GREX 2004
Nice 28-30 octobre 2004

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with support from Rodney Torii
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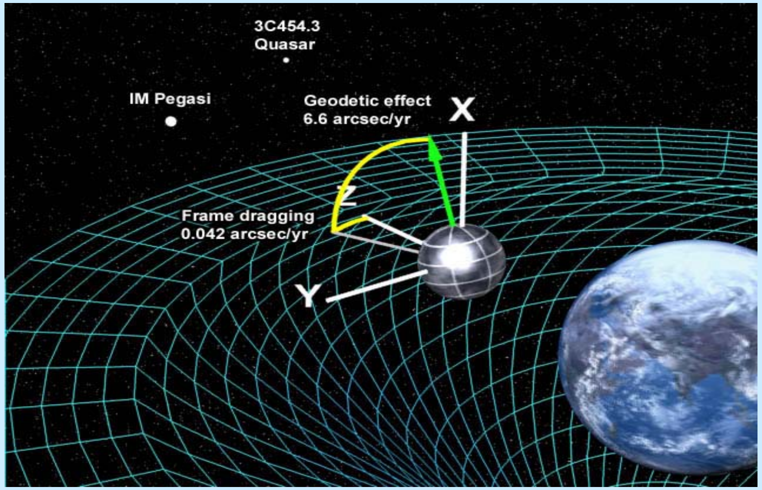
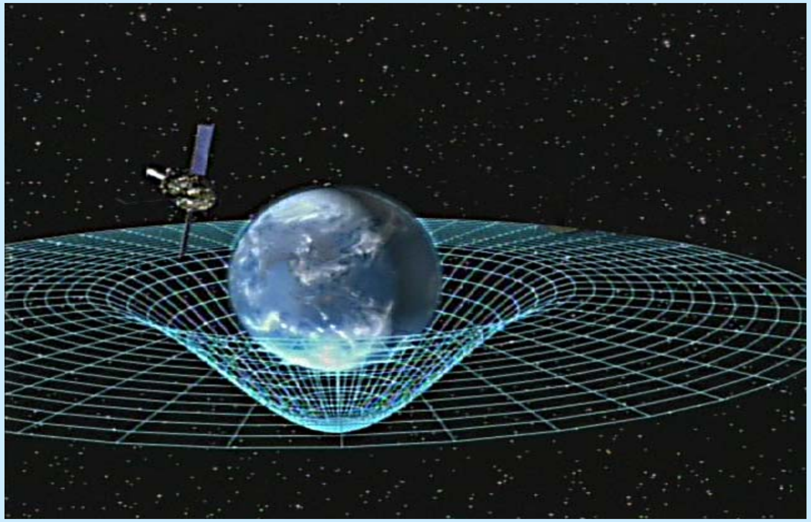


Gravity probe B
Mission present status



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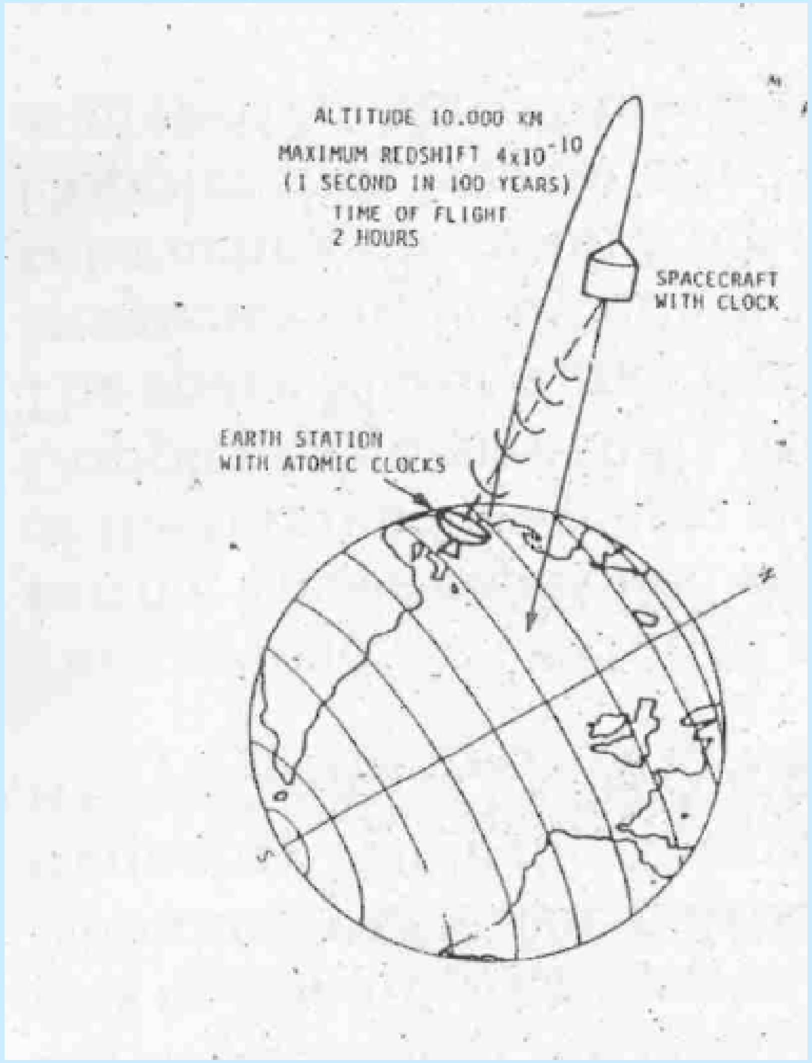
Precision Clocks in Space and GPA H-maser (1976)

- **Gravity Probe A (1976)**

Vessot *et al, PRL 45, 2081 (1980)*

  - ***Comparison of two clocks at different gravity potential***
  - ***on ground and on board a rocket with parabolic trajectory (10 000 km max. altitude)***
  - ***redshift of $4x10^{-10}$ measured with a 10^{-14} clock frequency stability***
  - ***70 ppm confirmation of combined redshift and 2nd order Doppler***



- **ACES/PHARAO (ISS : 2008 ? Or other S/C : ?)**

expected accuracy : 25 better

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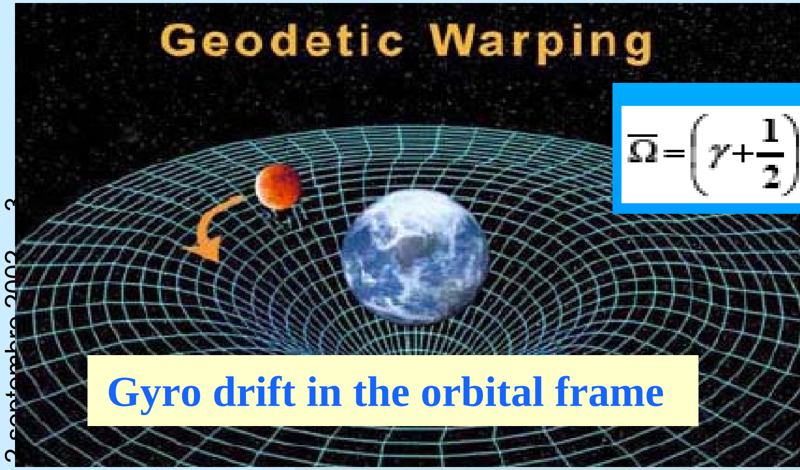
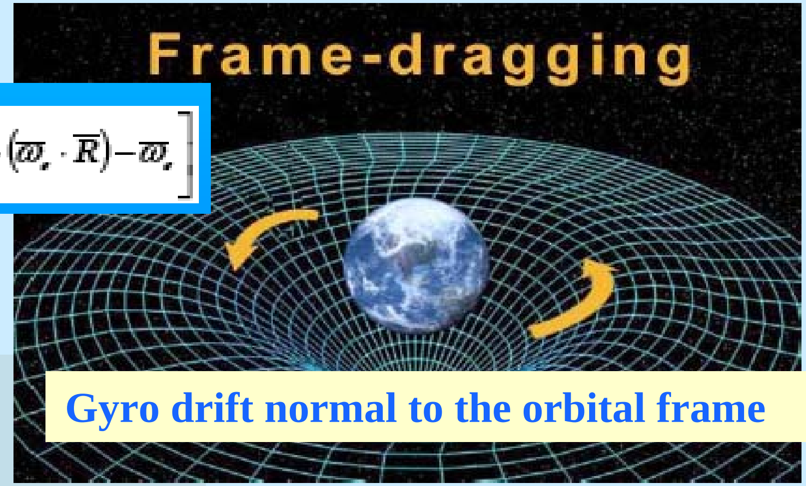
GRAVITY PROBE B SCIENTIFIC OBJECTIVES

Earth gravity field as a curvature of space time



Gyro drift in the orbital frame

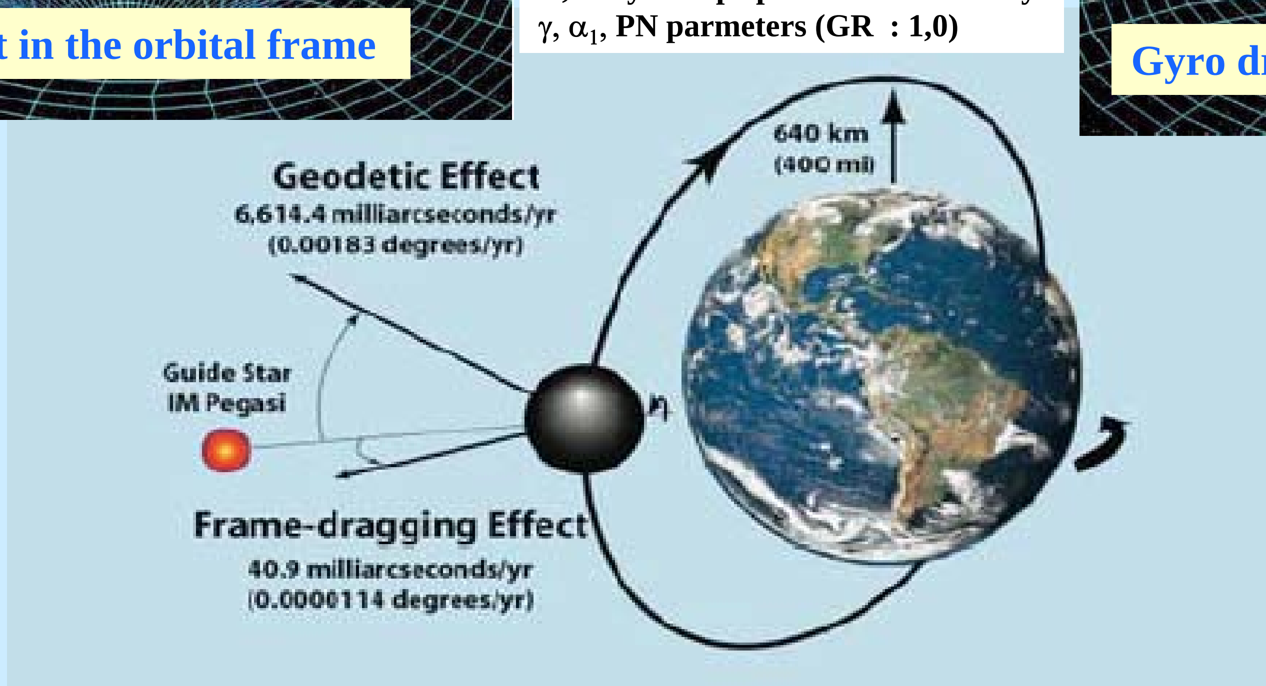
Earth rotation drags local space time



Gyro drift normal to the orbital frame

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

I, M, ω Earth Inertia, Mass, angular velocity
R, v Gyroscope position and velocity
γ, α_1, PN parmeters (GR : 1,0)



Gravito-magnetic effect

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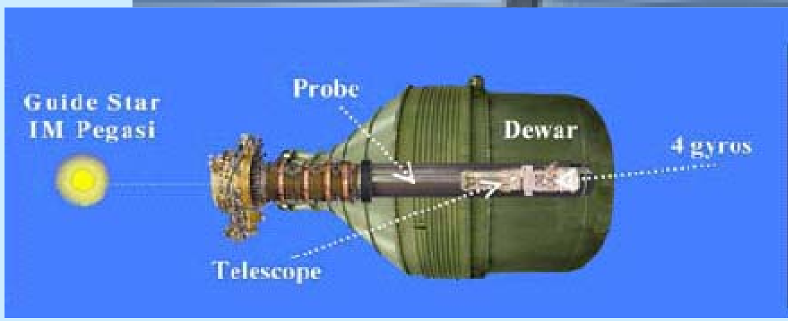
In orbit configuration



Circular Polar Orbit :

- Altitude : 640 km
- Eccentricity : 1-2 10^{-3}
- Inclination : 90.007 °

18 months operation
(16 months present evaluation)

1 telescope
4 gyros (0.3 marcsec/year resolution)
1 GPS receiver
Mass trim mechanism
12 thrusters

Needs of :
•Star reference frame
•Ultra-sensitive gyros
•No disturbation
•Integration of the signal

CONTROLLED SPACE ENVIRONMENT
with drag-free satellite orbit
and cryogenic experiment :

- ***magnetic shielding***
- ***squid rotation detection***
- ***low thermal noise***
- ***He thrust***

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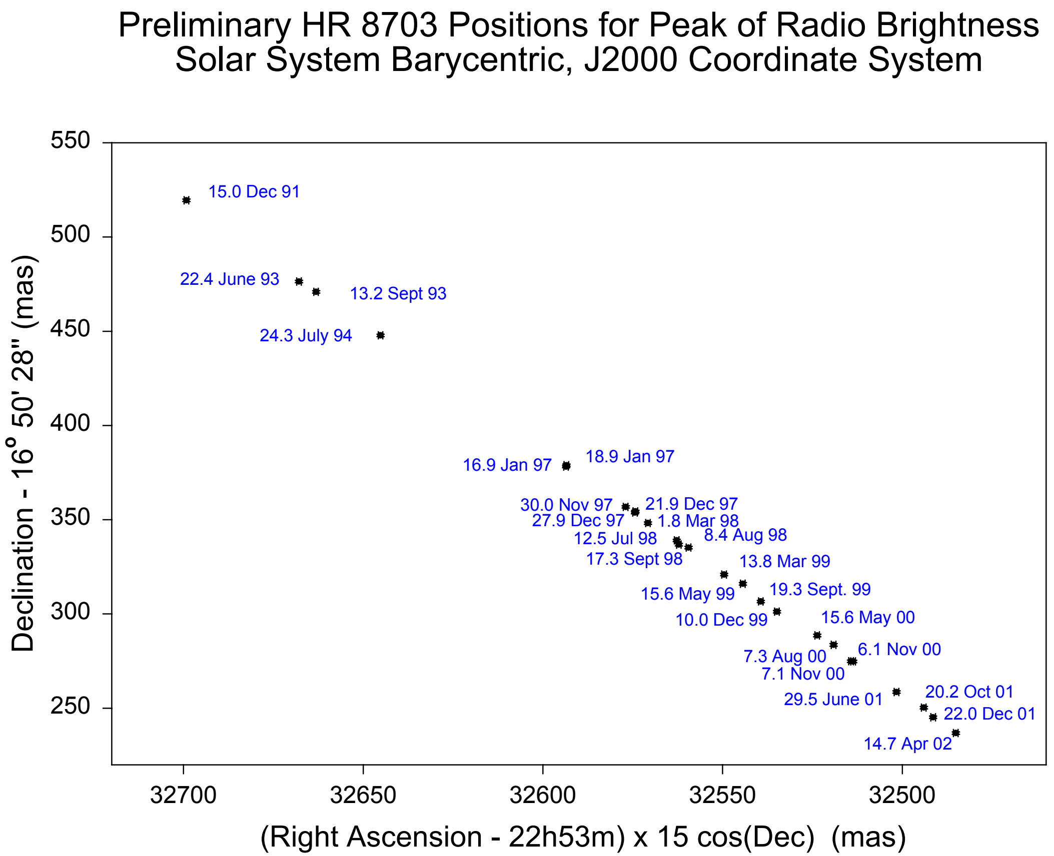
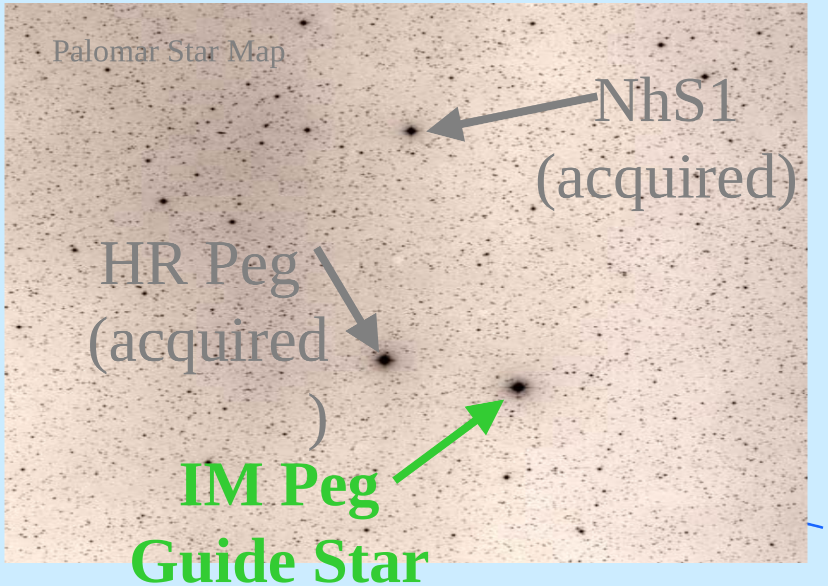
HR 8703 (IM PEG) Guide Star Identification



