Celebration of the 20th Anniversary of GP-B Launch

John Turneaure & Sasha Buchman

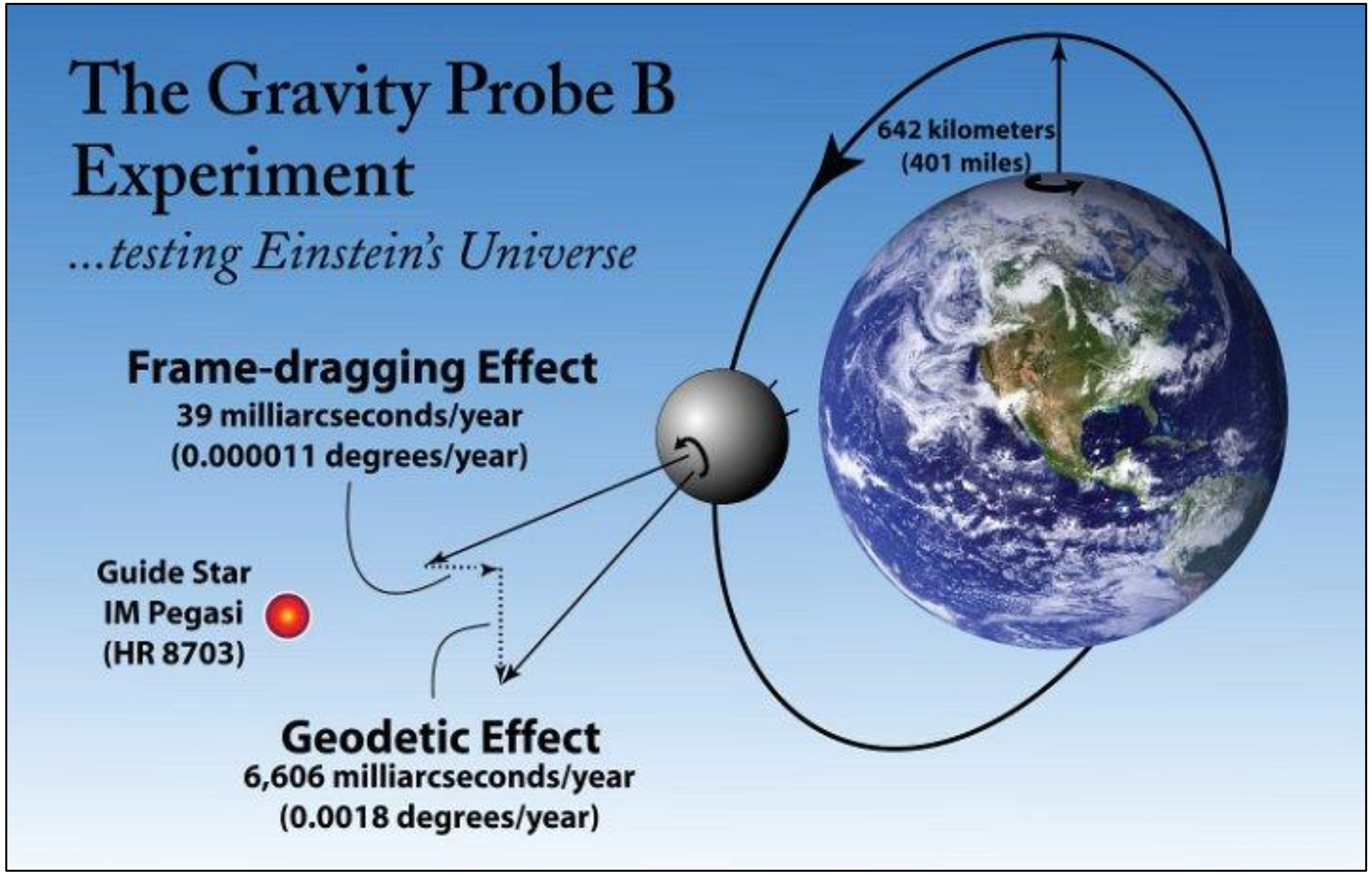
April 20, 2024

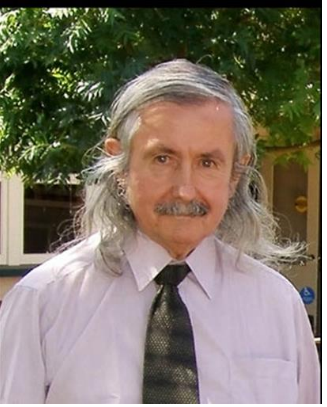
General Relativity: Status of Tests 1959/1960

