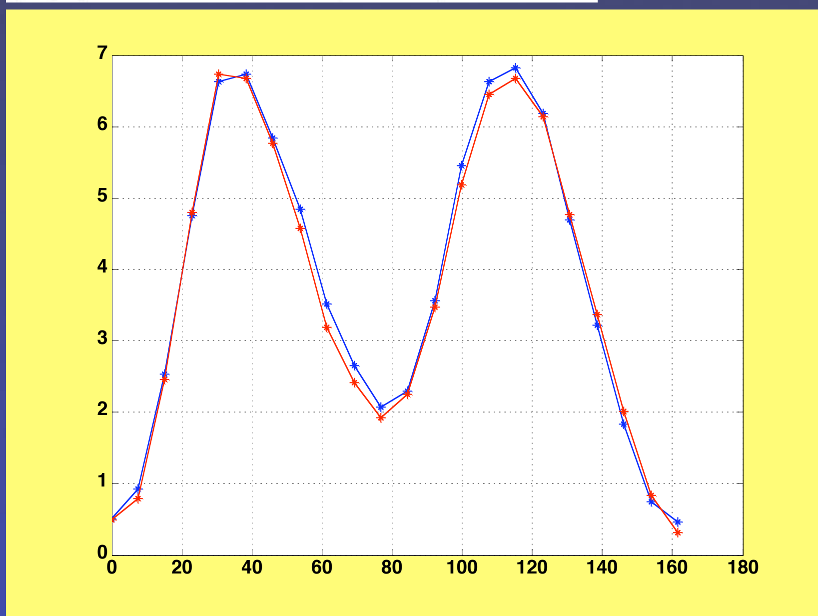
Gyro # 1 @ 3 Hz

36-hour Polhode Period

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



External forces acting through center of force, different than CM



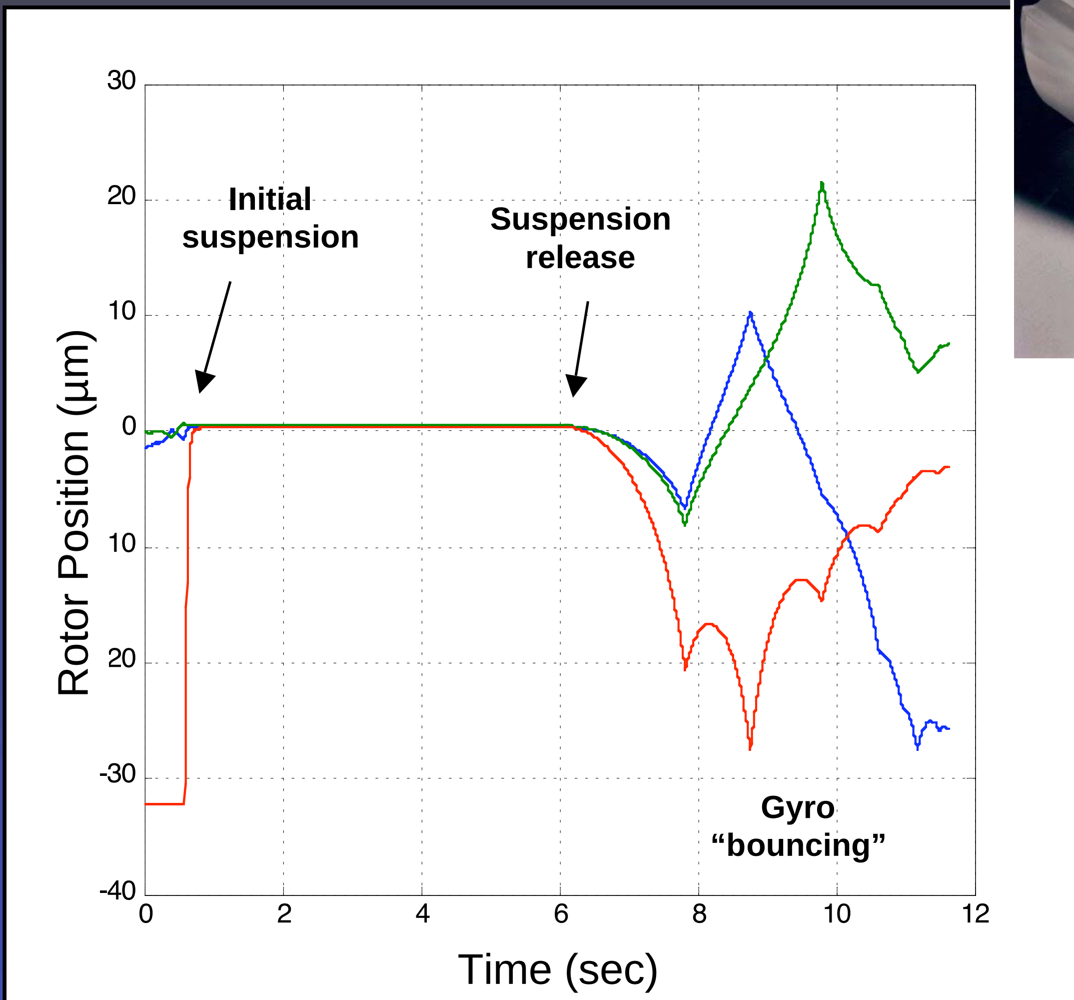
Gyro # 1 @ 79.3858 Hz

Mass Unbalance (nm)

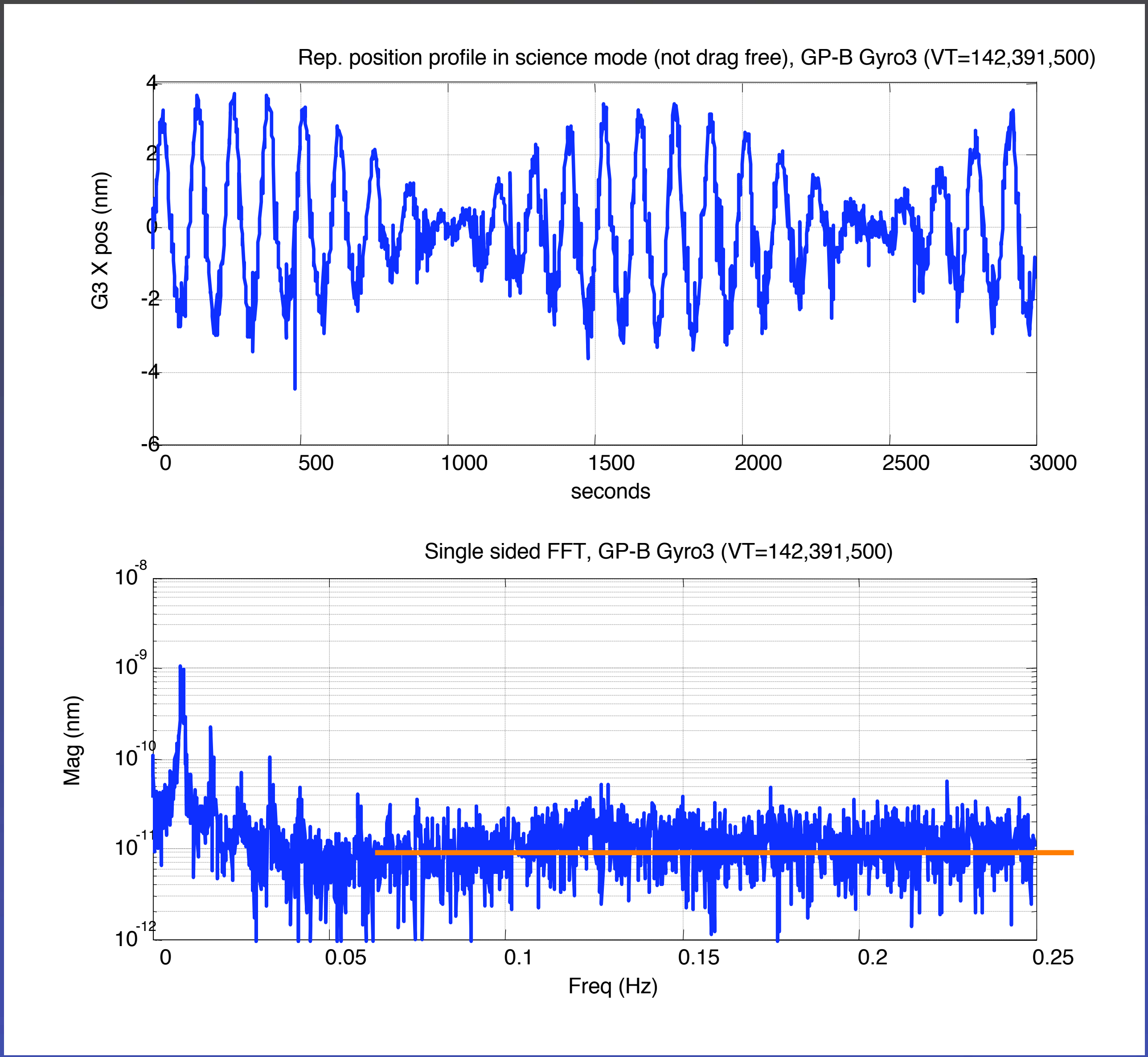
Gyro #	1	2	3	4
Prelaunch estimate	18.8	14.5	16.8	13.5
On-orbit data	6.9	4.4	3.3	6.0

GP-B Gyro On-Orbit Initial Liftoff

Initial Gyro Levitation and De-levitation
using analog backup system



Position Measurement Performance



Representative gyro position trace showing non drag-free gravity gradient effects in Science Mission Mode