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**



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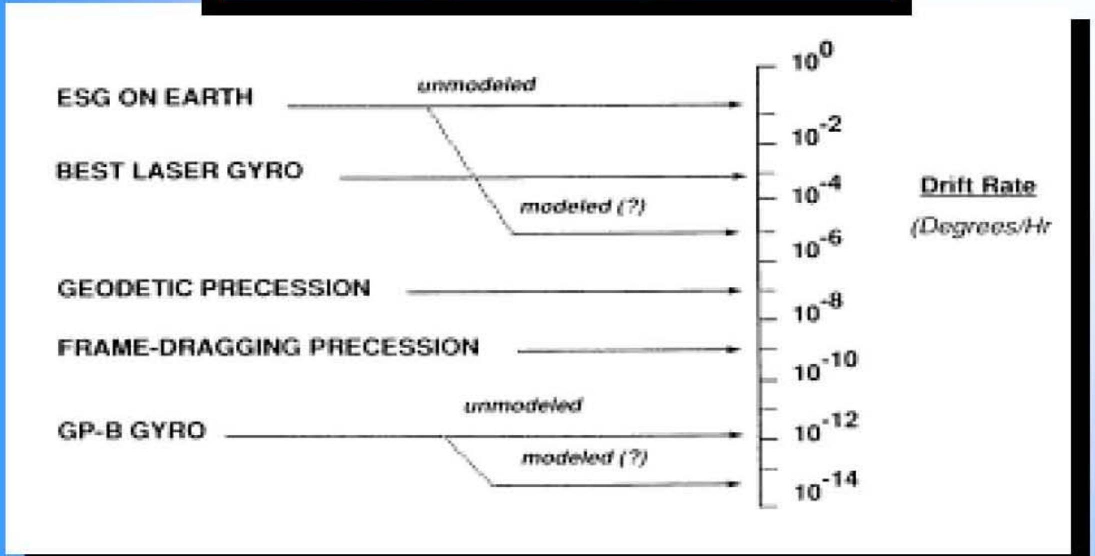
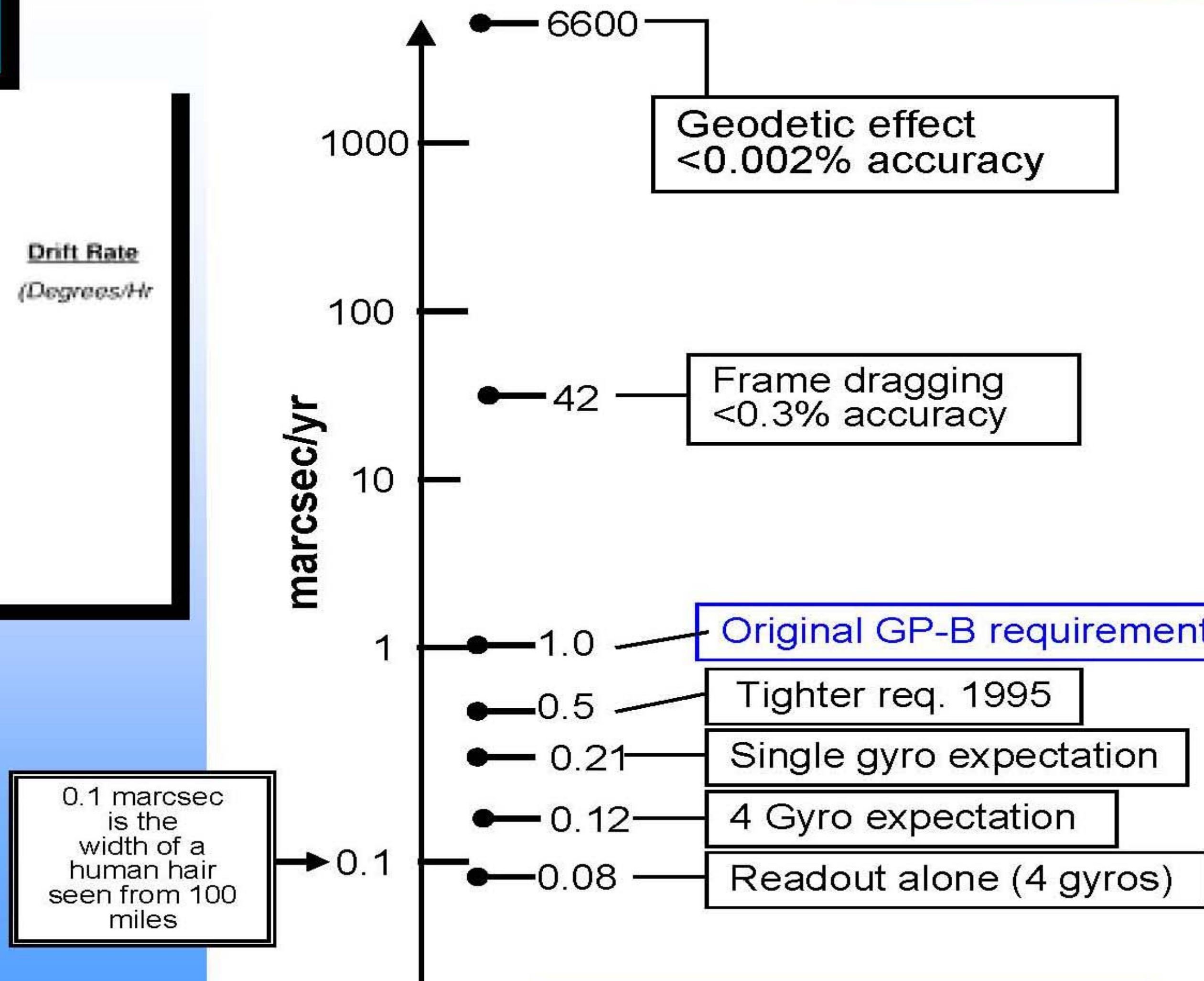
GP-B Performance

Why go to space?



- **Gyroscope drift**
  $\leq$ 0.09 marcsec/yr
- **Readout error effect**
  $\leq$ 0.16 marcsec/yr
- **Guide star proper motion uncertainty**
  $\leq$ 0.09 marcsec/yr

1 marcsec/yr = 3.2×10^{-11} deg/hr



Total Experiment Capability

1 deg/hour = 4.8 10^{-6} rds^{-1} & 1 marcsec/year = 1.58 10^{-16} rds^{-1}

Project Timeline : The basis

1893 Mach's Principal -The Science of Mechanics- acceleration relative to distant stars.

1887 Michelson & Morley Experiment : speed of light remains constant

1905 Einstein Special Relativity : propagation of matter and light at high speeds.

1915 Einstein General Relativity : gravitational forces in terms of space curvature caused by the presence of mass.
Fundamental principle : accelerated frames and in gravitation fields frames are equivalent.
General Relativity predicts : clocks evolution in gravitational fields (or accelerated frames), gravitational redshift, existence of gravitational lensing, gravitational waves, gravitomagnetism, Lense-Thirring effect, and relativistic precession of orbiting bodies.

1924 J. Lense and H. Thirring
calculated effect : a rotating object will slowly drag space and time around with it! A moon orbiting a rotating planet undergoes a relativistic advance of its ascending node. Frame Drag.

1929 A. S. Eddington : proposed an Earth based gyroscope or pendulum experiment of general relativity.
If the earth's rotation could be accurately measured by Foucault's pendulum or by gyrostatic experiments, the result would differ from the rotation relative to the fixed stars by this amount of 19 milliarcsecond/year precession.

Project Timeline : The Fondation

1961 First formal NASA contact : Fairbank writes Dr Abe Siberstein describing an instrument that would measure the geodetic precession to a few percent.

1962 Francis Everitt joins William Fairbank and Leonard Shiff at Stanford on the Gravity ProbeB.

1965 1st fused quartz telescope built.

1971 NASA begins examining feasibility of a flight experiment.
Ball Aerospace completed a Mission Definition Study.

1973 Dan Debra's successful flight of a drag-free satellite (the Transit navigation satellite).

1976 Gravity Probe A launch. 1 hour 55 minute flight of a MASER atomic clock demonstrating time change as weaker levels of gravity : test of redshift to an accuracy of 2.10^{-4} .

1977 End of longest single continuous research NASA grant ever awarded (63-77).

1980-82 Phase A at MSFC leading to larger dewar and satellite.

Project Timeline : The mission happens

1983 Stanford restructured program : science instrument within the dewar to be integrated and launched in 1991 on the shuttle : STORE (Shuttle Test of the Relativity Experiment)

1985 Gyro production throws out Beryllium, Hollowed Beryllium, Hollow Quartz spheres and focuses on Quartz rotors...

1986 Challenger explodes.

1989 Stanford's first prolonged levitation of a quartz sphere.

1992 First Flight Hardware within the Science Mission starts to be built : Dewar...

1995 NASA cancels Shuttle Test and directs Stanford to go directly to flight.

2001 Integrate Payload with Spacecraft.

April 20th 2004 Gravity Probe B successfull launch
out of Vandenburg Air Force Base at 9:55am.

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The Satellite

VEHICLE
Length 6.43 meters
Diameter 2.64 meters
Weight 3,100 kg
Spacecraft Power: 293 Watts

LAUNCH 20 April 2004

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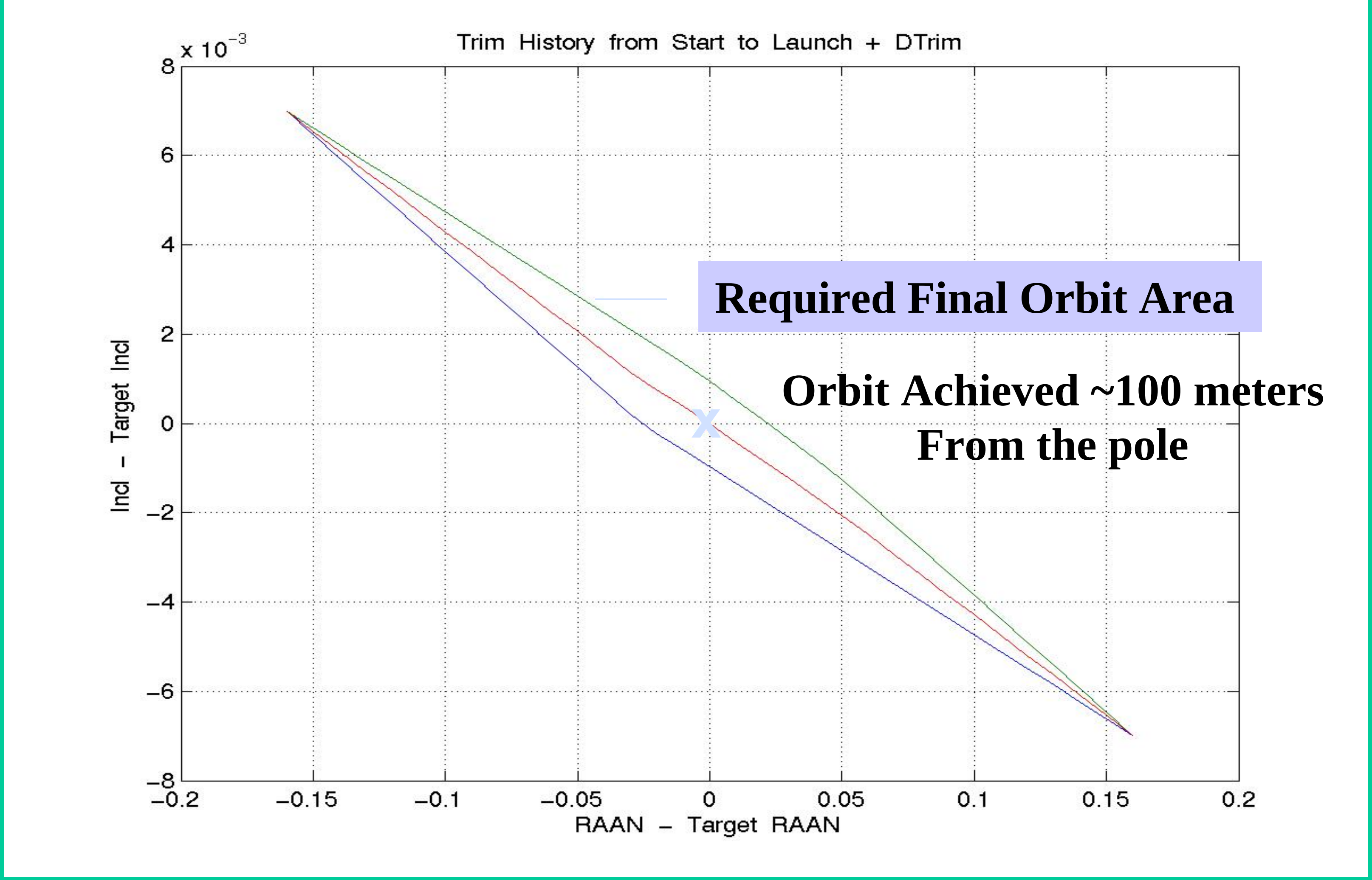
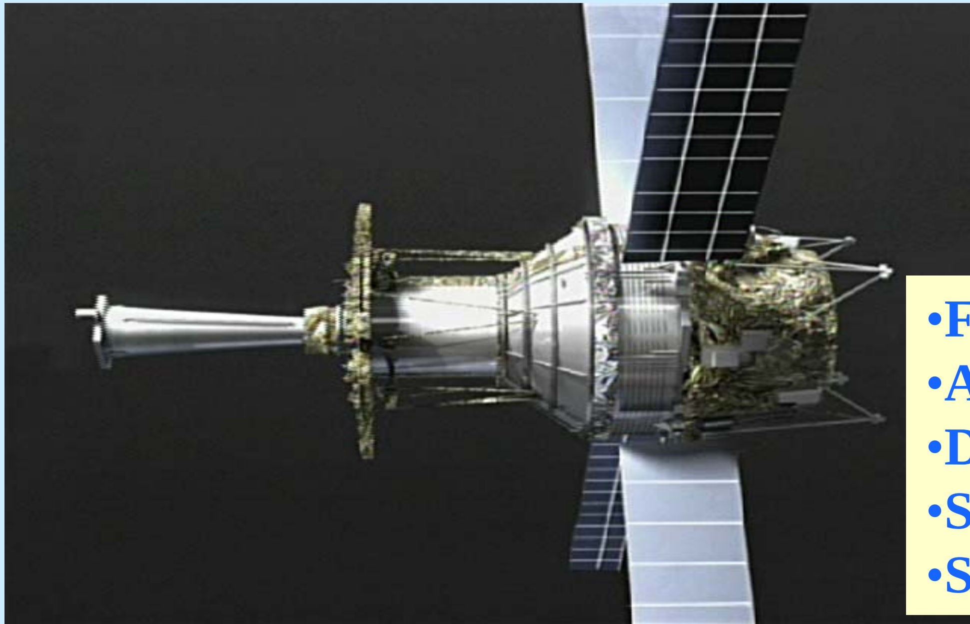
The Actual Orbit - Delta II



Delta II Nominal Accuracy

PAYLOAD GENERAL CONFIGURATION



- **From cryogenic (He liq. 1.8 K) to room temperature**
- **Alignment : Telescope, Gyros, S/C spin axis**
- **Drag free satellite : 10^{-9} g**
- **S/C mass centring**
- **Satellite rotation : ~ 10^{-2} Hz (period : 1 to 3 mn)**