- 1915/1916: Presentation & publication of General Theory of Relativity by Einstein
- GR theory accounted for an unexplained 38 arc-sec/century advance of the perihelion of Mercury observed by Leverrier in 1845
  - The modern experimental value is 43 arc-sec/century
- First measurements of the bending of starlight during a solar eclipse in 1920 agreed with GR value of -1.75 arc-sec
  - Sobral expedition in Brazil: 1.13 ± 0.07 times GR value
  - Principe island off the coast of Africa: 0.92 ± 0.17 times GR value

1959/1960: The beginning of GP-B

- Leonard Schiff investigated the possibility of testing GR with gyros in Earth polar orbit (G. Pugh – had similar idea)
- Leonard Schiff had discussions with Bill Fairbank and Bob Cannon about this possible experiment
- These discussions piqued Bill Fairbank's interest in pursuing such an experiment

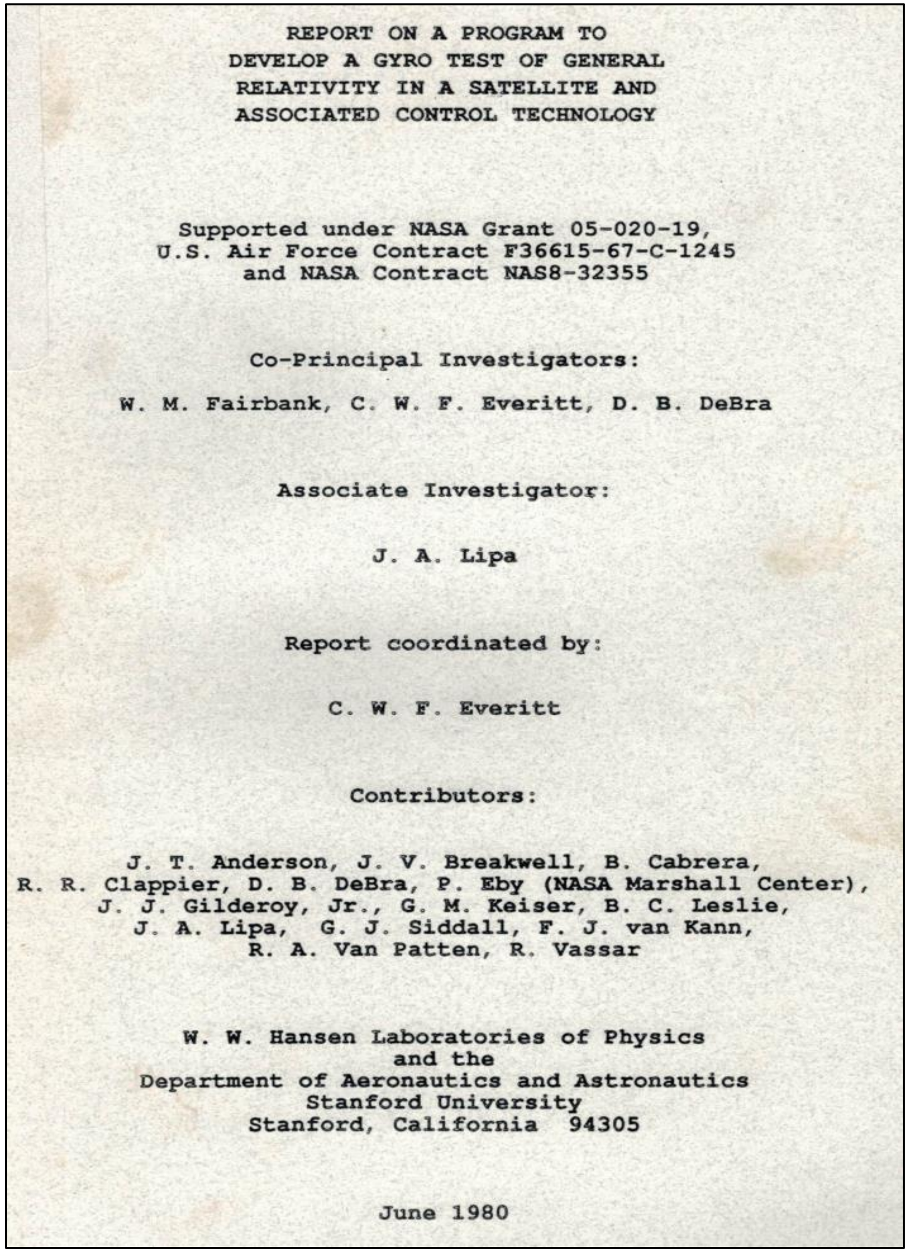




Francis Everitt at Stanford – Fall 1962
20 years of GP-B development: 1962 - 1982