Measurement noise 0.45 nm rms

Noise floor

Near-Zero: Ultra-low Pressure
(after spoiling with helium)

Gyro spin-up: He gas at 7K thru channel)

Final spin speeds

Gyro1	79.4 Hz
Gyro2	61.8 Hz
Gyro3	82.1 Hz
Gyro4	64.9 Hz

Gyro spindown periods on-orbit (years)

	before bakeout	after bakeout
Gyro1	~ 50	15,800
Gyro2	~ 40	13,400
Gyro3	~ 40	7,000
Gyro4	~ 40	25,700

2300 yr requirement

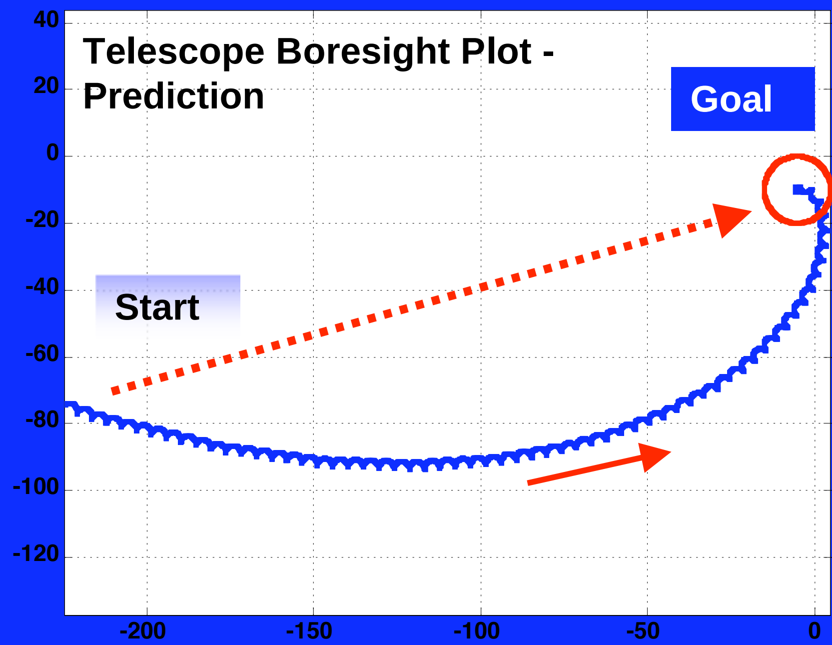
The Cryopump: 230 m^2 area

Demonstrated performance:

Pressure < 2 x 10^{-9} Pa

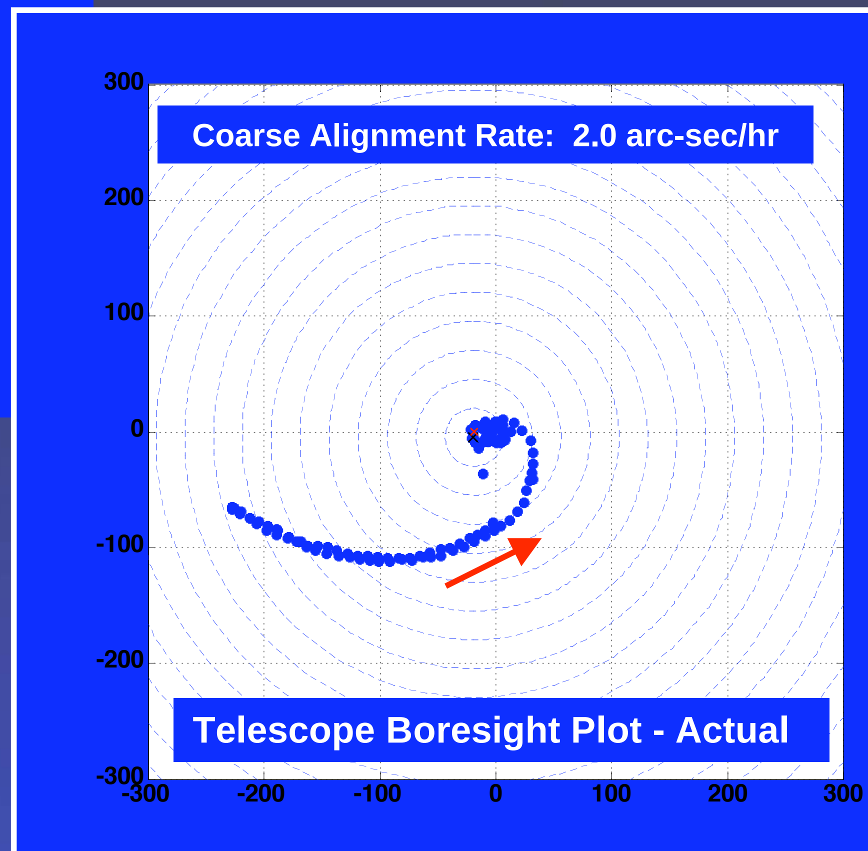
(1.5 x 10^{-11} Torr)

Establishing Initial Conditions: Spin Axis Alignment



- Residual suspension torques on rotor shape used to effect alignment.
- Provides an early calibration of a primary error source – found to be 20% of pre-launch predicts!

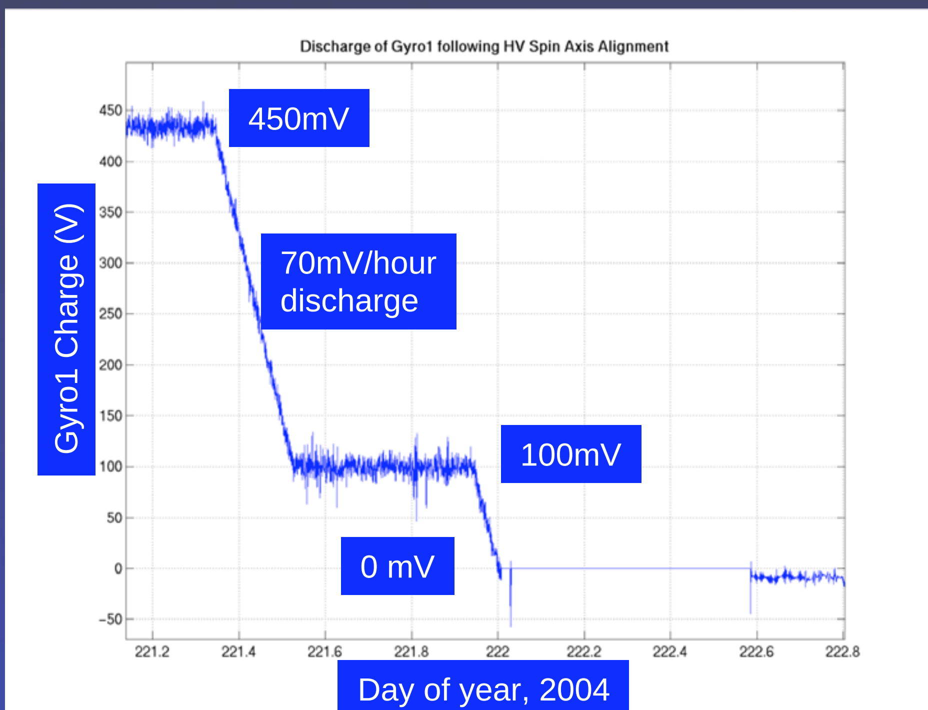
Demonstrated performance: final alignment to within 10 arc-sec of goal.

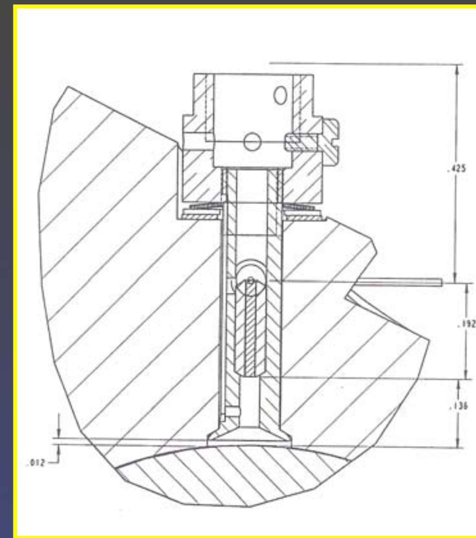


Near-Zero: Rotor Electric Charge

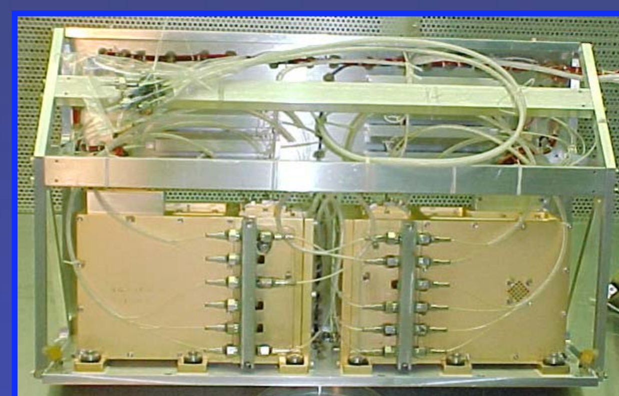
- Rotor charge controlled via UV excited electron exchange with dedicated electrode.
- Charge rates ~ 0.1 mV/day
- Continuous measurement at the 0.1 mV level; control requirement: 15 mV