4 gyros (redundancy & performance improvement), drift rate : 0.3 marsec/year
leads to accuracy : $\gamma \sim 2.10^{-5}$ * $\alpha_1 \sim 3\ 10^{-3}$ **

*(to be compared to : * CASSINI mission, ** Lunar Laser ranging Exp. Laser Pos., LageosII I.Ciufolini and E.Pavils) NATURE 431, 938-960, oct. 2004*

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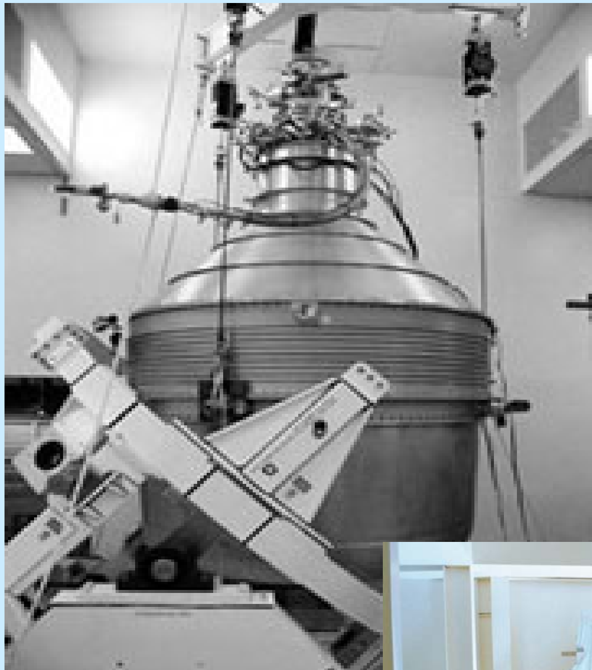
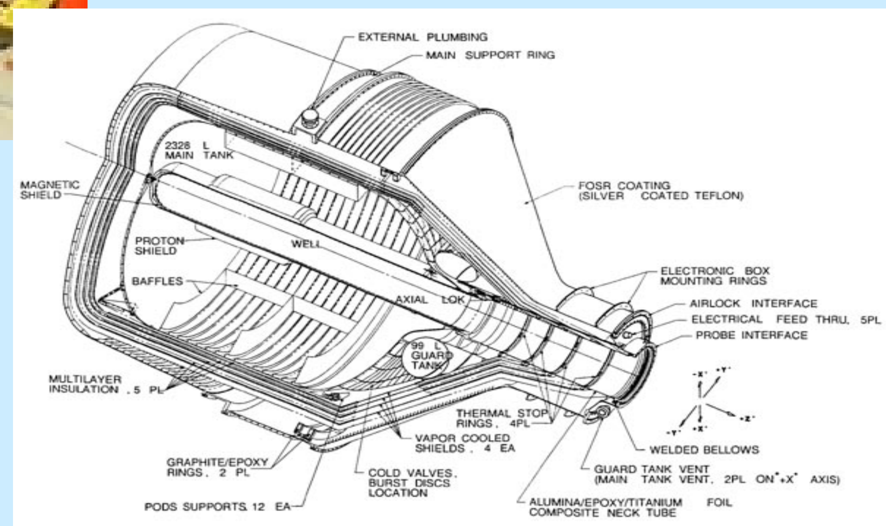
The Payload with the Dewar

PAYLOAD and DEWAR
2 441 liters of supercooled helium at 1.8 Kelvin (-271.4 C)
2.74 m tall / 2.64 m diameter
Porous plug at the top : as the internal liquid helium heats up, it evaporates and the gas is vented out taking heat with it.
Payload Power Usage: 313 Watts



High structural stability
Low temperature
Fine management of He behaviour
Fine magnetic shielding
Fine mass centering



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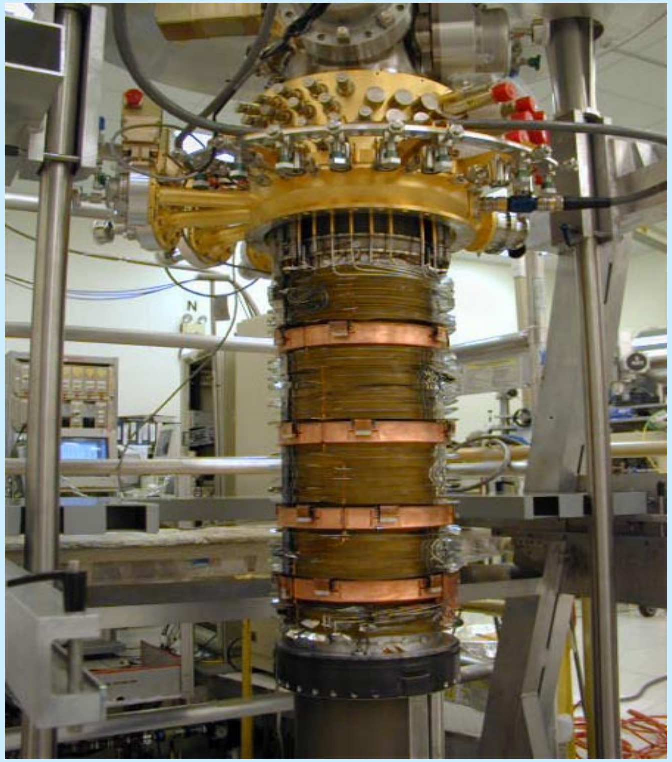
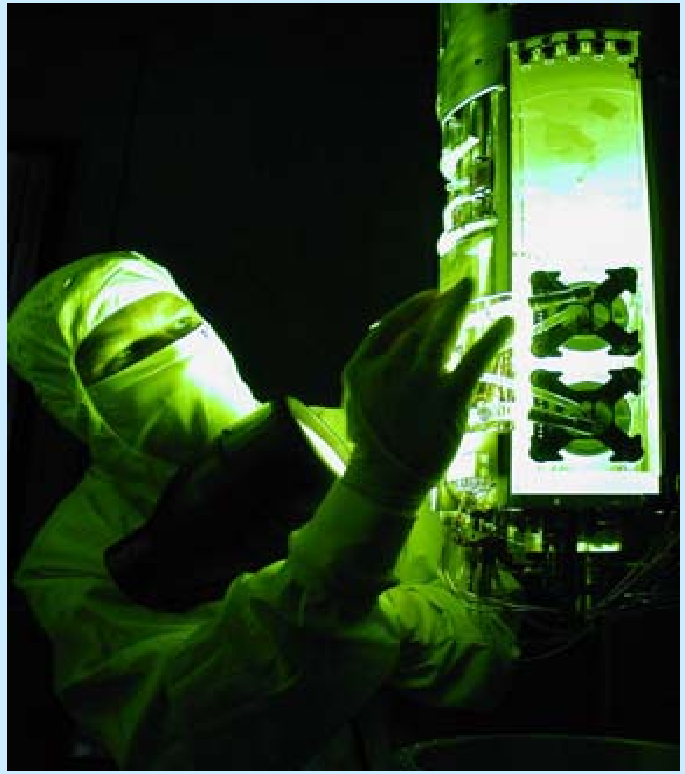
The Probe

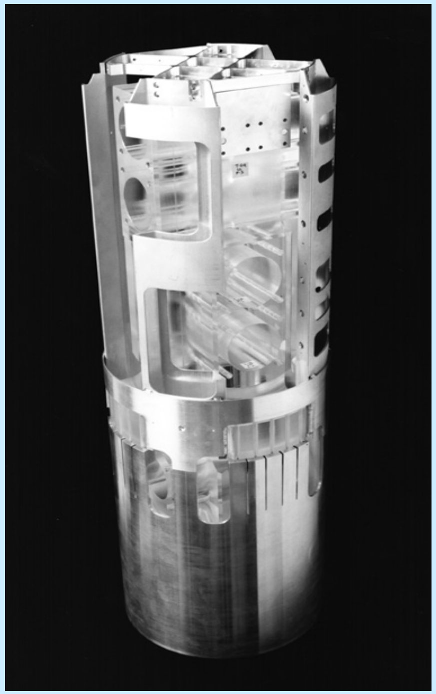
PROBE
length- 2.74m (9 feet).
working temperature- 1.8 Kelvin (-271.4 C).
The probe contains 450 plumbing lines and electrical wires.
The entire probe was assembled in a class-10 cleanroom.



The Quartz Block

QUARTZ BLOCK
weight : 34 kg
length : 55 cm
diameter : 18.5 cm
block lapped and polished (14 months to hand-polish)
telescope mounting surface of the block had to be polished to within 0.01 µm





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The Gyroscopes

GYROSCOPE

Ball (rotor) size- 3.81 centimeter diameter(1.5-inch)

Homogeneous fused quartz : 2 10^{-6}

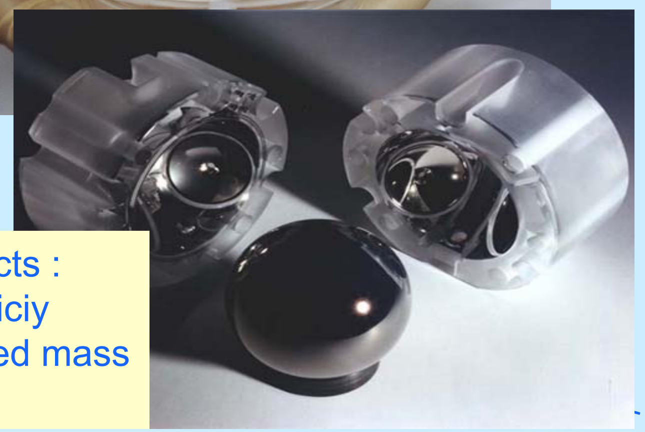
Sphericity : less than 40 atomic layers from perfect (1nm)

Coating- Niobium (uniform layer 1,270 nanometers thick)

Electrostaticaly suspended (25 µm gap).

Spin Rate- Between 5,000 and 10,000 RPM (obtained once by He flow)

accuracy : 0.3 marcsec/year drift (0.5 10^{-16} rd/s)



Major deffects :
- non sphericiy
- unballanced mass
- friction

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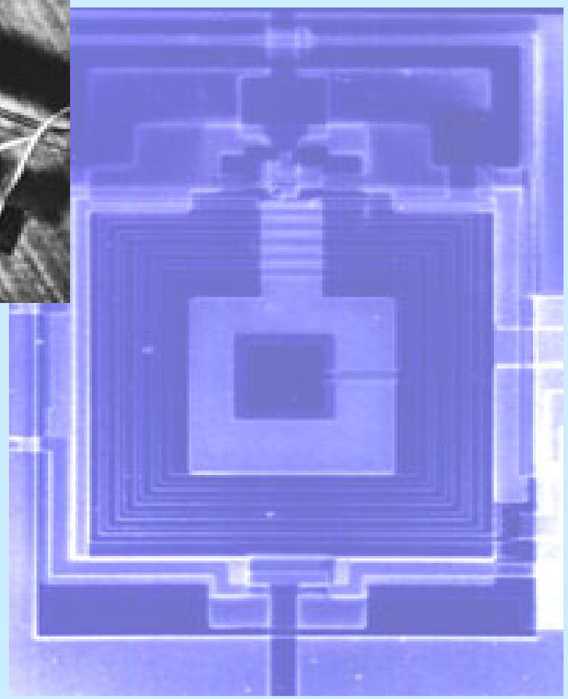
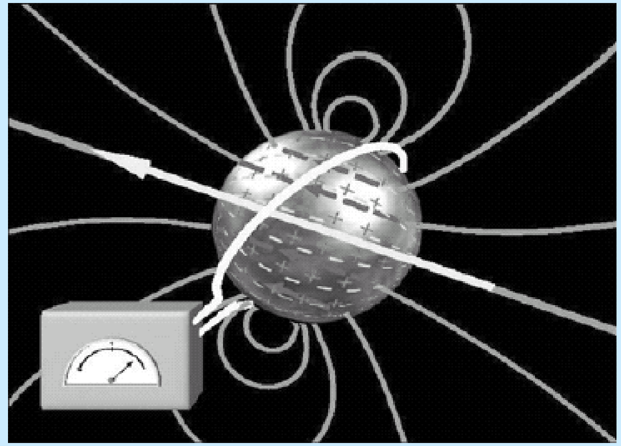
The SQUID's rotation measurement

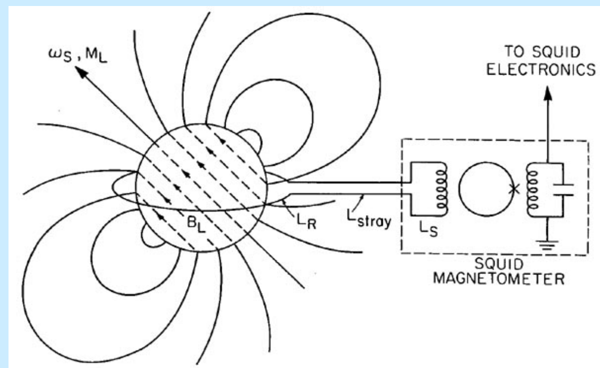
SQUID's
cryogenic magnetic field variation sensor.
superconducting loop with 2 Josephson junctions
sensitivity : 5×10^{-14} gauss (5×10^{-18} Tesla)
10^{-13} of the Earth's magnetic field.

Rotation Measurement :
London Effect
10^{-10} °/ hour (< 10^{-6} best nav. gyro performance)





London effect induces magnetic moment
the variation of orientation is detected
by SQUID



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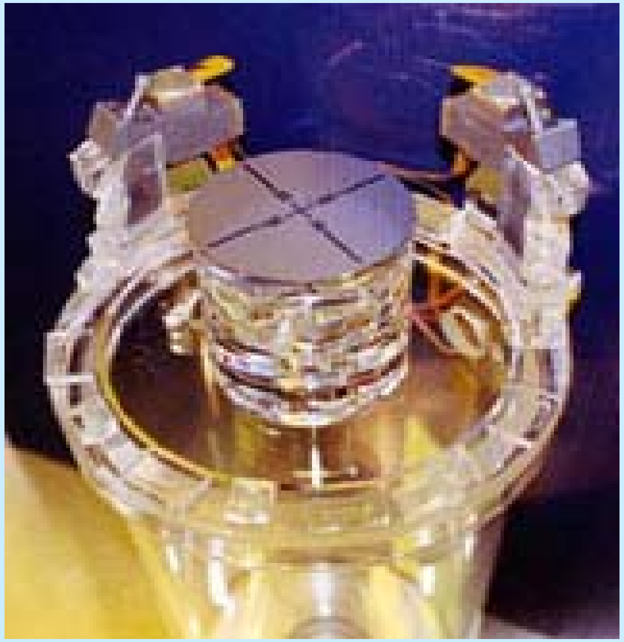
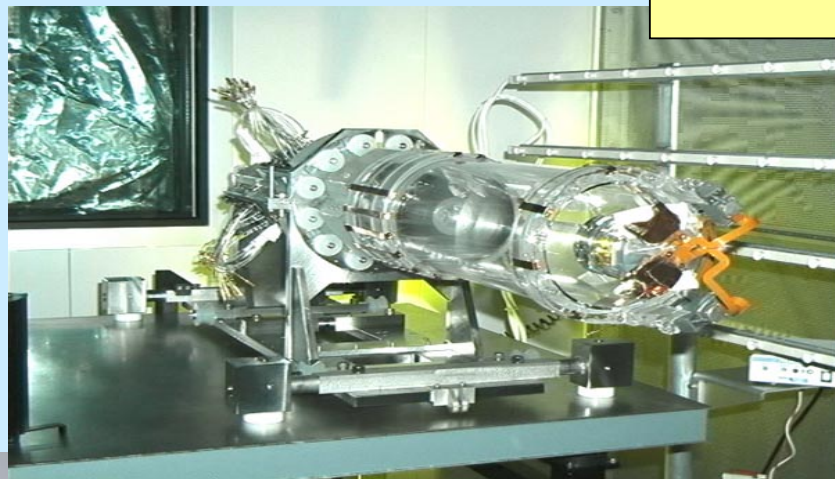
The Telescope

CASSEGRAIN TELESCOPE
Composition- Homogeneous fused quartz
Length 35.56 centimeters (14 inches)
Aperture 13.97 centimeter (5.5-inch)
Focal length 3.81 meters (12.5 feet)
Mirror diameter 14.2 centimeters (5.6 inches)
Guide Star HR 8703 (IM Pegasi : Mag 5.6)
Accuracy : 0 .1 milliarcsecond i.e. 5.10^{-10} rd