- Started with a blank sheet
- Began study of an experiment to observe the geodetic and frame-dragging precessions of a gyro in Earth polar orbit
- Some key technologies did not yet exist
    - London Magnetic Moment had not yet been observed
    - SQUID magnetometers did not yet exist
- Technical advances and an error analyses made during this period were used as the starting point for R&D for GP-B flight system
- The basic configuration of the experiment was established
- This work was documented in the "Green Book" June 1980

The “Green Book”



REPORT ON A PROGRAM TO
DEVELOP A GYRO TEST OF GENERAL
RELATIVITY IN A SATELLITE AND
ASSOCIATED CONTROL TECHNOLOGY

Supported under NASA Grant 05-020-19,
U.S. Air Force Contract F36615-67-C-1245
and NASA Contract NAS8-32355

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June 1980

1 marcsec = 4.85×10^{-9} radian

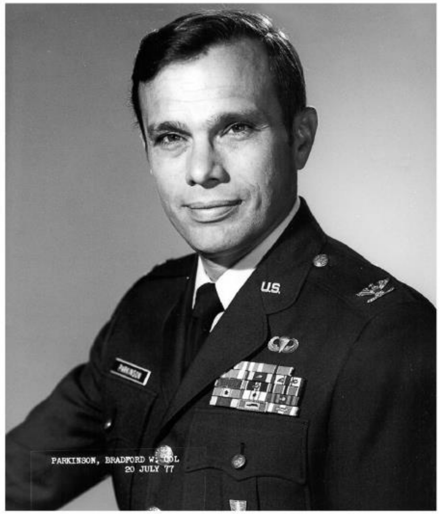
Distance / object width $\cong 2 \times 10^{8}$

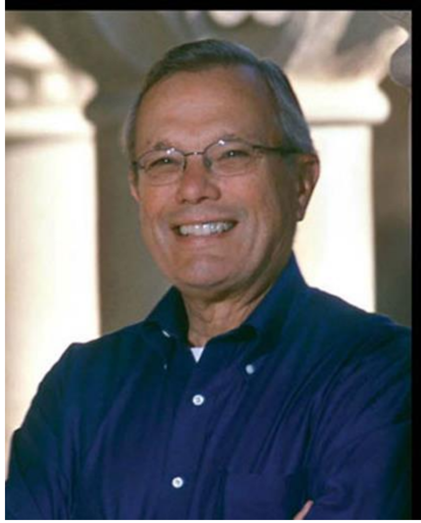
1 marcsec/year = 3×10^{-11} deg/hour

Best gyroscopes $10^{-4} – 10^{-5}$ deg/hour

Seven GP-B Near Zeros

Type of Zero	Value	
• 1. Temperature	1.8 K	(> 1.5 year)
• 2. Rotor asphericity	$< 0.8\ \mu in_{p\text{-}v}$	(Earth < 20 $ft_{p\text{-}v}$)
• 3. Rotor inhomogeneity	$< 3 \times 10^{-7}$	(< 0.3 ppm)
• 3a. Mass unbalance ($\Delta r_m/r$)	$< 5 \times 10^{-7}$	($\Delta r_m < 0.4\ \mu in$)
• 4. Rotor electric dipole moment	$< 10^{-10}$ esu	(UV charge mgm.)
• 5. Residual acceleration	$< 10^{-10}$ g	(Space drag-free)
• 6. Residual pressure	$< 10^{-10}$ torr	($\sim 10^{-14}$ torr)
• 7. Residual magnetic field	$< 10^{-7}$ G	(0.2 ppm of Earth)





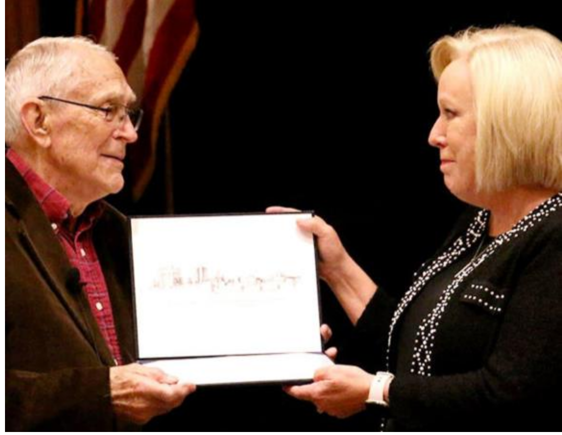
GP-B Development & Preparation for Flight
1984 - 2004

https://einstein.stanford.edu/


Gravity Probe B
Payload
Components
Dewar & Probe
Science
Instrument
Assembly
Telescope
Quartz Block
Image Divider &
Detector Package
Assemblies
Detector Mount Assembly
Gyro Housing Assembly
Gyroscope Rotor & Housing
SQUID with Housing