Discharge of Gyro1



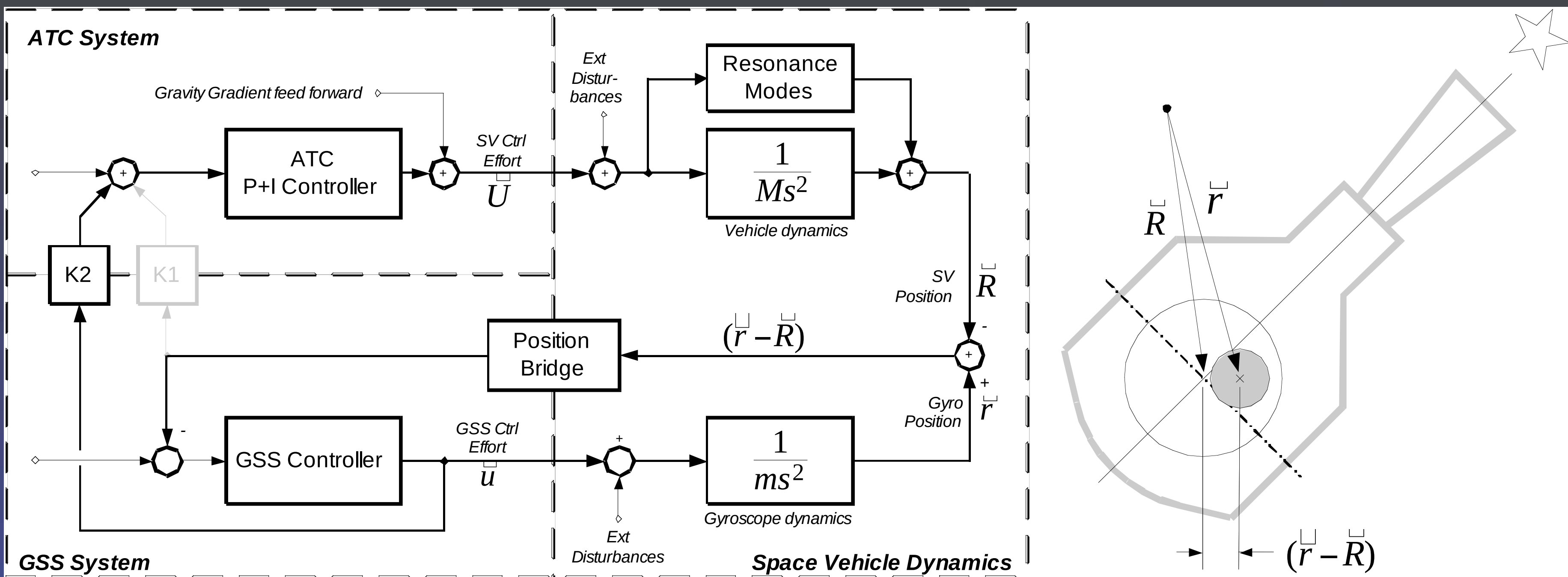


Ti Steering Electrode



UV Lamp Assembly

GP-B Drag-Free & Attitude Control:
A 9 degree of freedom problem

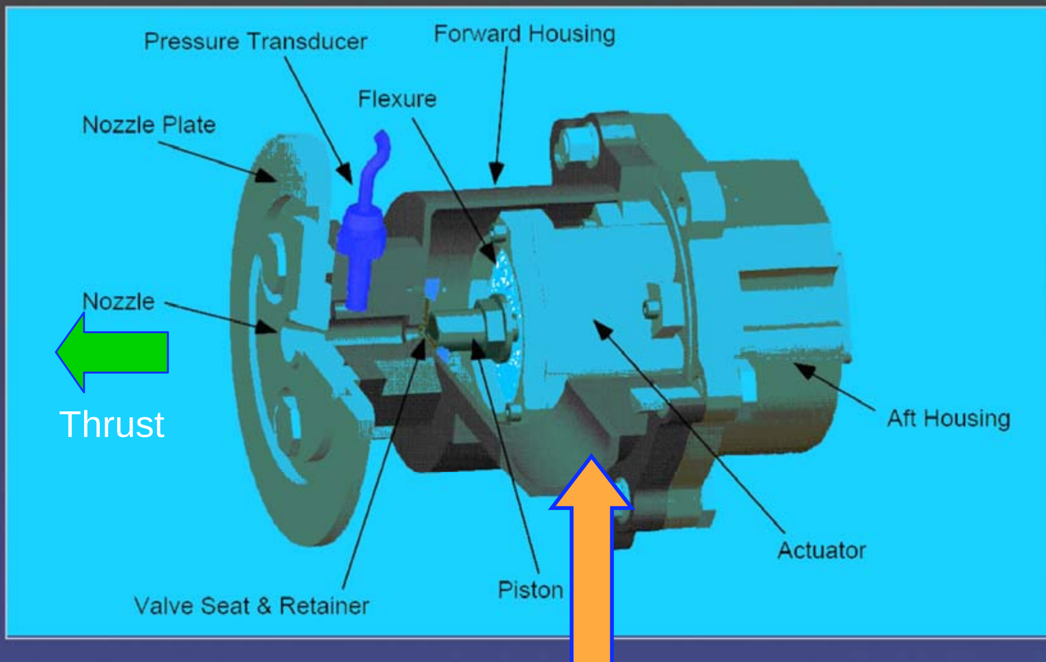


Satellite actively controls 9 interacting DOF:

- 3 in attitude of spacecraft to track guide star & maintain roll phase
- 3 in translation: drag-free about geometric center of gyro housing
- 3 in translation of gyroscope with respect to housing

Dynamics coupling is complex

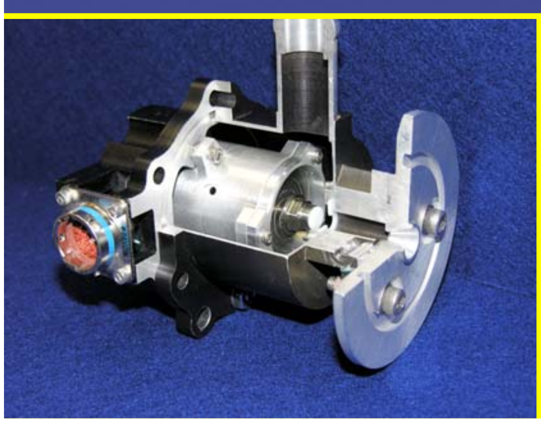
Flight Proportional Thruster Design

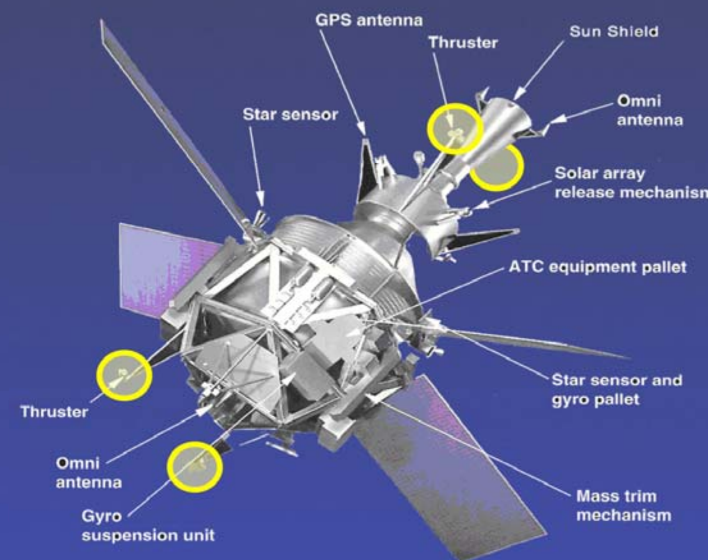


- Thrust: 0 – 10 mN
- I_{SP}: 130 sec
- Mdot: 6-7 mg·s^{-1}
- Noise: 25 μN·Hz$^{-1/2}$
- Operates under choked flow conditions
- Pressure FB makes thrust independent of temperature

Propellant: Helium Dewar Boiloff
Supply: 5 to 17.5 torr

Re ~10 – Laminar flow!