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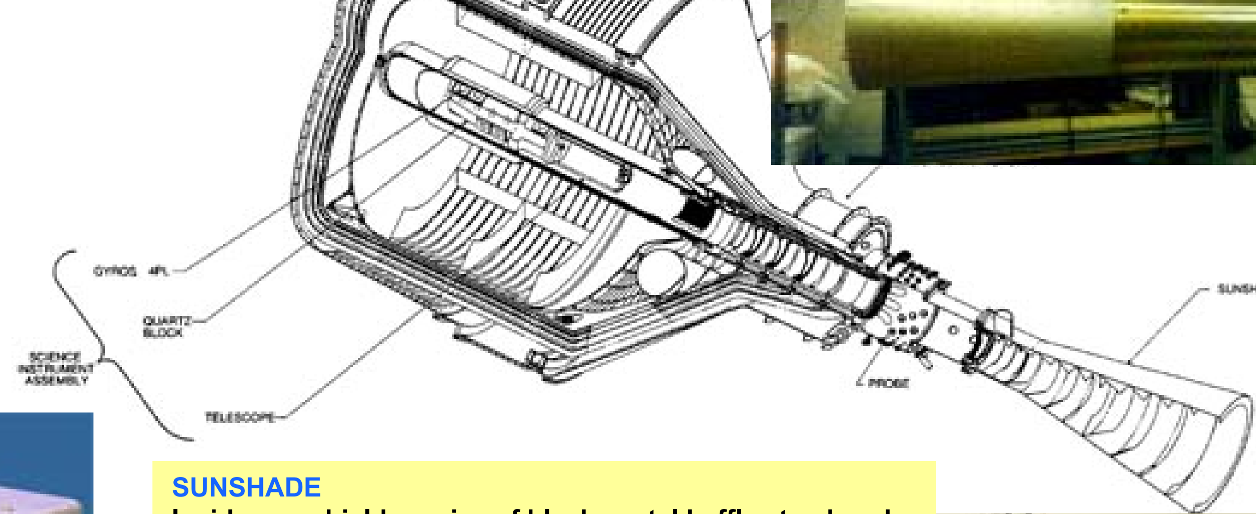
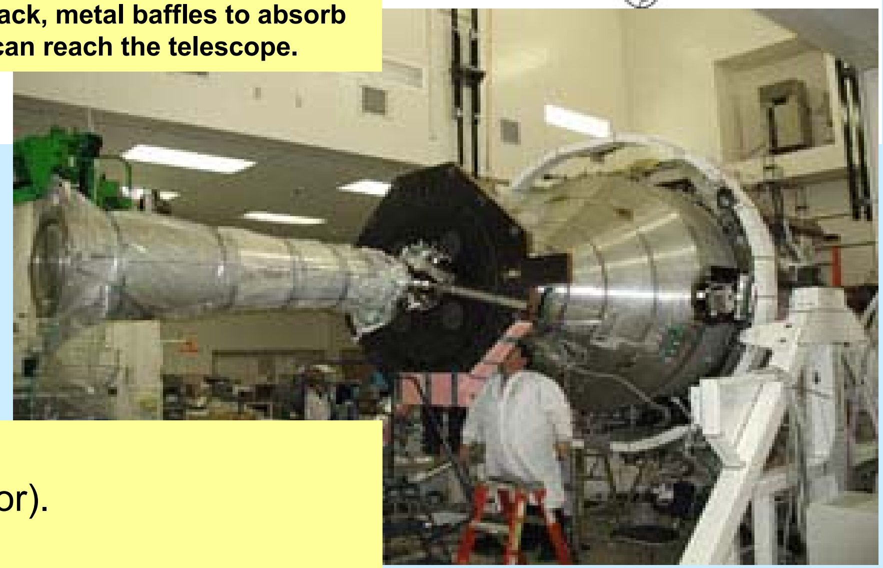
The star tracker & Sunshade



SUNSHADE
Inside sun shield : series of black, metal baffles to absorb incoming stray light before it can reach the telescope.



STAR TRACKER

Two star trackers : wide field and narrow field (star sensor).

Star sensor : field of view ~ 1° (1.7 10^{-2} rd)
resolution ~ 1 arcminute (3 10^{-4} rd)
in GP-B telescope field of view,
-> Guide star's position to 1 milliarcsecond (5 10^{-9} rd).

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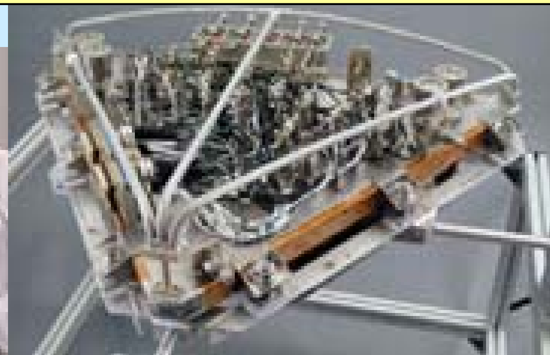
The GMA (*Gas Management Assembly*) and the Thrusters

GMA

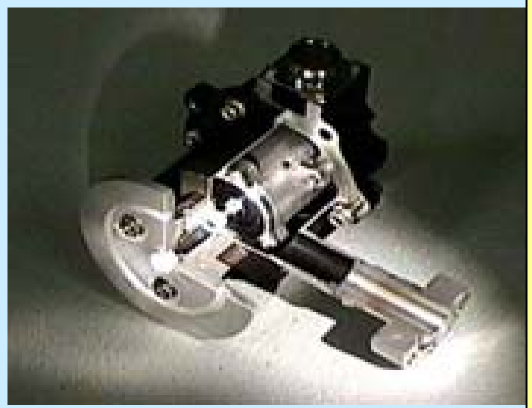
Helium gas (.99999% pure) used to spin up the gyroscope ball.
Helium gas used for thrusters of the drag free control.
Fine distribution and management of the evaporated He to be ejected from the dewar



THRUSTER

12 pairs of thrusters on the vehicle.
Use of the evaporated liquid helium from the dewar as a propellant
linear thruster independent of the inlet pressure

Objective :
- Fine control of the satellite attitude and orbit
- Satellite rotates to modulate the SQUID output (reduction of noise)



GP-B Set-up Highlights

GP-B Launch: 20 April 2004 – 09:57:24

Weeks 1 - 4
- a) SQUID set-up & telescope set-up
- b) gyro suspension
- c) low-T bakeout
- d) first drag-free

Weeks 5 - 8
- a) 'flux-flush'
- b) 0.3 Hz spin
- c) lock on guide star
- d) charge control

Weeks 9 - 12
- (a) increase S/V roll rate
- (b) reboot flight computer
- (c) 3 Hz spins

Weeks 13 - 16
- (a) final 60 - 80 Hz spins
- (b) ATC tuning
- (c) 'coarse' gyro alignment

Weeks 17 - 19
- (a) final 77.5 s period roll
- (b) ATC tuning
- (c) fine (~ 5 arc-s) gyro alignment

Entered Science Phase: 27 August 2004 – 12:00:00

On-Orbit GP-B Technology Demonstrations

Electrostatic Positioning System	—	0.45 nm rms position noise
Gyroscopes	—	Spin-down < 1 μHz/hour Charging < 0.3 pC/day
Charge Control System GSS Charge Measurement UV Charge Discharge Rate	—	< 5 pC control < 1 pC rms > 0.3 pC/min
SQUID Readout	—	$< 3\times10^{-5}\ \Phi_0/Hz^{1/2}$ at 0.5 rpm Beats requirement, all SQUIDS
Magnetics	—	AC attenuation ~ 10^{12} dc trapped flux ~ 1 μG
Telescope System	—	< 34 marcsec/√Hz readout noise

$\Phi_0 = h/2e \sim 4.10^{-15}$

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Technologies Demonstrated On-Orbit by GP-B

Orbit Accuracy	—	Inclination error < 0.00007 deg, (< 100m) orbit average to star < 0.004 deg
Proportional Helium Thruster	—	1 – 10 mN/thruster
Drag Free Control	—	< 10 nm vehicle position mean cross-track average < 10^{-11} g
GPS System Time transfer accuracy Navigation accuracy	—	> 95% lock ratio at all roll rates < 3 μsec UTC to vehicle time < 7 m rms, < 0.7 cm/s
Superfluid Flight Dewar (2400 *l*) Porous plug	—	Lifetime ~ 15 months, Dynamic flow range 2-18 mg/s

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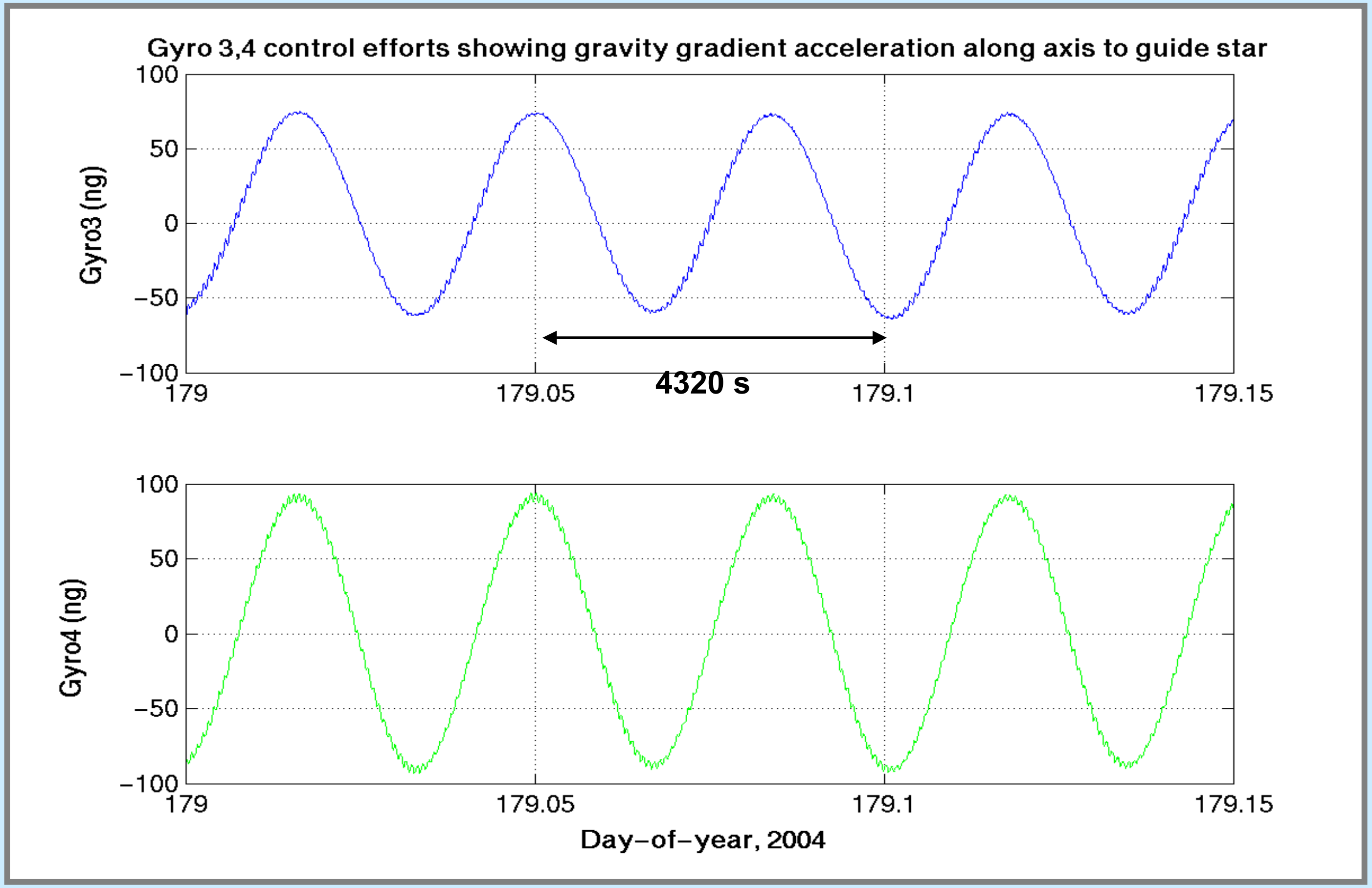
Gravity Gradient Measured by Gyroscopes

Gyro #3, #4 Suspension Control Effort (2+ orbits)

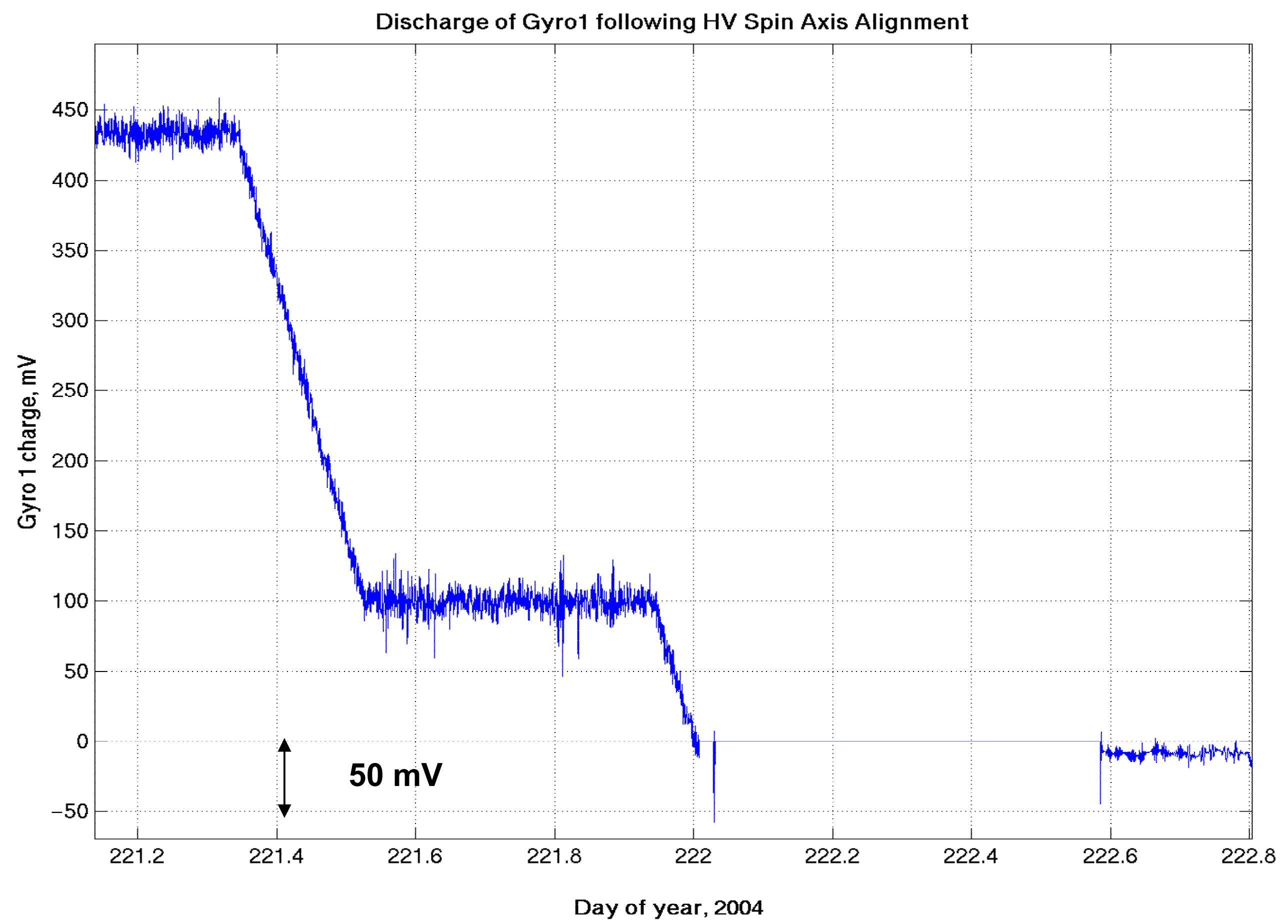


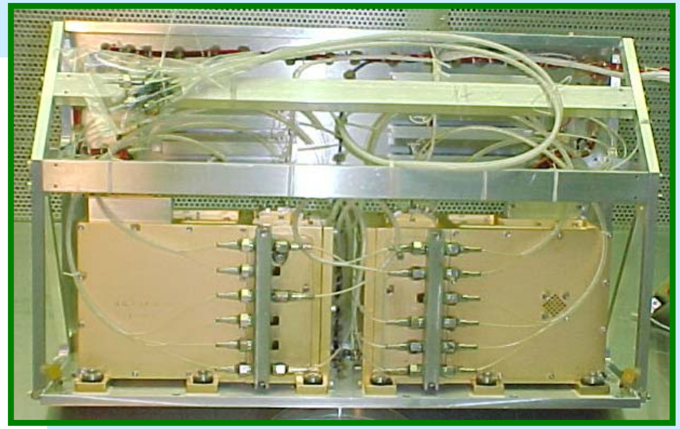
- **2 Gyros not at drag-free point**
- **Projection of gravity gradient along electrostatic suspension axis @ twice the orbital frequency**