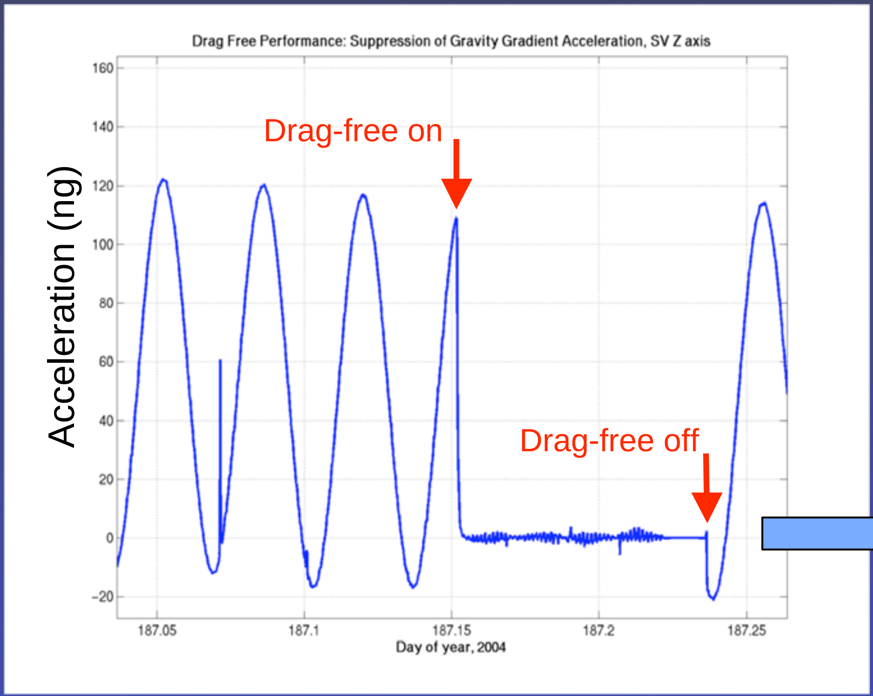


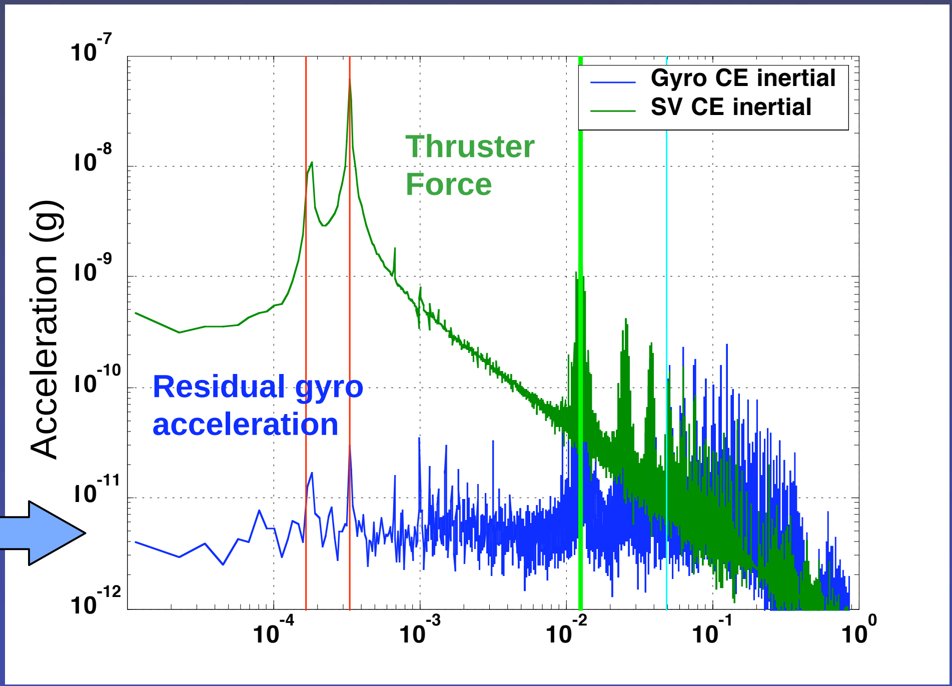
Location of thrusters on Space Vehicle

Drag-Free Control: Near Zero Acceleration Environment

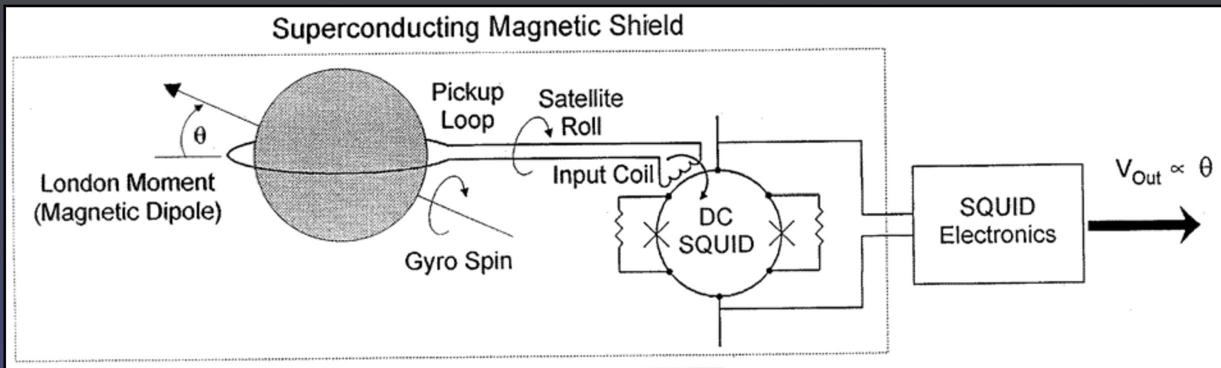
On Orbit Performance -

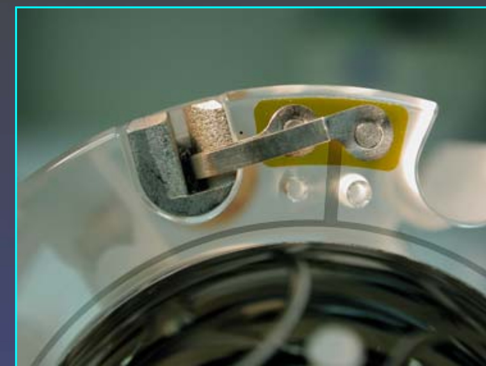
Cross track drag free performance better than 4×10^{-12} g 0.01mHz to 0.1 Hz



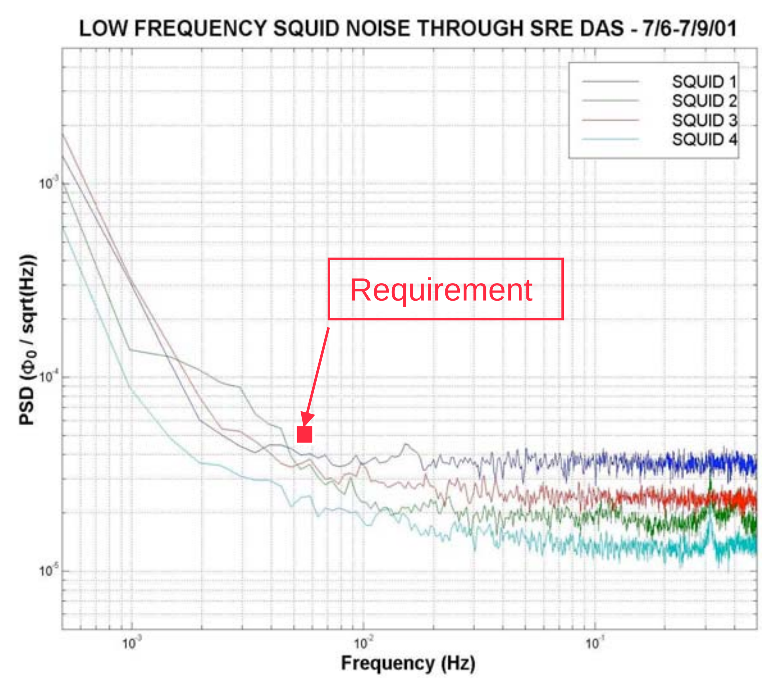


The London Moment Readout





"SQUID" ⟶ 1 marc-s in 5 hours

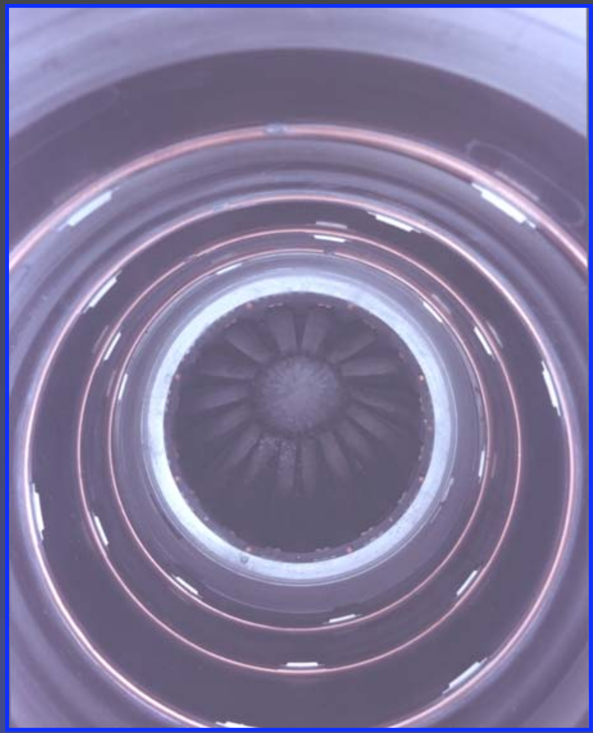


- Centering stability < 50 nm
- DC trapped flux 10^{-6} gauss
- AC shielding > 10^{12}
- 1marcsec ~10^{-13} gauss

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

Near Zero: 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} [=120 dB!] from a combination of cryoperm, lead bag, local superconducting shields & symmetry.**