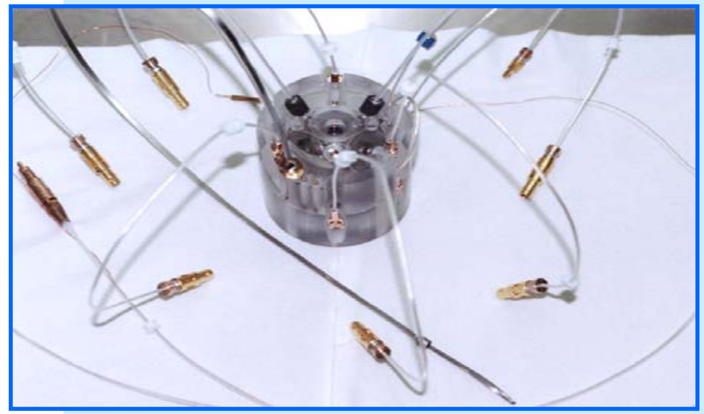
Raw gravity gradient resolution < 10^{-9} g

GP-B Charge Management

Discharge of Gyro #1

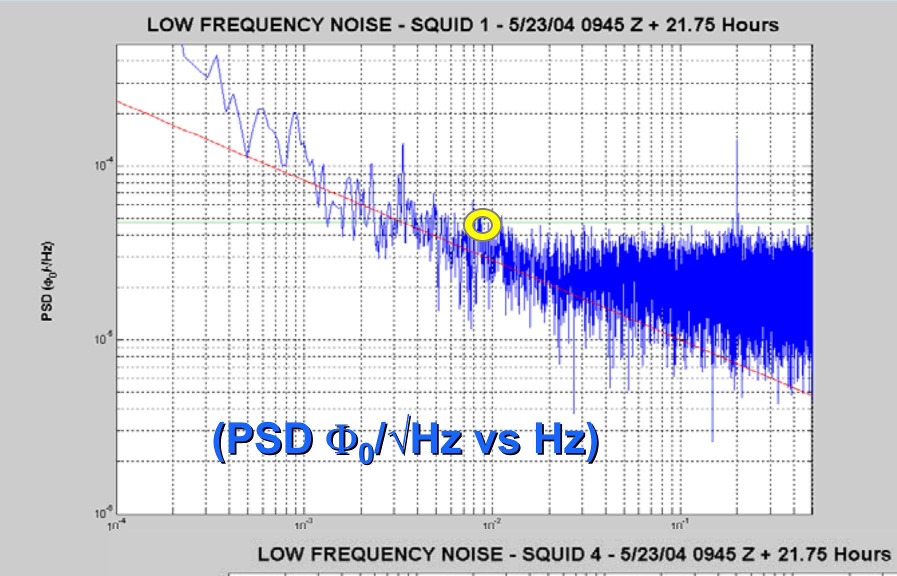


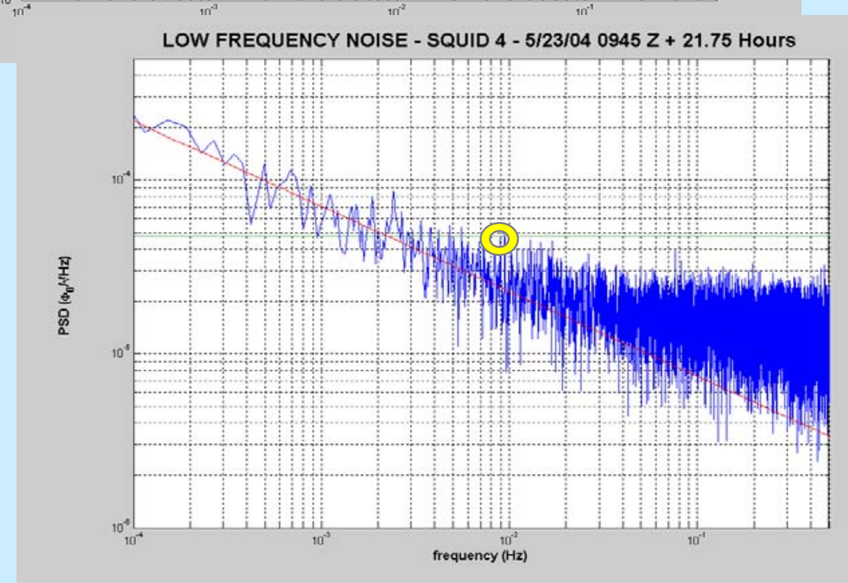




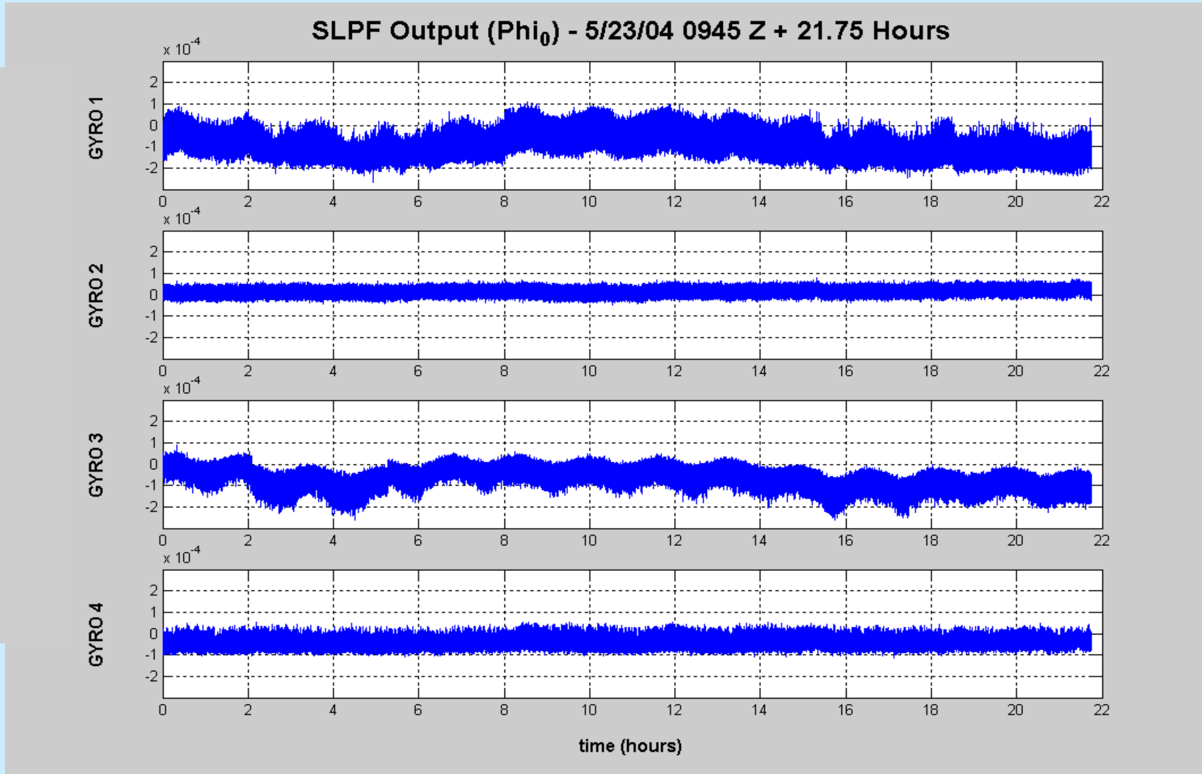
Discharge of Science Gyros Demonstrated

Superconducting SQUID Readout



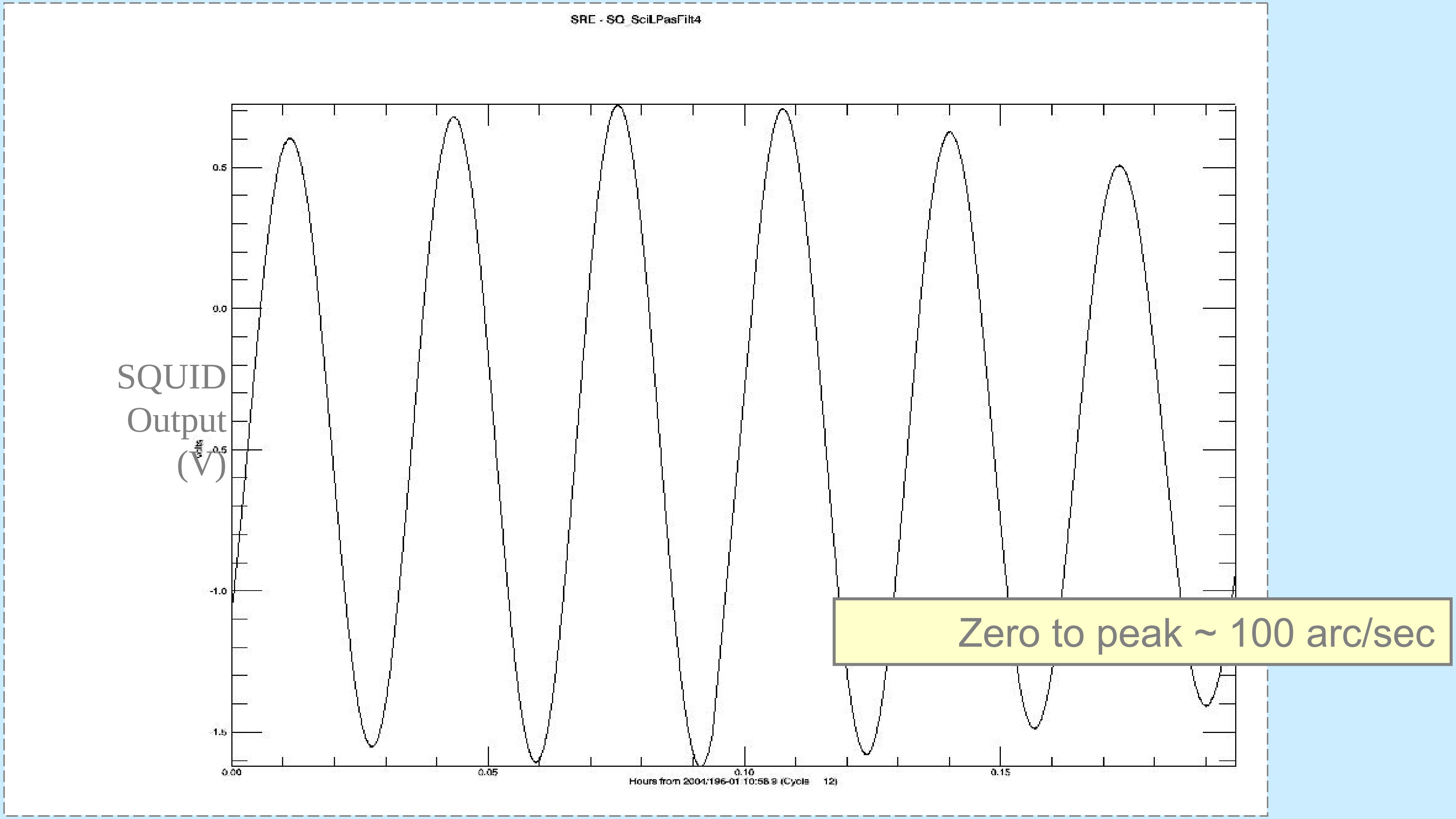


“SQUID” – ultra sensitive low noise magnetometer reads angle to 1 milliarc second in 5 hours



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

Gyro #4 London Moment Readout Data



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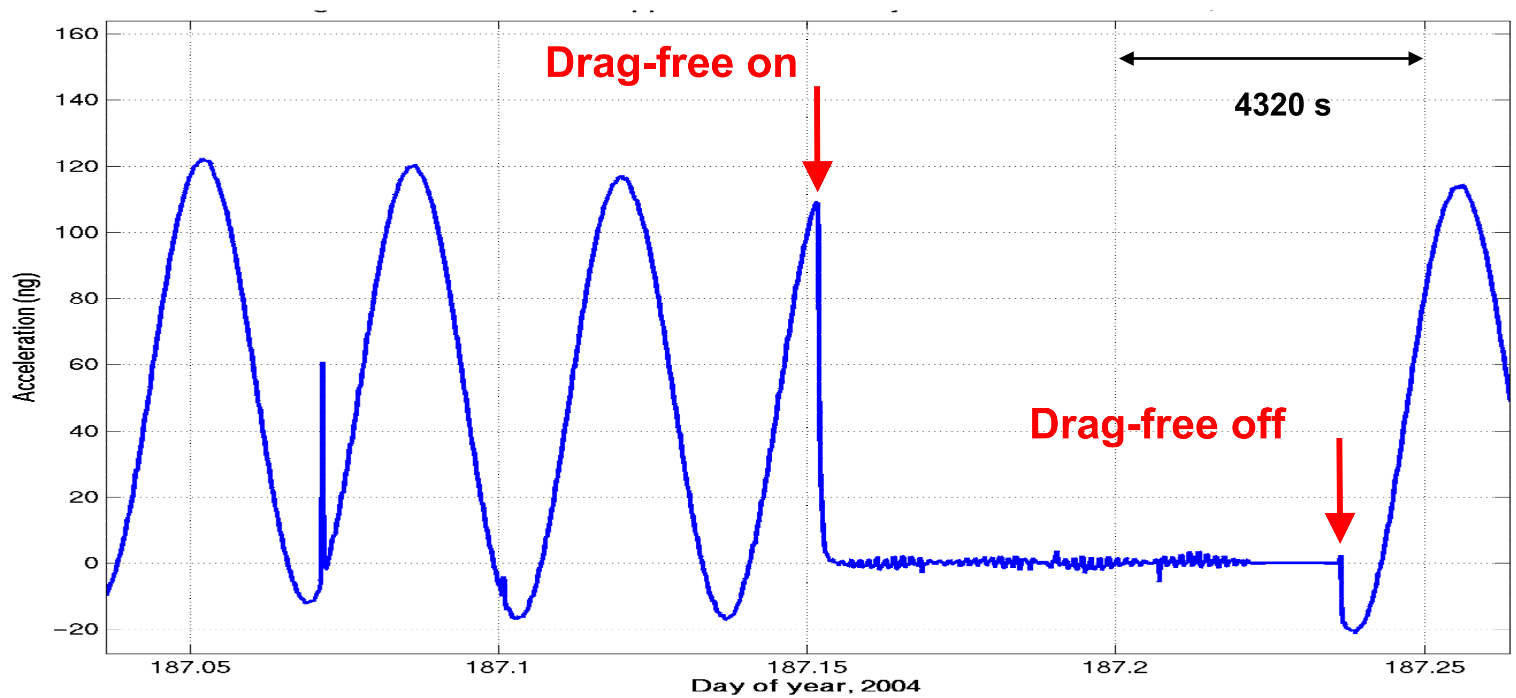
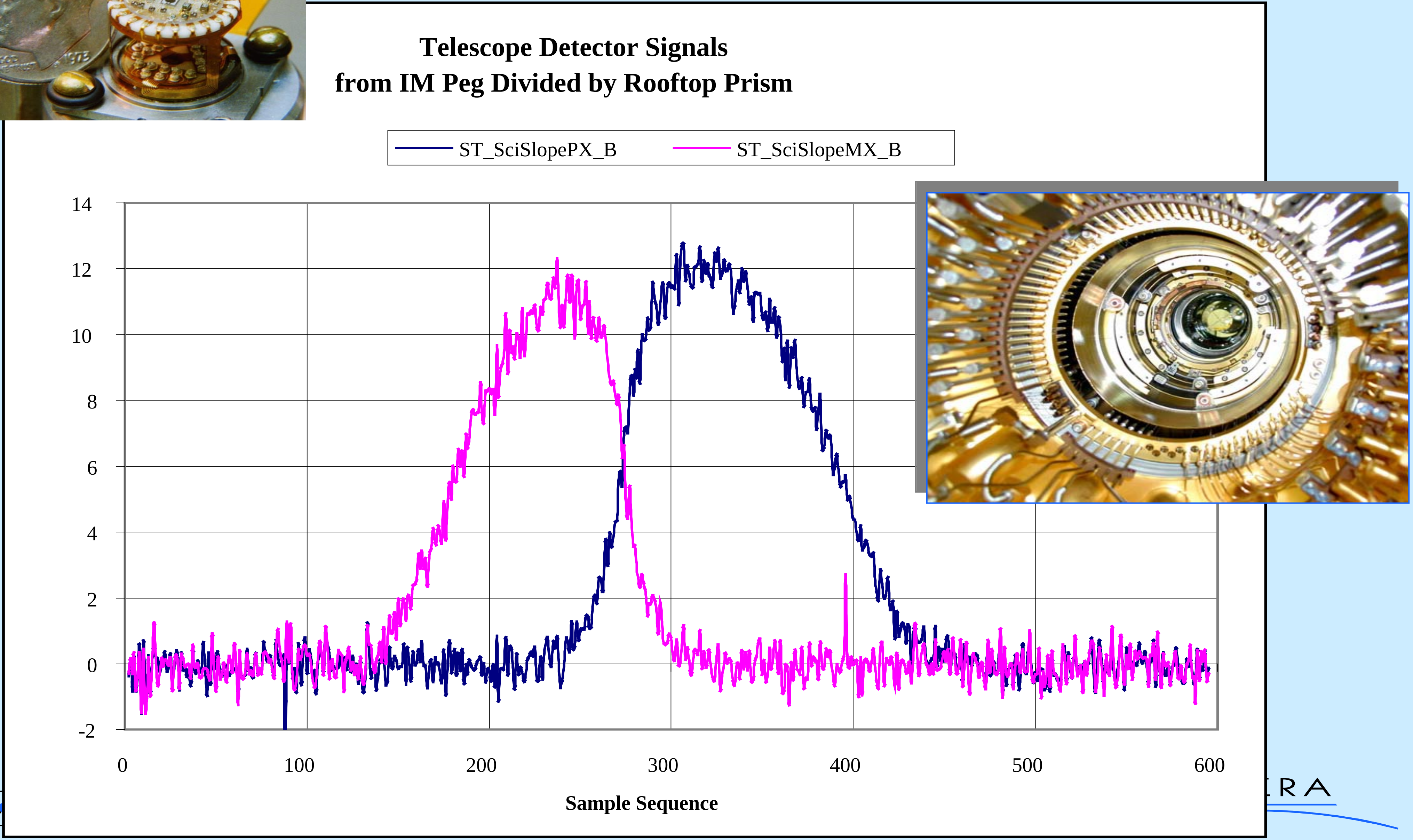
Drag-Free Performance

Suppression of Z axis gravity gradient acceleration

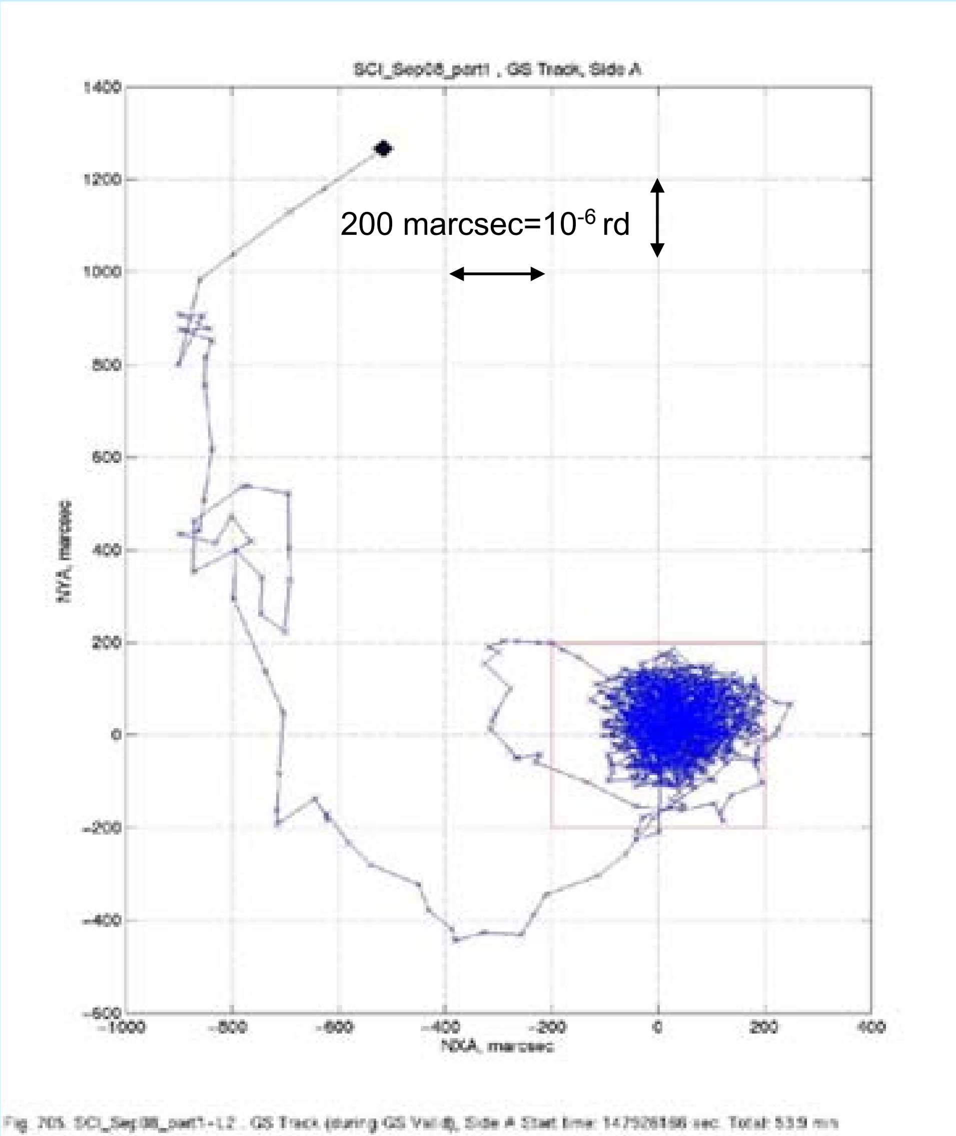


Twice orbital term reduced by > 100

GP-B Telescope Pointing

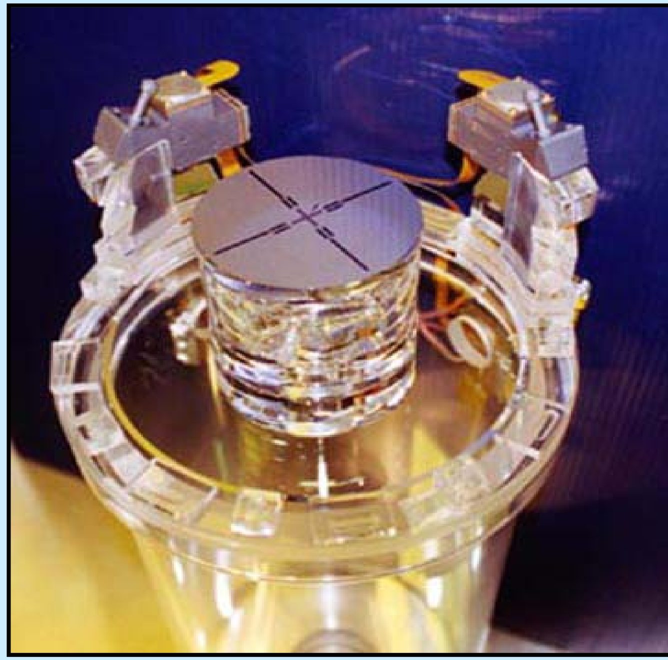


Acquiring Guide Star

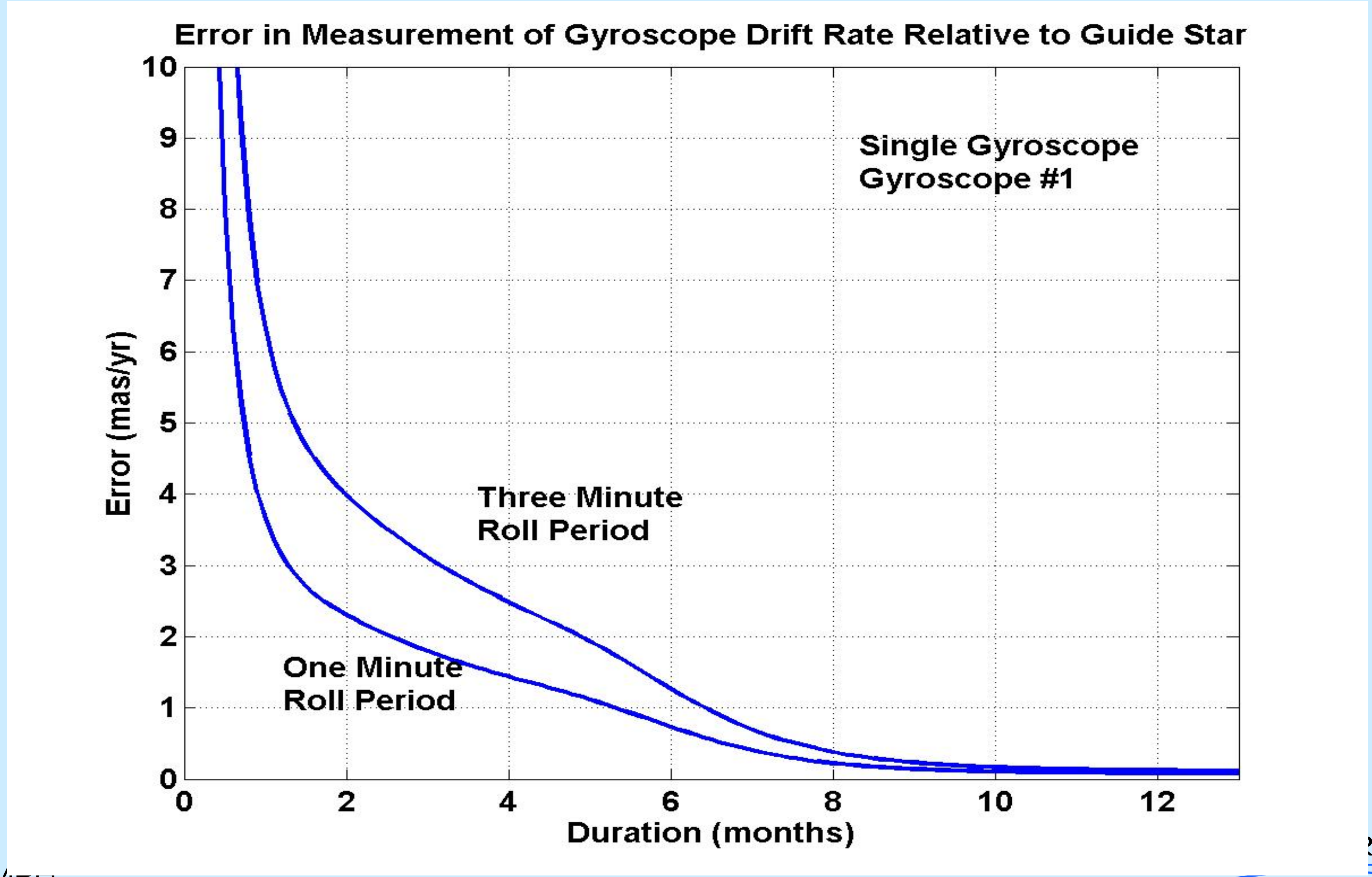


Drive in time ~ 110 s

RMS pointing ~ 80 marc-s



The Science Mission



Thanks to Rodney Torii

THE END

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The Thrusters

THRUSTER
12 pairs of thrusters on the vehicle.
Use of the evaporated liquid helium from the dewar as a propellant
linear thruster independent of the inlet pressure

Objective :
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- Satellite rotates to modulate the SQUID output (reduction of noise)

Polhode Motion

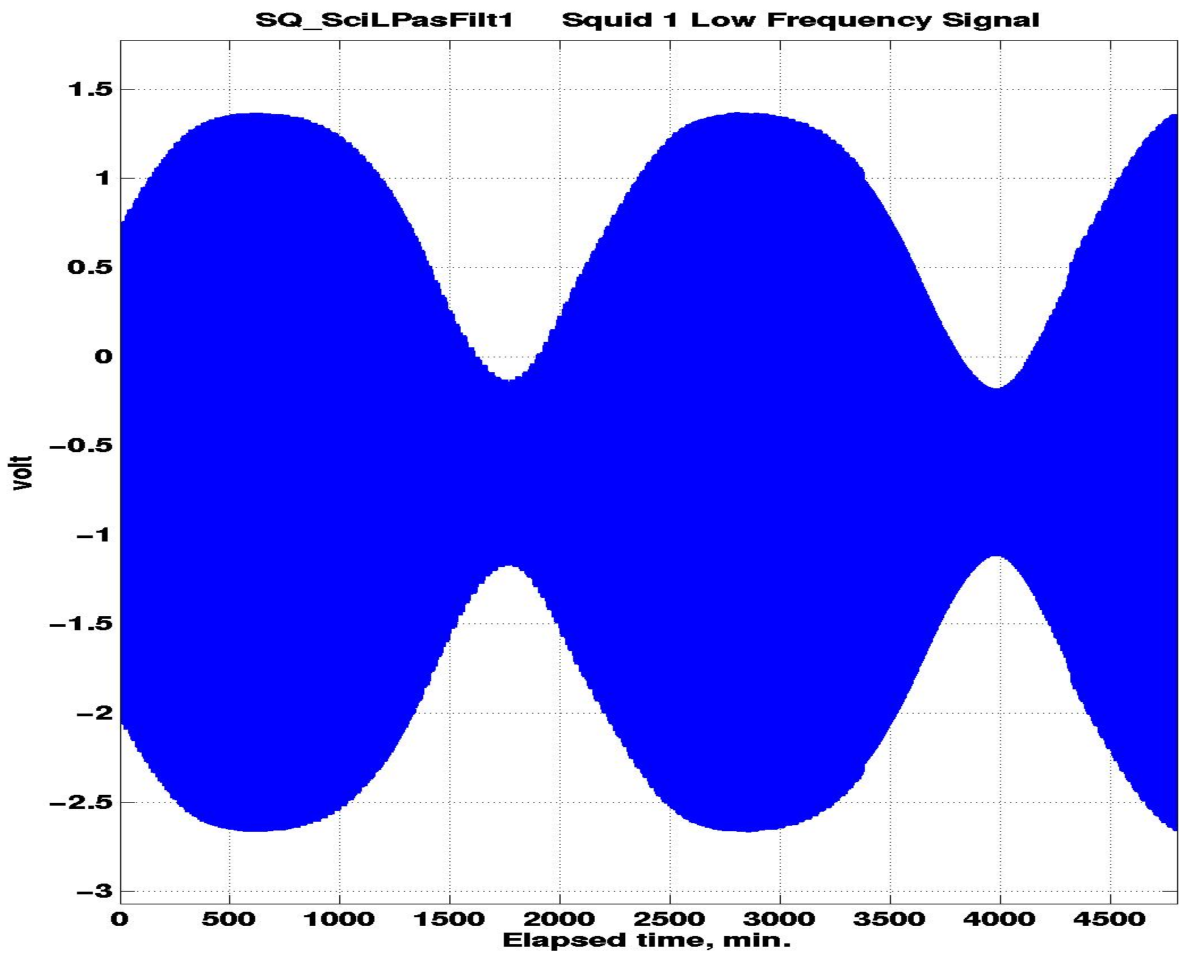


Fig. 5. IOC_Jul04_part2 Level 1 Data. Starts at VT: 142159589.1 sec. + 200 min. (2004/186−00:06:29.1)

Gyro # 1

Spin Speed – 3 Hz

July 4 - 7, 2004

36-hour Polhode Period

$F_{polhode} = \Delta I/I \cos(\theta) F_{spin}$

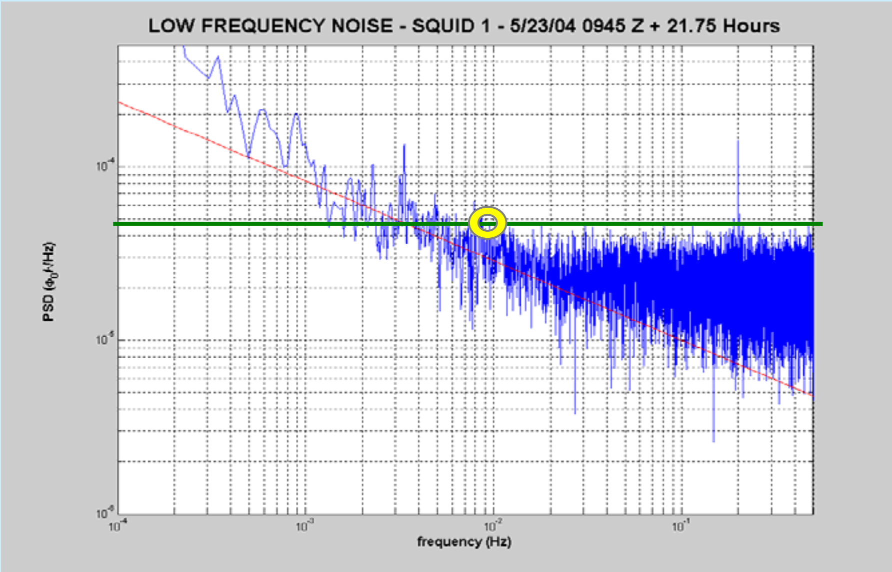
$\Rightarrow \Delta I/I < 2\text{x}10^{-6}$