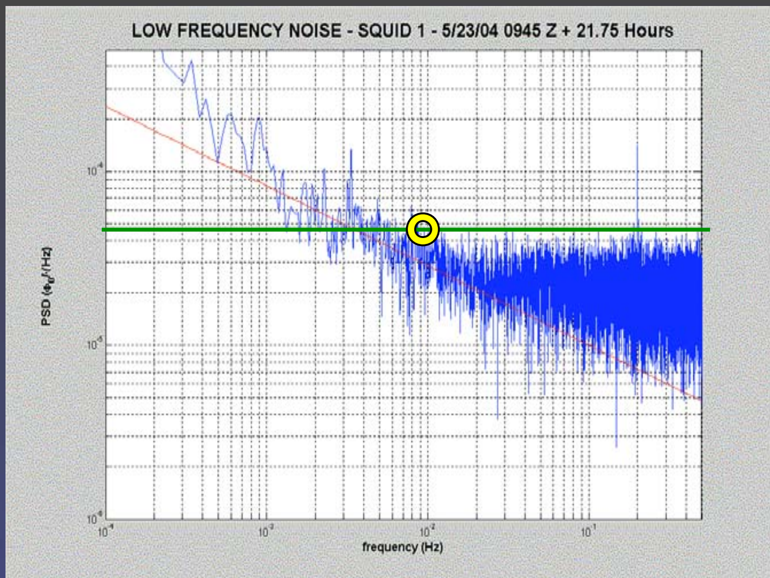
Lead bag in Dewar

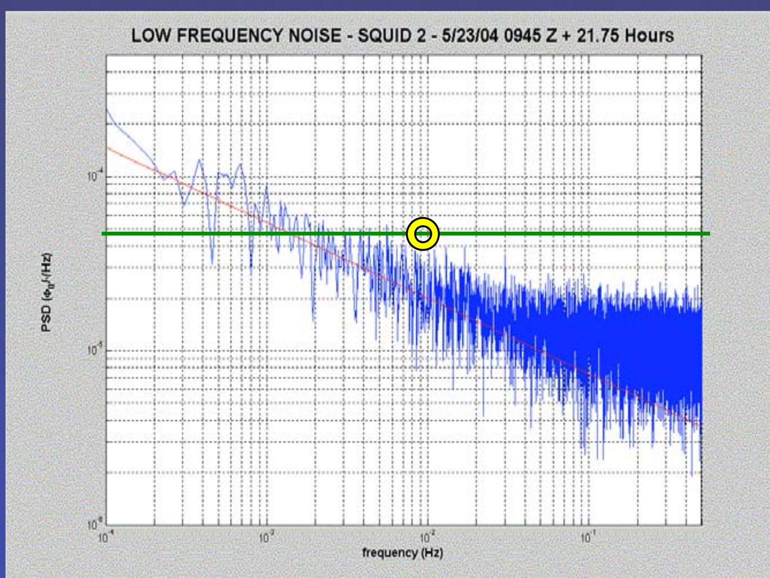
On Orbit Performance Met Requirements

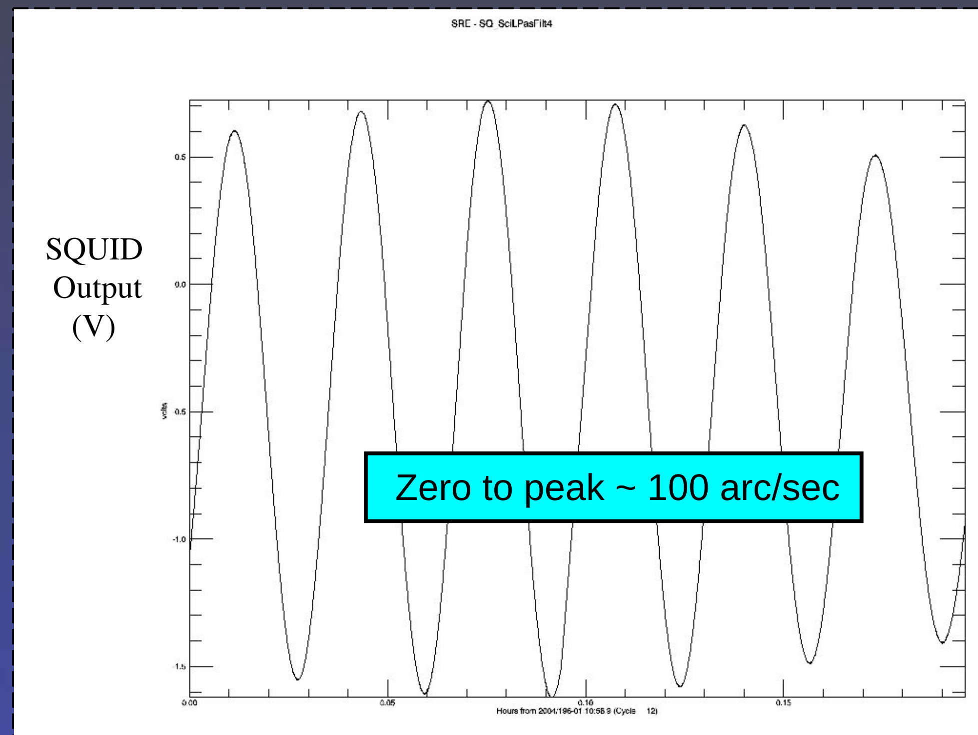
Trapped field:	**Gyro 1**	**3.0 MicroGauss**
	Gyro 2	**1.3 MicroGauss**
	Gyro 3	**0.8 MicroGauss**
	Gyro 4	**0.2 MicroGauss**

Expanded lead bag

Gyro Readout Performance On-Orbit







Guide Star & Telescope

Selection
Proper Motion Measurement
Telescope Design
Tracking Verification

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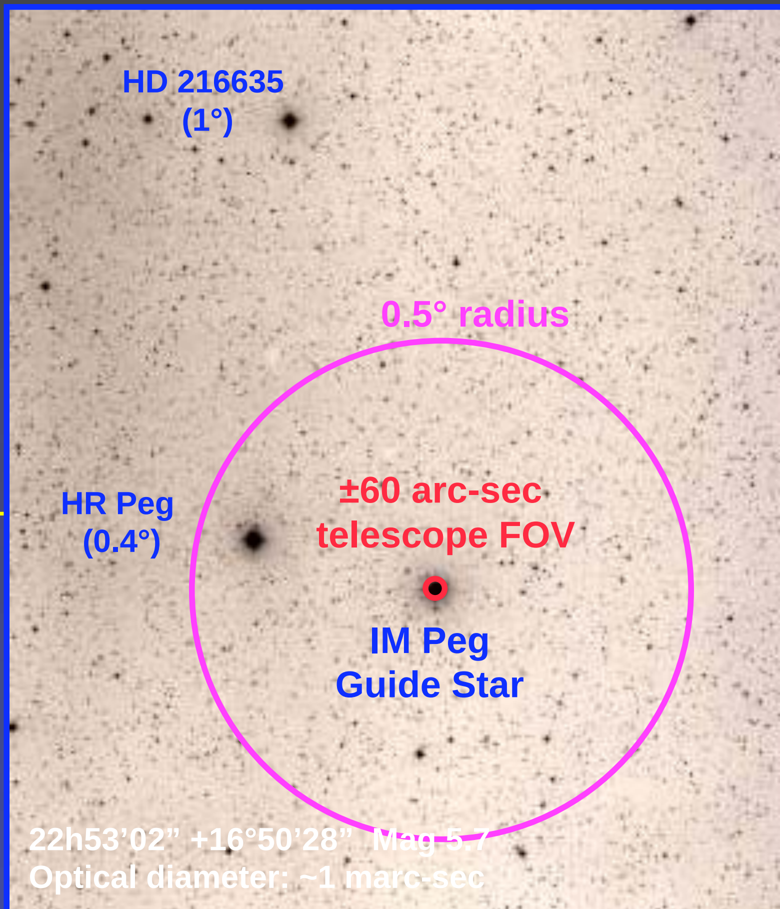
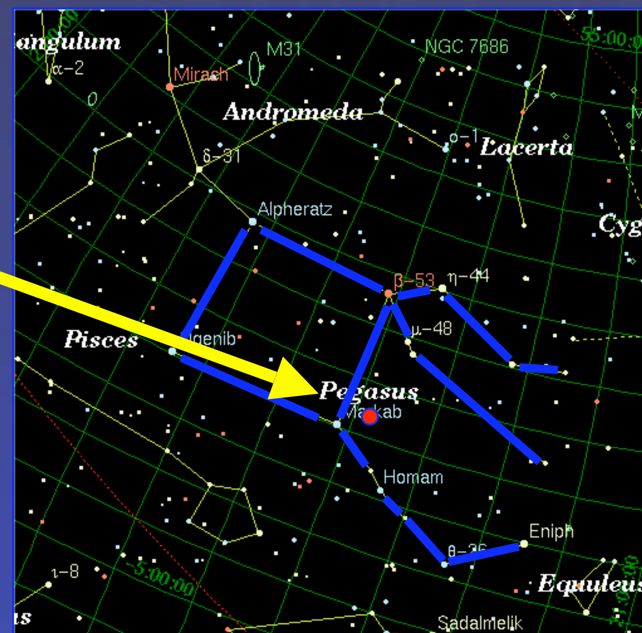
Guide Star Selection

Palomar star map

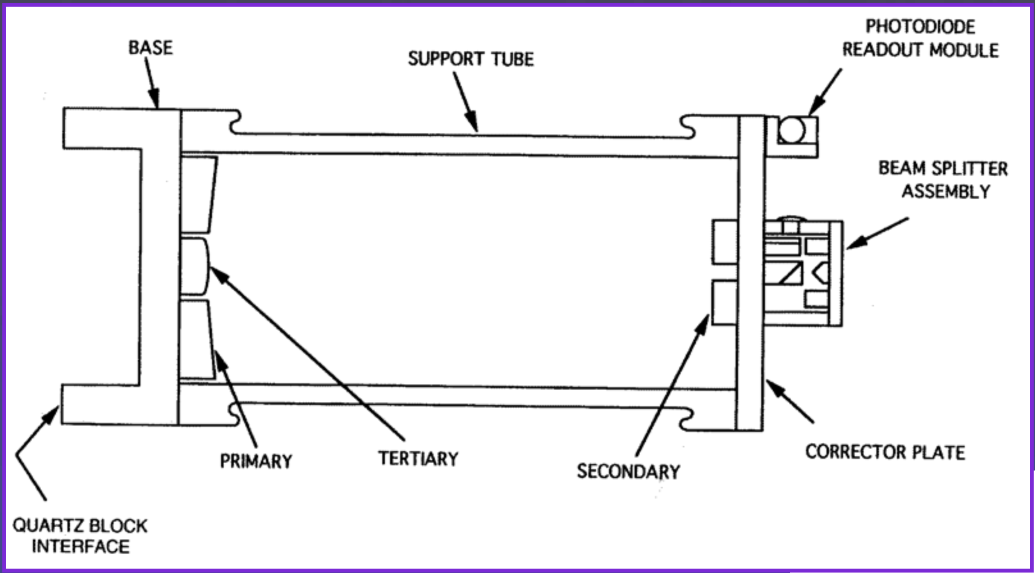


Criteria:

- **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**



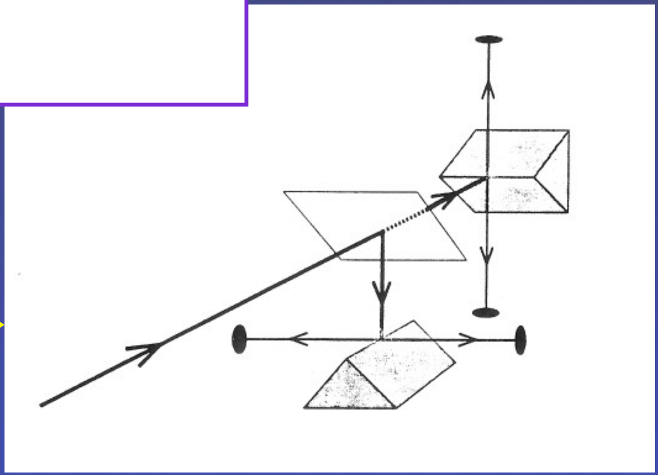
Star Tracker Concept



Some dimensions

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

Beam splitter assembly (detail)



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	<u>At focal plane:</u>	
Focal length	3.81 m	Image diameter	50 µm
Aperture	0.14 m	0.1 marc-s =	0.18 nm

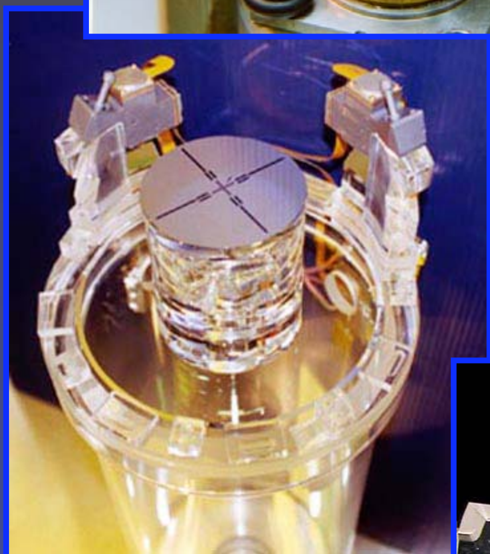
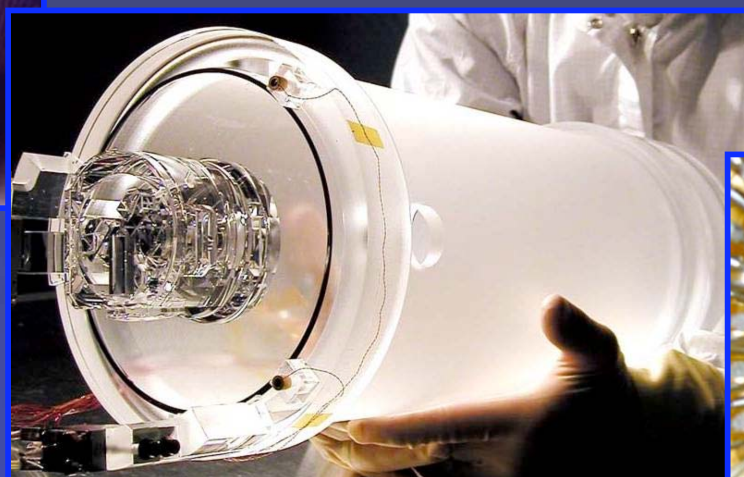