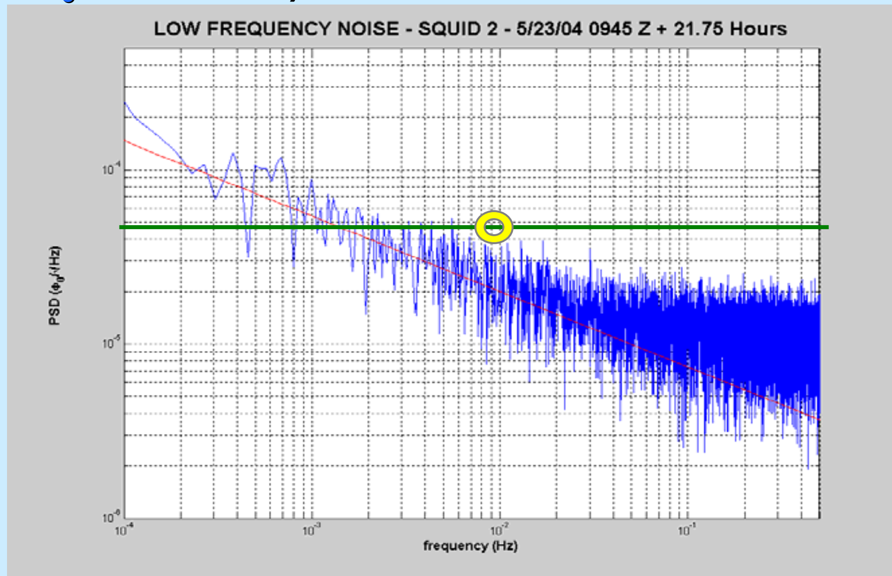
DMPH

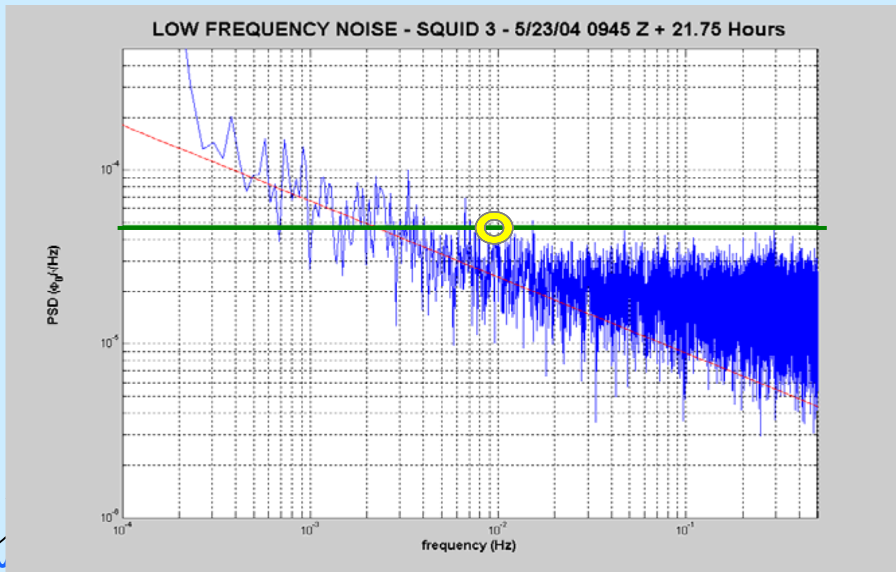
ONERA

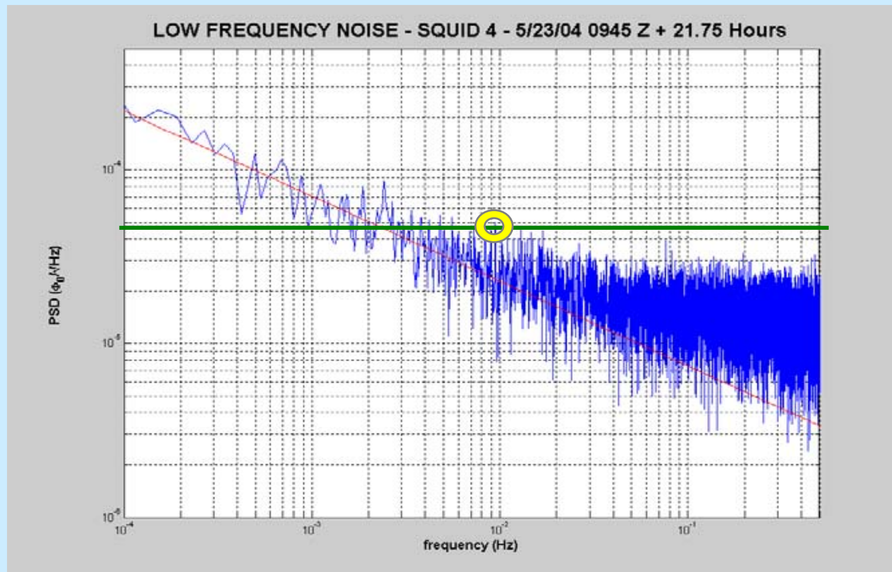
SQUID Readout Noise Beats Spec

(PSD $\Phi_0/\sqrt{Hz}$ vs Hz)









GPB MISSION PRESENT STATUS (Cospar july 04)

•Satellite in nominal orbit and nominal operation

•Drag free and attitude control being optimised :
telescope pointing not yet stabilized along reference star

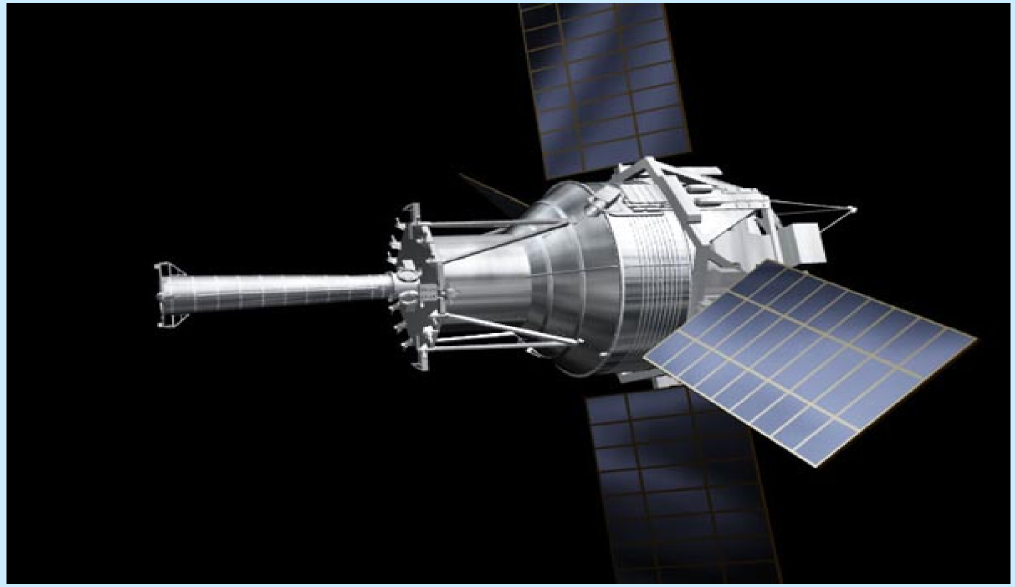
•2 gyros rotates at nominal frequency

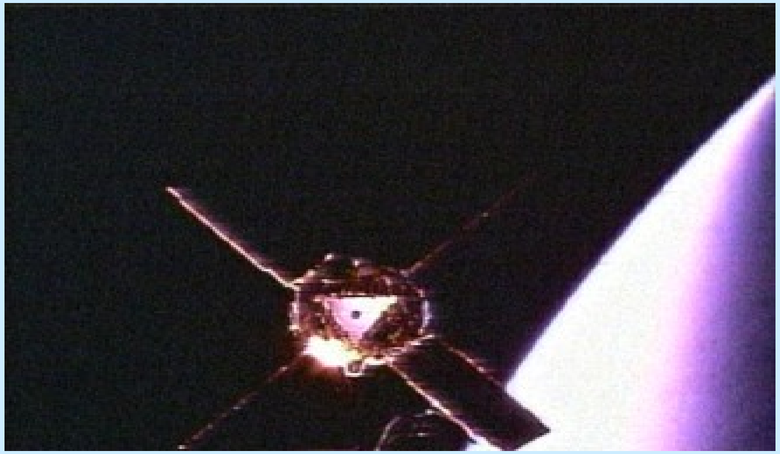
• He Dewar : 14 months mission evaluated

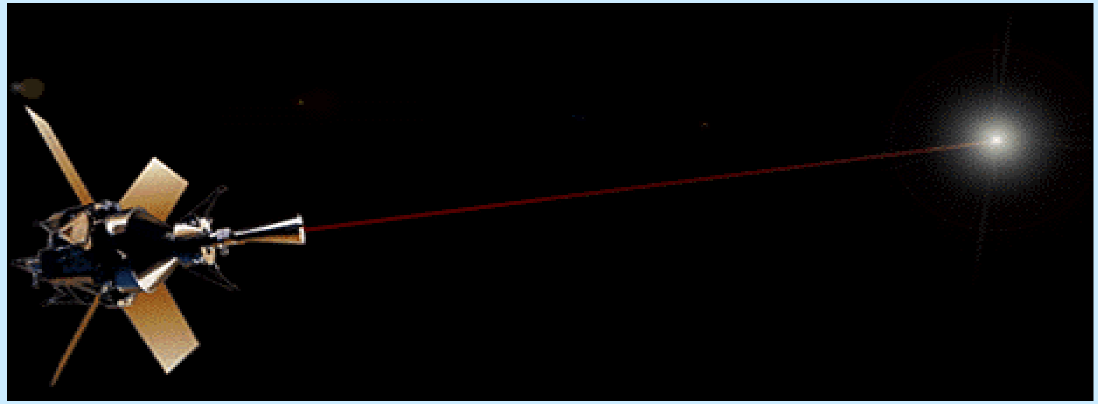
•Calibration phase running :
no scientific results before 6 months

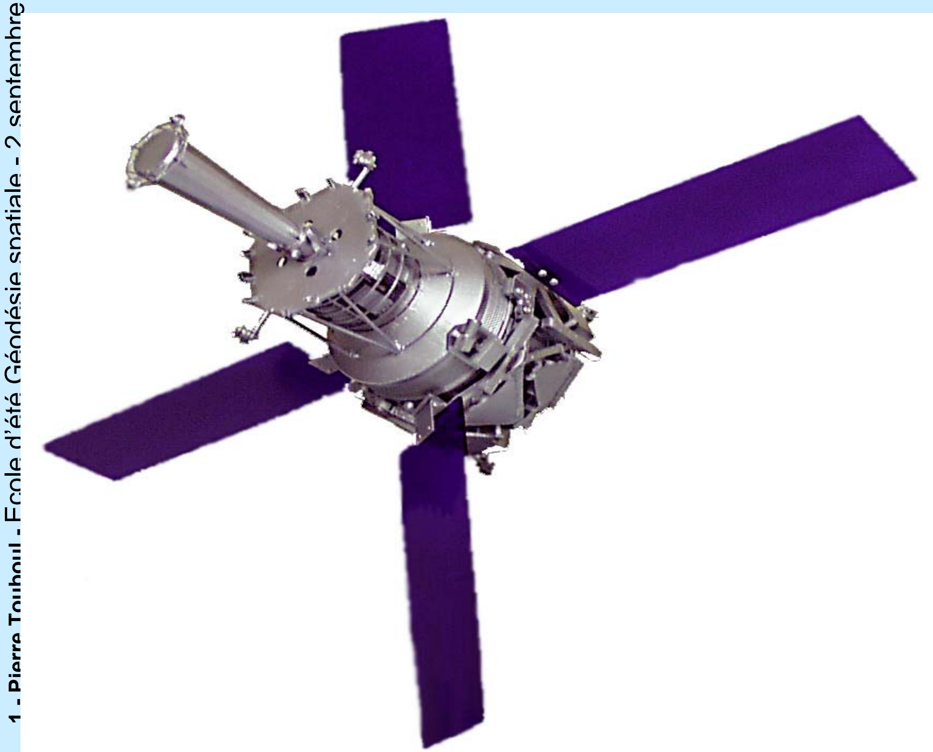
DMPH

ONERA









The Solar Arrays

so·lar cell

def: A semiconductor device that converts the energy of sunlight into electric energy. Also called a photovoltaic cell.

SOLAR ARRAYS FACTS

Each panel is 3.5 meters long by 1.3 meters wide

The release mechanism is made up of Nitinol rods, commonly called "memory metal". When the rods are heated, they change shape and release the panels.

The 9,552 individual Gallium Arsinide solar cells have an effeciency of 18.5%

The total power needed to run the entire satellite would barely power the average microwave.

The Truss Structure

Truss

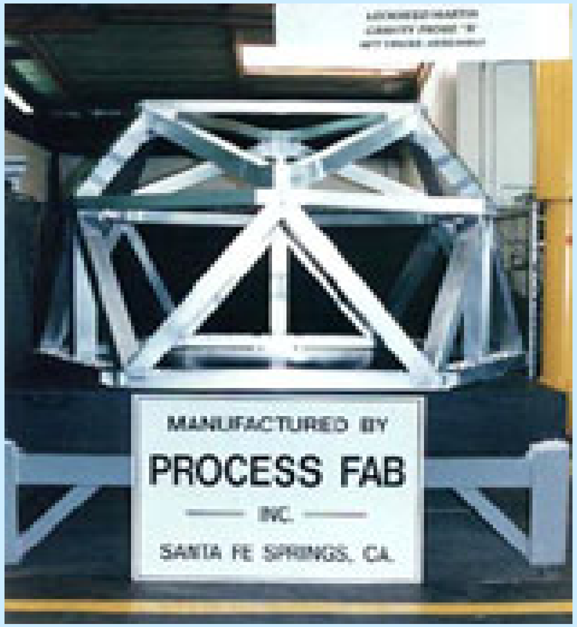
def: An engineered structure of short framing members, such as beams, chords, and diagonals, assembled into a rigid support structure.

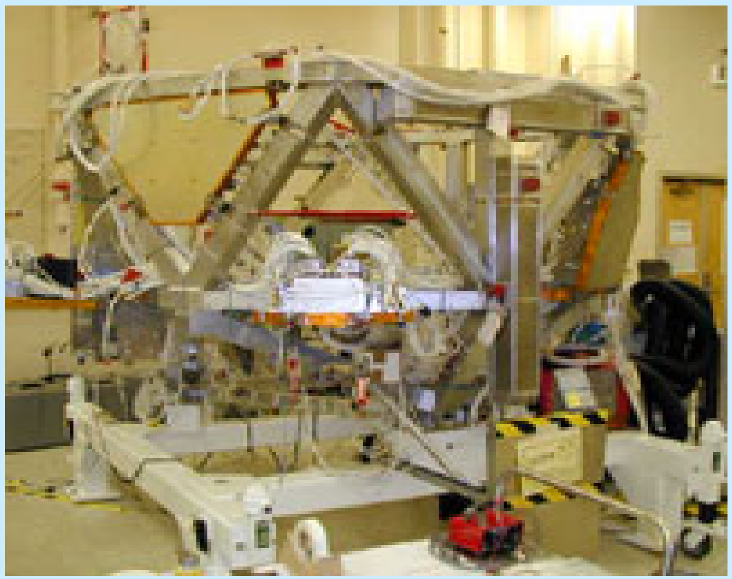
TRUSS STRUCTURE FACTS

The truss structure is made of aluminum alloy beams, heliarc welded at the joints. Mechanical joints were not stiff enough to maintain the satellite's critical geometry.

The structure's "open" frame design exposes the dewar to space, improving heat radiation.

Equipment is attached by self-integrated pallets. Individual subsystems can be removed without disassembling the entire space craft.





DMPH

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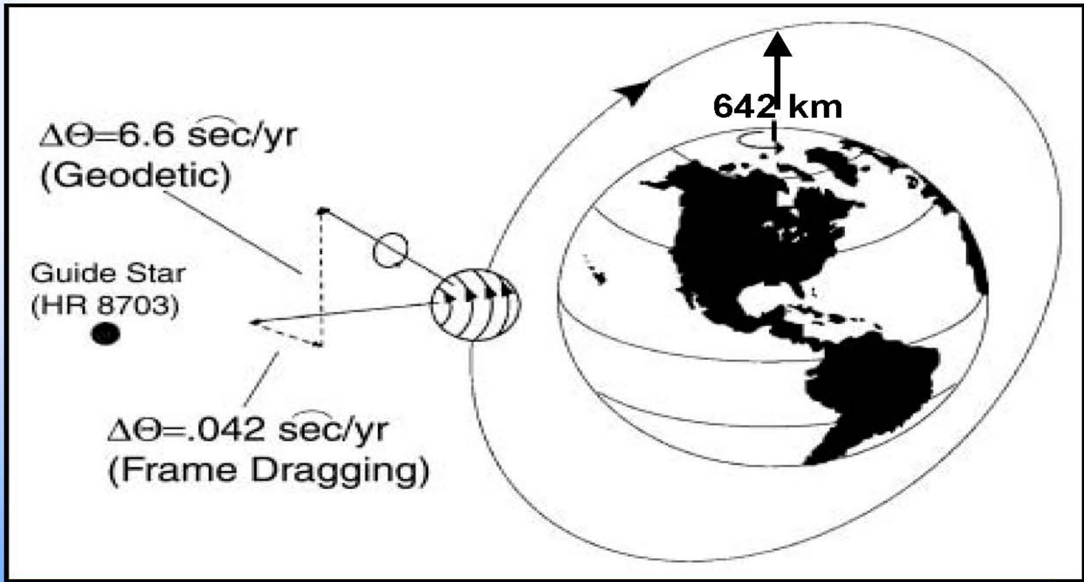
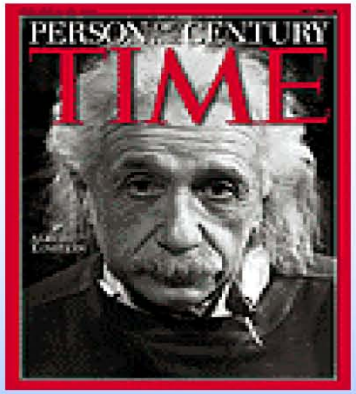
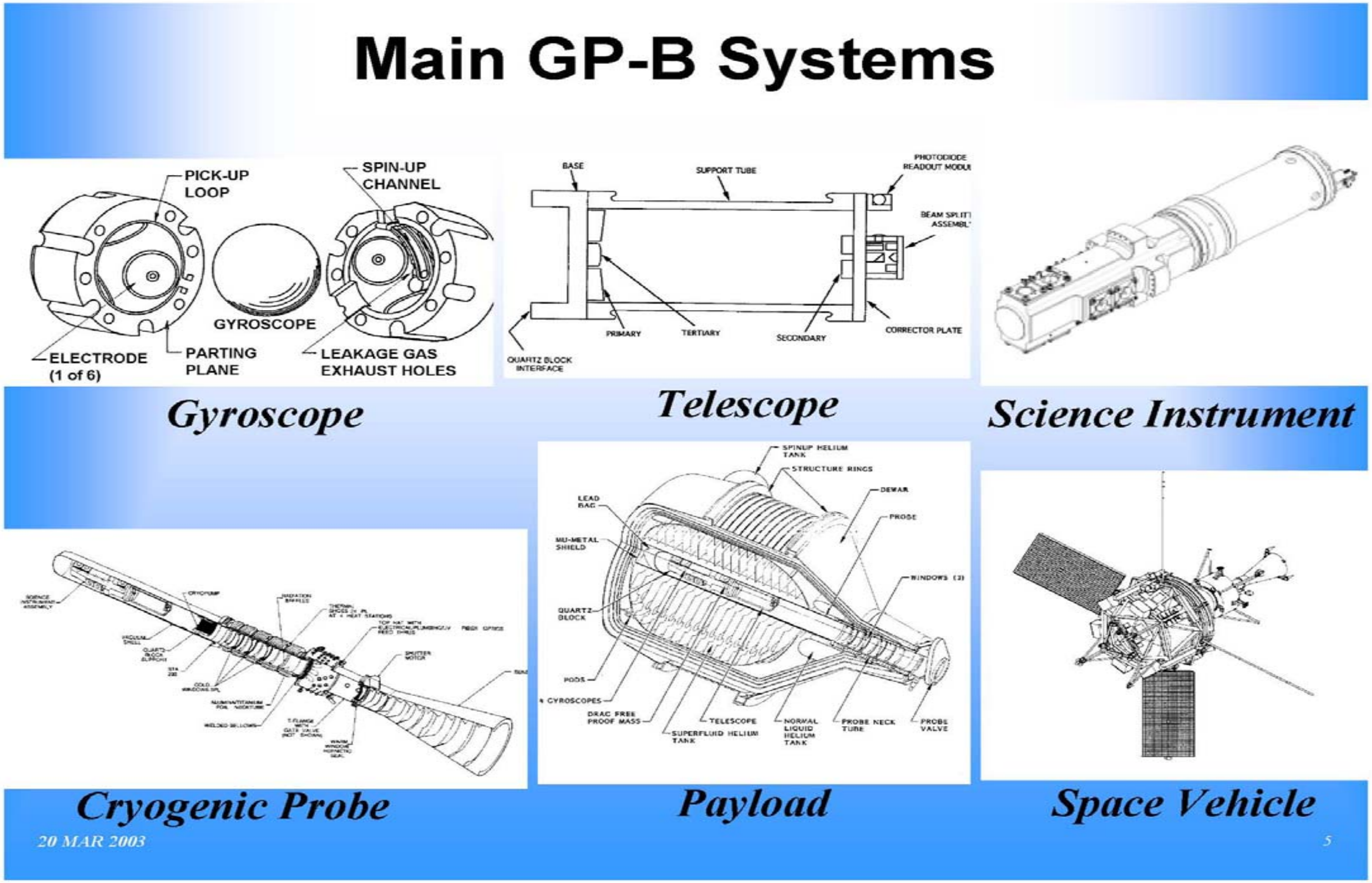
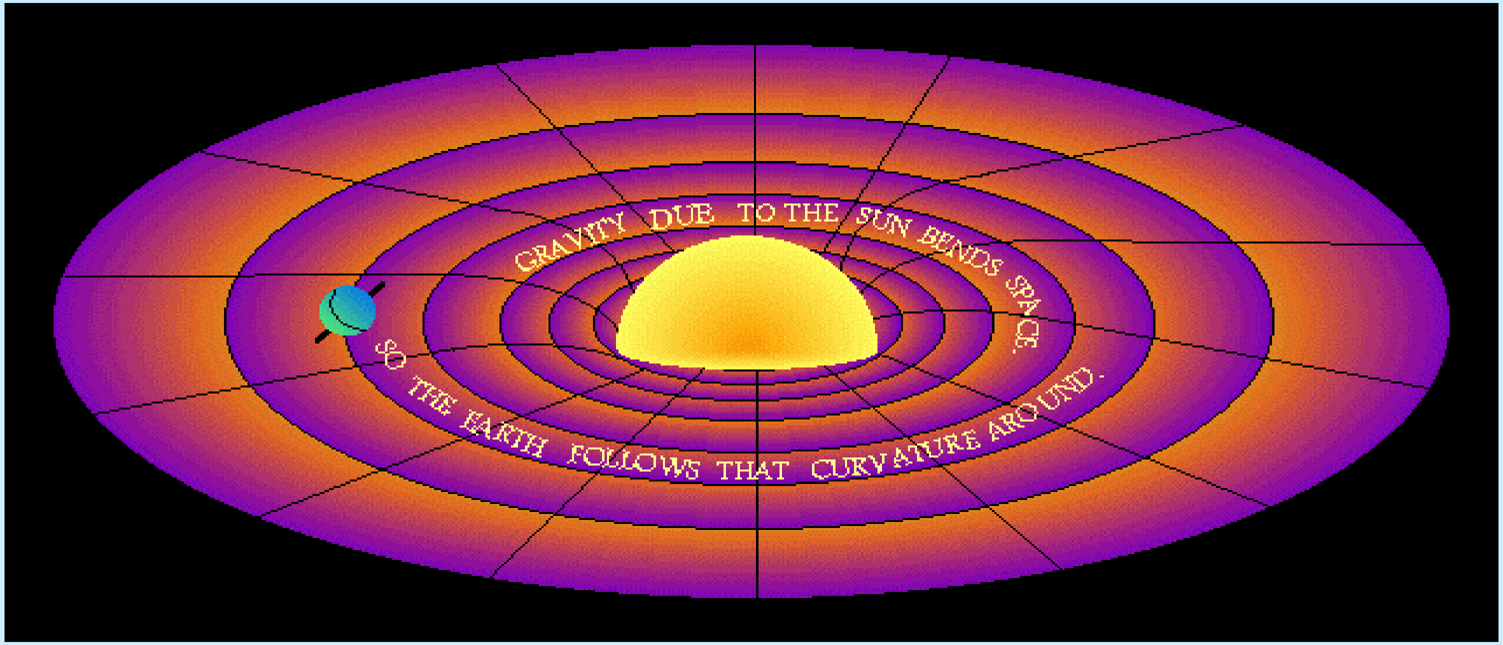
The Relativity Mission Concept
(Invented in 1959)

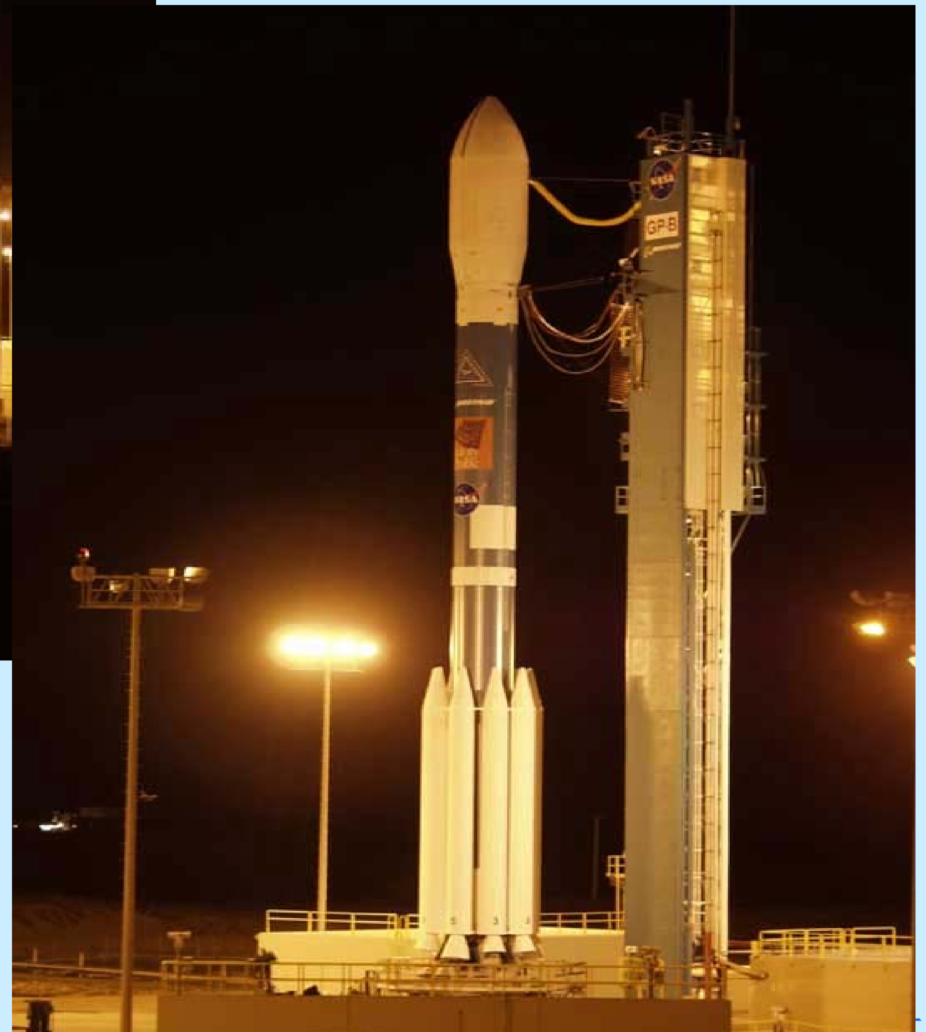




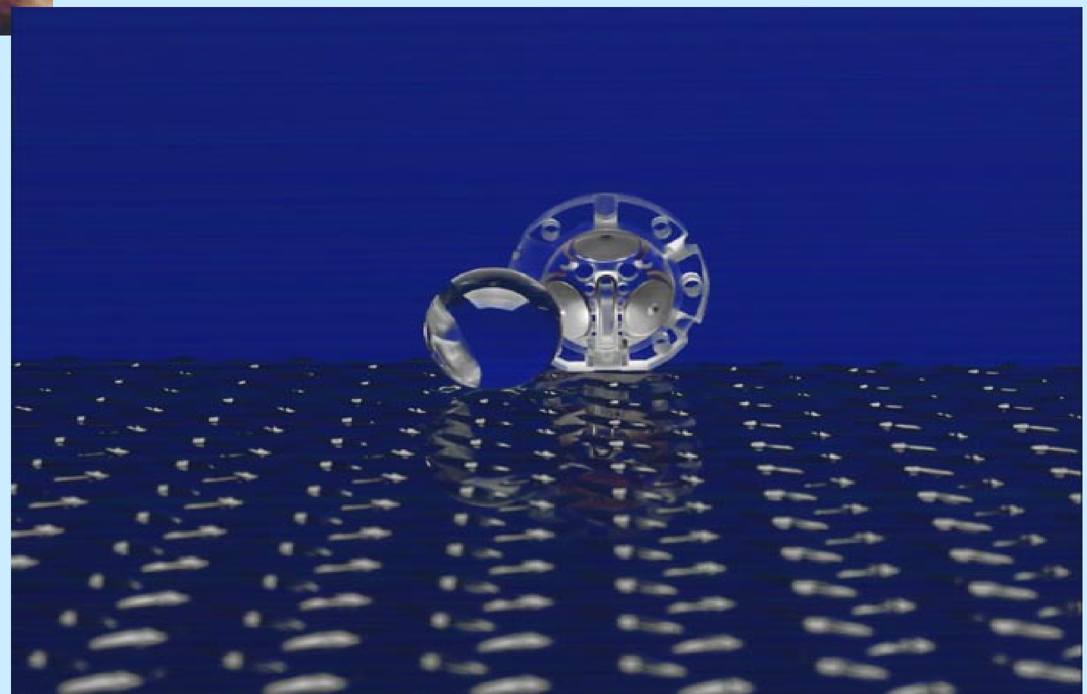
$$\overline{\Omega}=\left(\gamma+\frac{1}{2}\right)\frac{GM}{c^2R^3}(\overline{R}\times\overline{v})+\left(\gamma+1+\frac{\alpha_1}{4}\right)\frac{GI}{2c^2R^3}\left[\frac{3\overline{R}}{R^2}\cdot(\overline{\omega}_e\cdot\overline{R})-\overline{\omega}_e\right]$$


Main GP-B Systems
PICK-UP LOOP
SPIN-UP CHANNEL
GYROSCOPE
ELECTRODE (1 of 6)
PARTING PLANE
LEAKAGE GAS EXHAUST HOLES
Gyroscope
BASE
SUPPORT TUBE
PHOTODIODE READOUT MODUL
BEAM SPLITT ASSEMBL
PRIMARY
TERTIARY
SECONDARY
CORRECTOR PLATE
QUARTZ BLOCK INTERFACE
Telescope
Science Instrument
SPINUP HELIUM TANK
STRUCTURE RINGS
DEWAR
PROBE
LEAD BAG
MU-METAL SHIELD
WINDOWS (2)
QUARTZ BLOCK
PODS
GYROSCOPES
DRAG FREE PROOF MASS
TELESCOPE
SUPERFLUID HELIUM TANK
NORMAL LIQUID HELIUM TANK
PROBE NECK TUBE
PROBE VALVE
Cryogenic Probe
Payload
Space Vehicle
20 MAR 2003
5


GRAVITY DUE TO THE SUN BENDS SPACE.
SO THE EARTH FOLLOWS THAT CURVATURE AROUND.



DMPH



DMPH