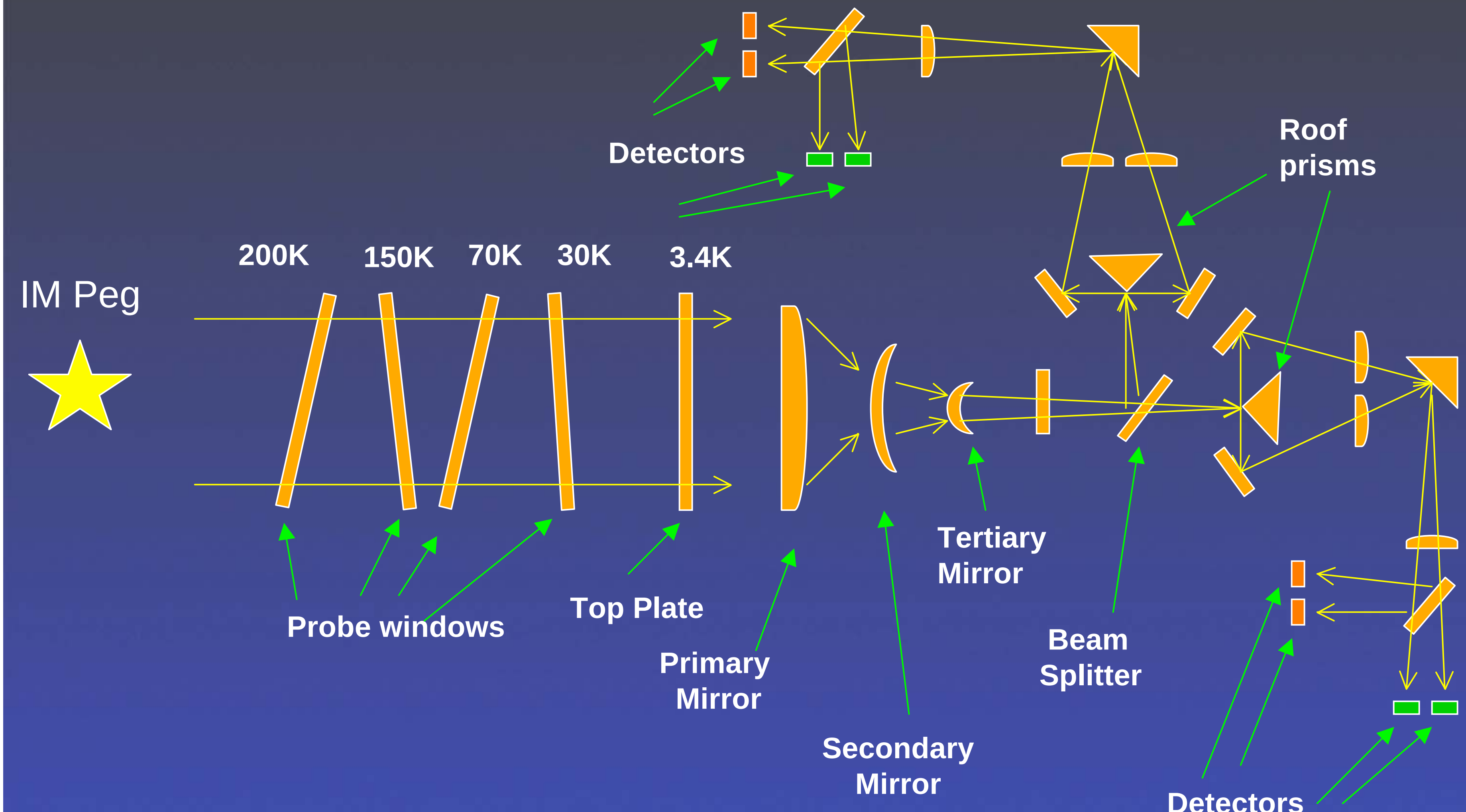
Image divider



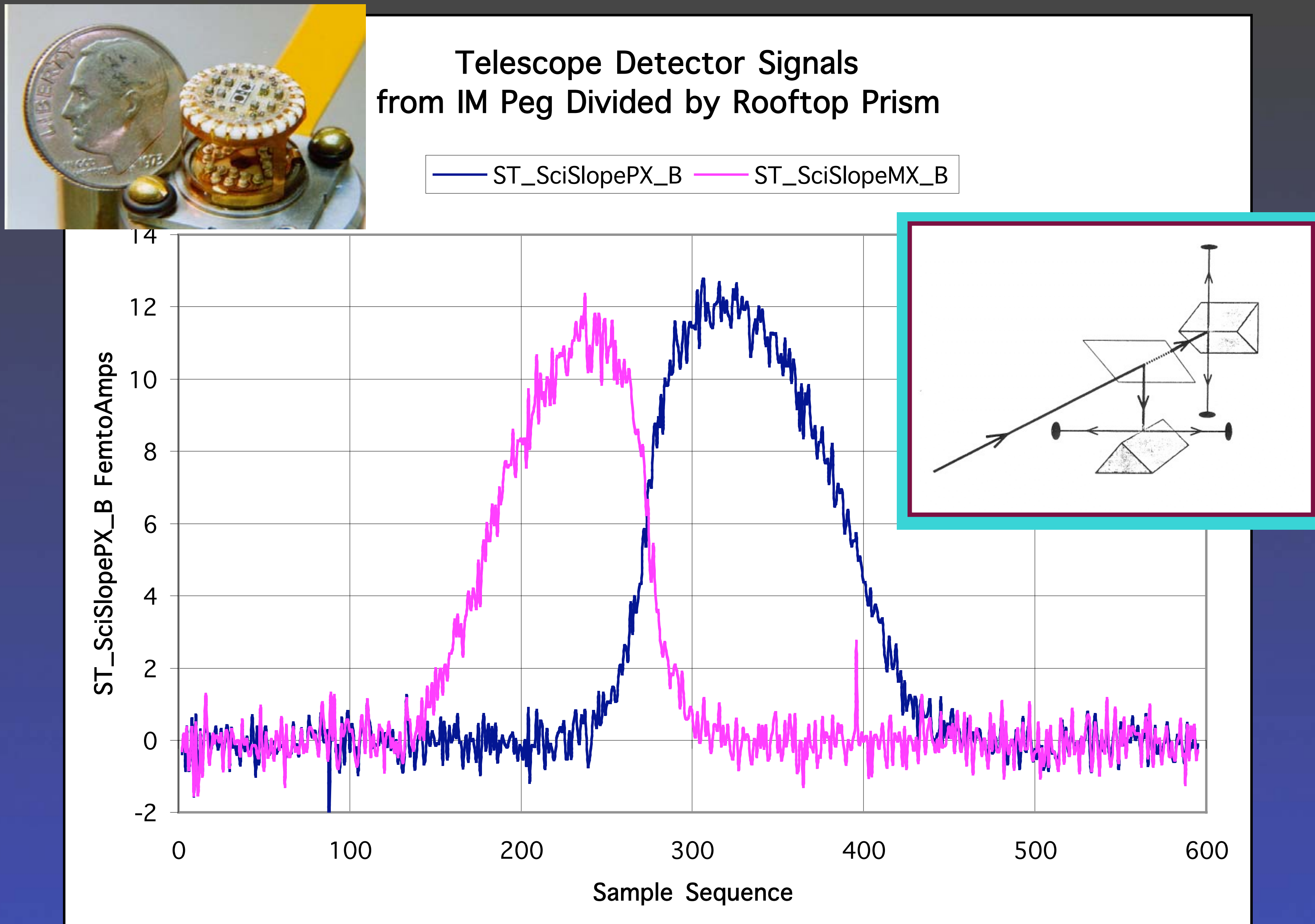
Integrated Telescope

Telescope in Probe

Star Tracking Telescope Optical Path



Star Tracker On-Orbit



Acquiring Star

Drive-in time ~ 110 s

RMS pointing ~ 90 marc-s

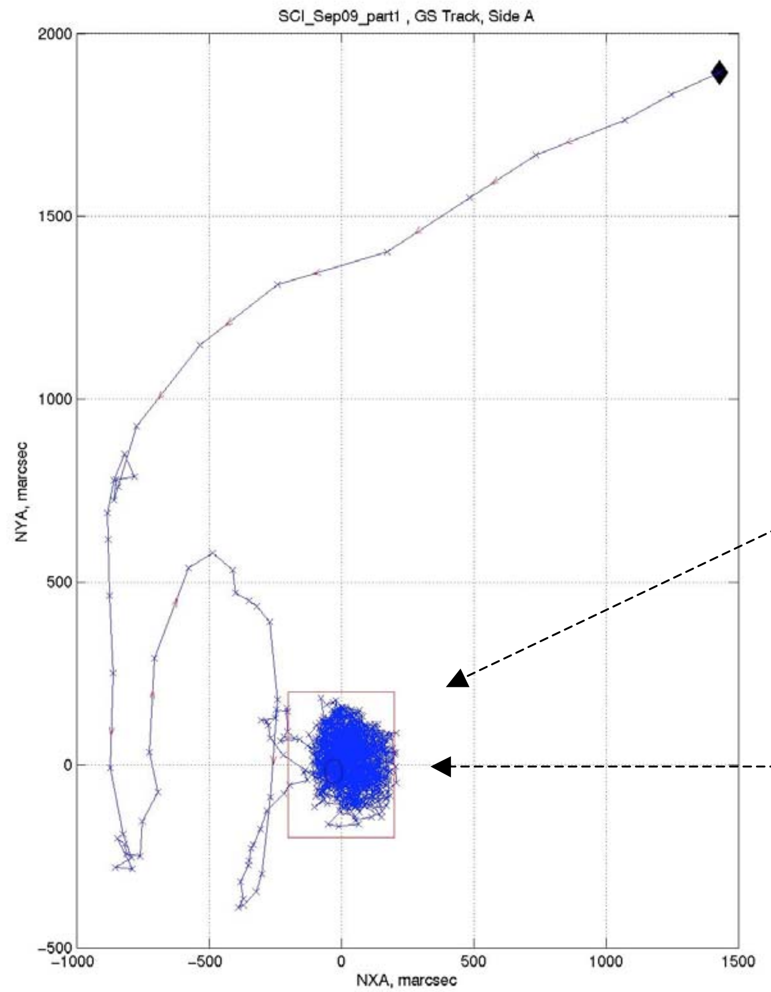
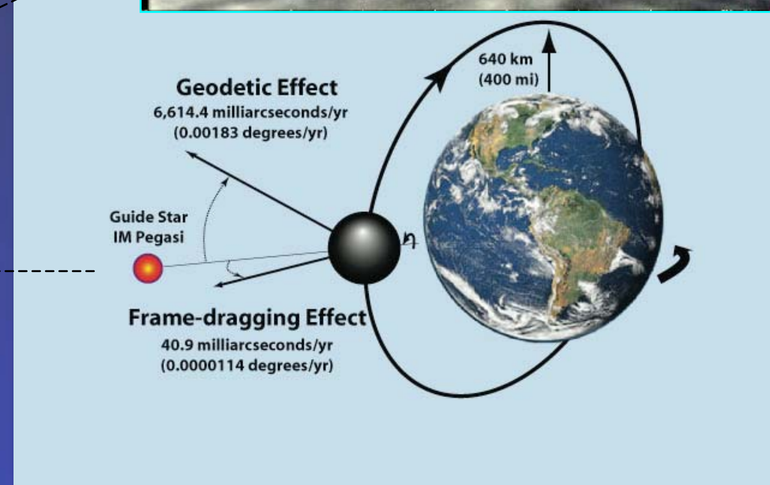
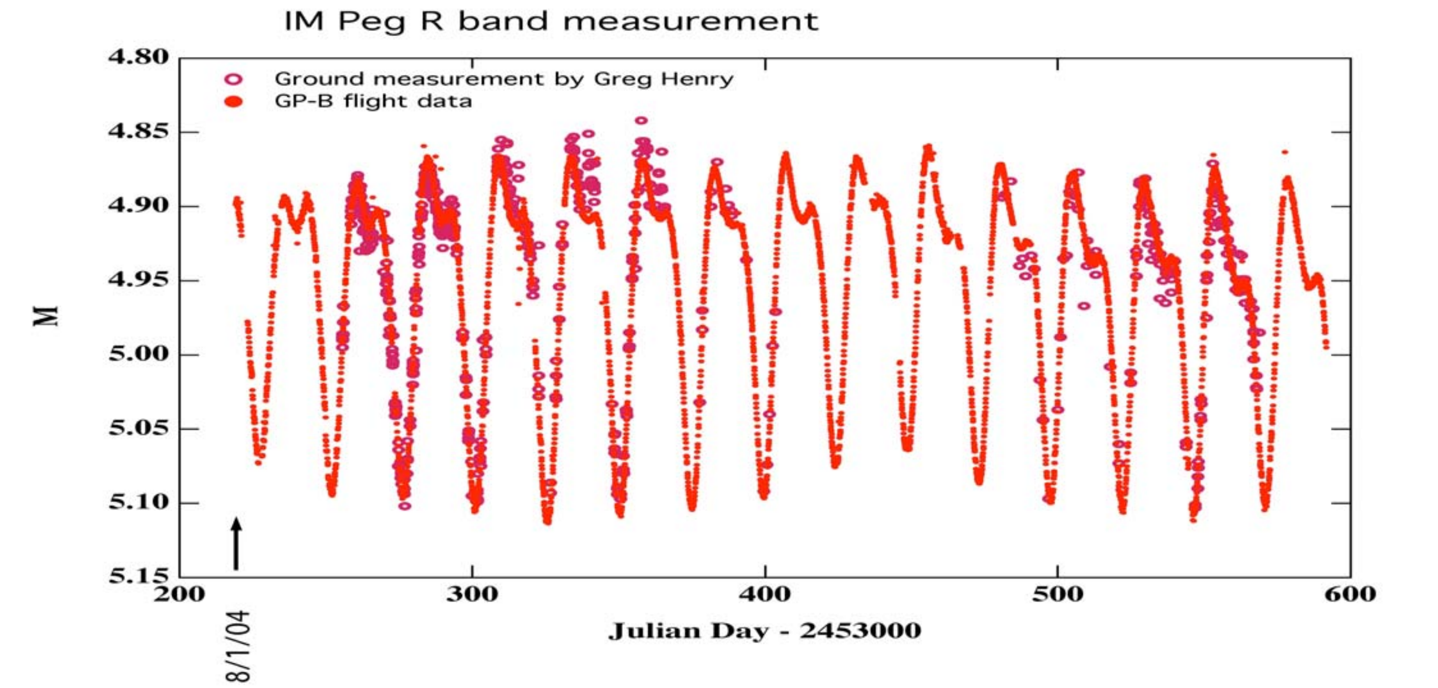


Fig. 705. SCI_Sep09_part1-L2 . GS Track (during GS Valid), Side A Start time: 148031616 sec. Total: 54.0 min



Guide Star Verification



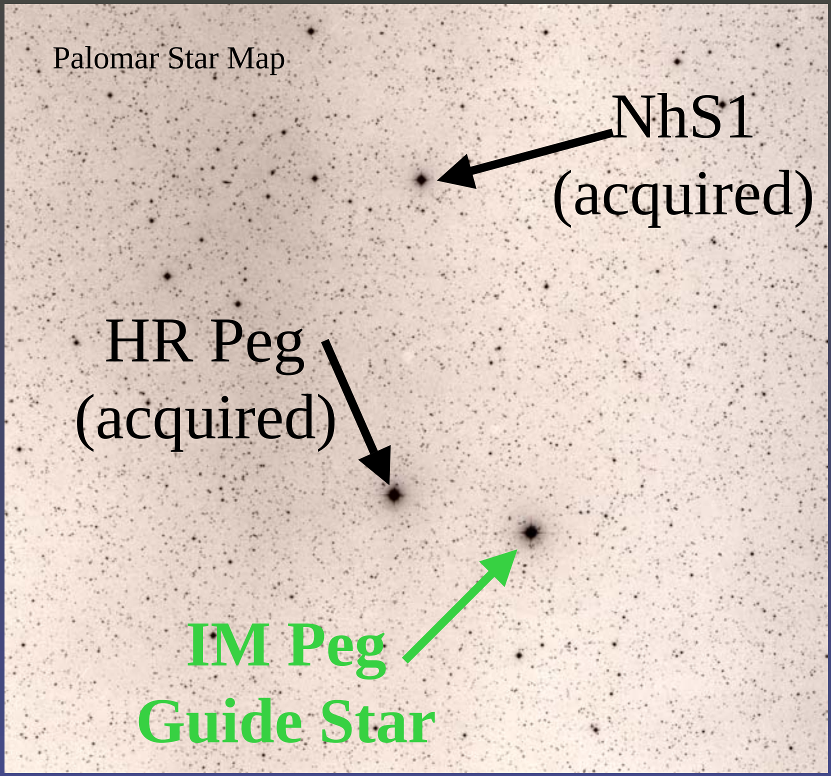
Comparison of ground and flight photometry

Acquisition of proper star verified by:

- Neighbor star visits
- Photometry comparisons with ground based measurements

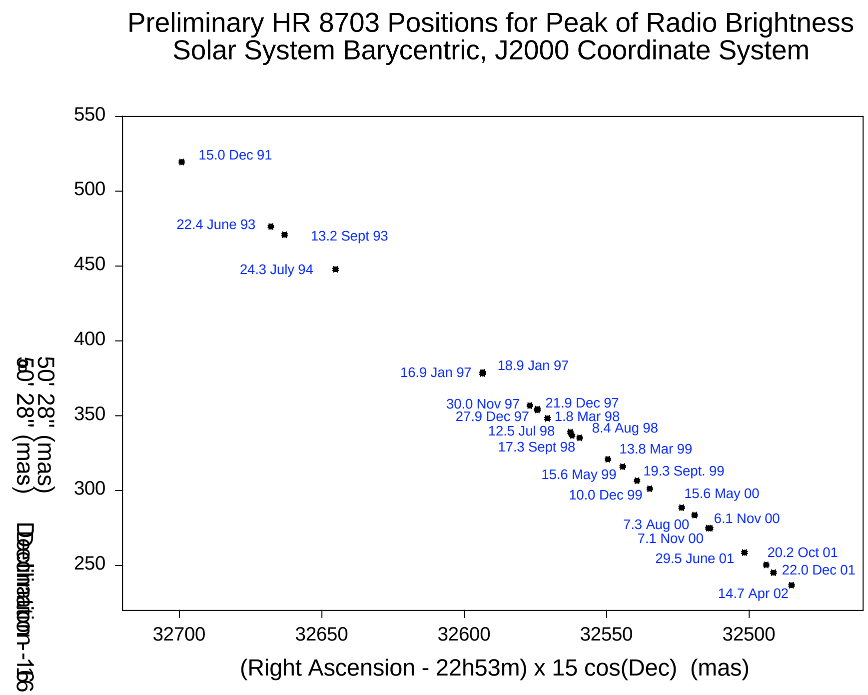
Over 1 year of observations, IM Peg has become one of the most observed stars in the heavens

IM Peg (HR 8703) Guide Star Identification



Very Large Array, Socorro, New Mexico

- Optical & radio binary star
- Magnitude - 5.7 (variable)
- Declination - 16.84 deg
- Proper motion measured by SAO using VLBI



On-Orbit: GP-B Mission Operations

Anomaly Room

Mission Operations Center

GP-B Communications, Commands, and Telemetry

GP-B science signal 12.9 mHz

- **TDRSS Network**
  - 20-40 minutes/contact
  - ~12 contacts per day
  - 1-2 Kbits/sec data rate
- **Ground Stations**
  - 10-12 minutes/contact
  - 4 contacts per day
  - 32 Kbits/sec data rate
- **1.5 Tbytes/year**

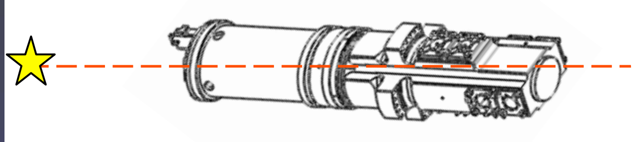
TDRSS Satellite

GP-B Satellite

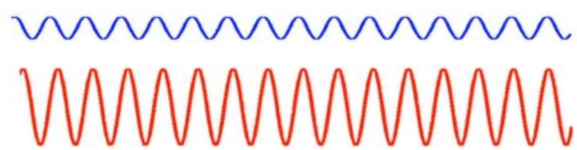
Ground Station

Dither & Aberration: Two Useful Tools

Dither -- Slow 30 marc-s oscillations injected into pointing system

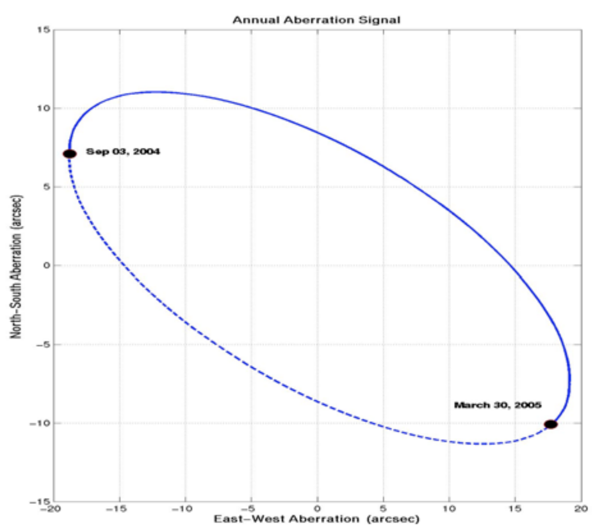


{ gyro output
telescope output



scale factors matched for accurate subtraction

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



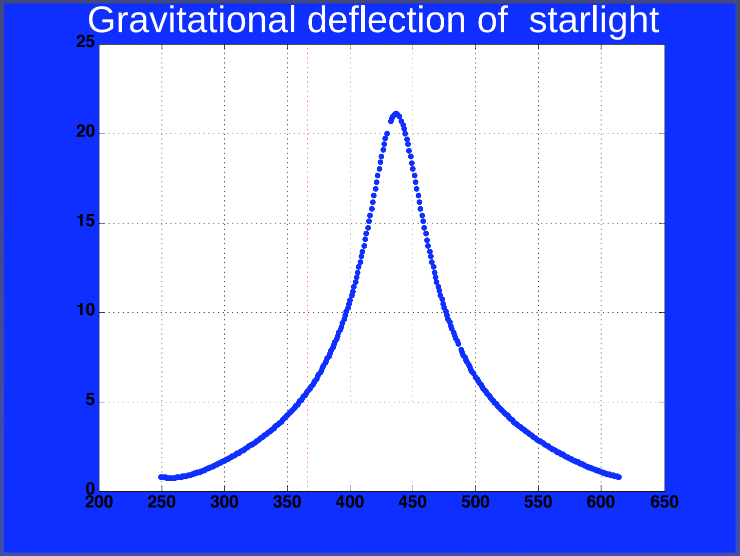
Orbital motion → varying apparent position of star
(v_{orbit}/c + special relativity correction)

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

Built-In Checks

- 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.**



Closest approach 16 degrees

The GP-B Mission Timeline

A. Initial orbit checkout (121 days) Completed Aug. 2004

- ATC setup
- Gyro spin-up
- Re-verification of ground calibrations [scale factors, tempco's etc.]
- Disturbance measurements on gyros at low spin speed
- ~10000 separate commands, virtual 24 hour contact thru GSN and TDRSS

B. Science Phase (350 days) Completed Aug. 2005

- Exploiting the built-in checks
- Completed approximately July 2005

C. Post-experiment tests (56 days) Completed Sept. 29 2005

- Refined calibrations through deliberate enhancement of disturbances, etc.

The Final Phase of the GP-B Mission

- **Data Ground Analysis**
  - Anticipated completion April 2007
  - ~ 1.5 Terabyte sof data
    - ~ 700 sensors
    - ~ 10,000 monitors
    - Nominal data rate: 0.1-1 Hz
    - Snapshots: 220-2200 Hz
  - > 99% data recovery

- **Data release on COBE/WMAP model**
  - All data released to public coinciding with publication of refereed papers