Gyro rotor and housing halves

Gyro Rotor - I



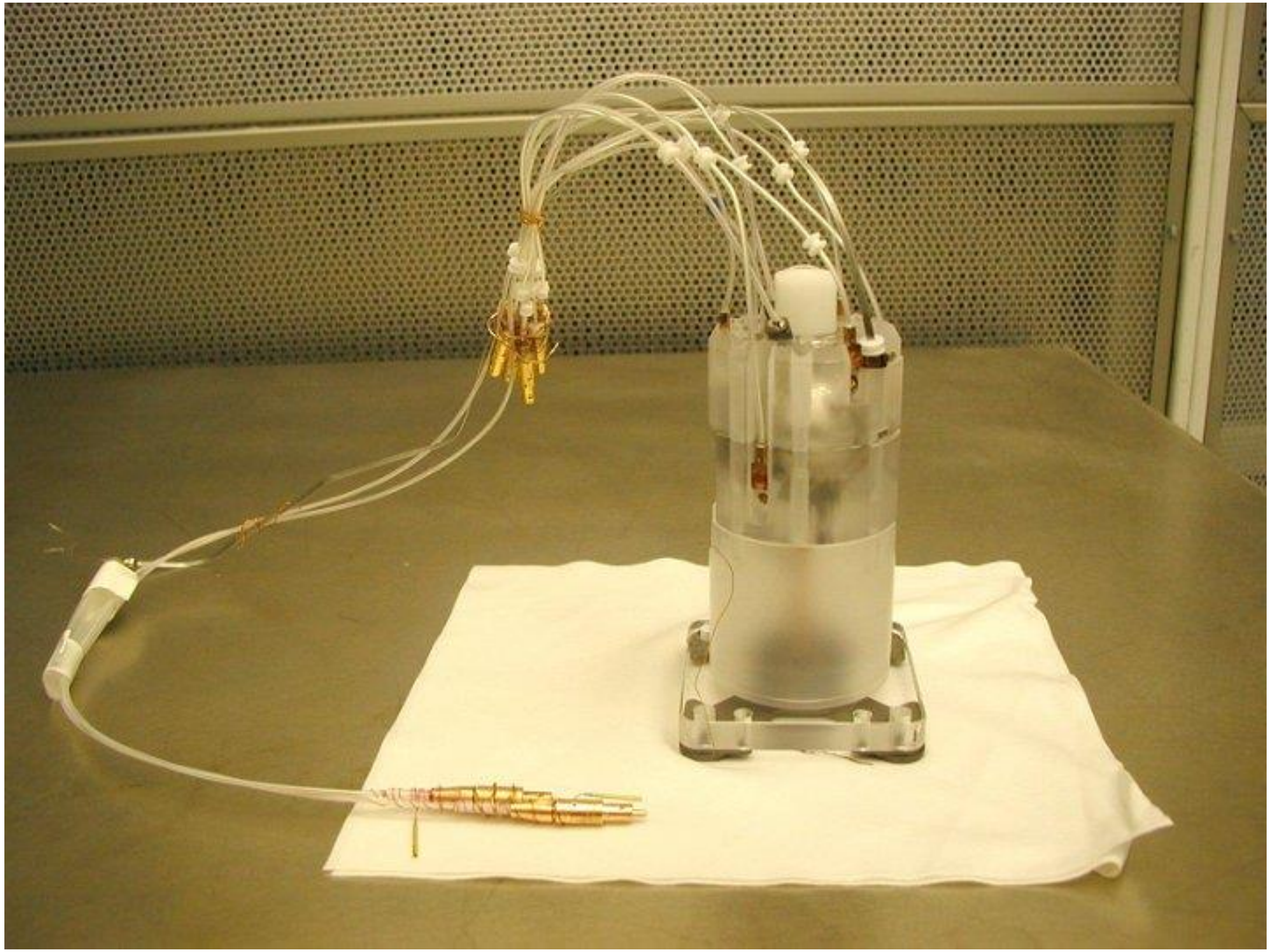
- Heraeus-Amersil (Homosil fused quartz)
  - Crushed, cleaned & fused very pure mined quartz
- University of Aberdeen (Mike Player & students)
  - Verified homogeneity of fused quartz cubes to 3×10^{-7} ($\Delta\rho/\rho$)
- Speedring (Joe Hayden) or Davidson Optronics (Don Davidson)
  - Cubes ground into spheres
- Stanford (initially Marshall Space Flight Center)
  - Designed advanced polishing machine (Dan DeBra)
  - Designed metrology for diameter measurement (Dan DeBra & students)
  - Lapped and polished spheres to final size and sphericity (Frane Marcejla)

Gyro Rotor - II

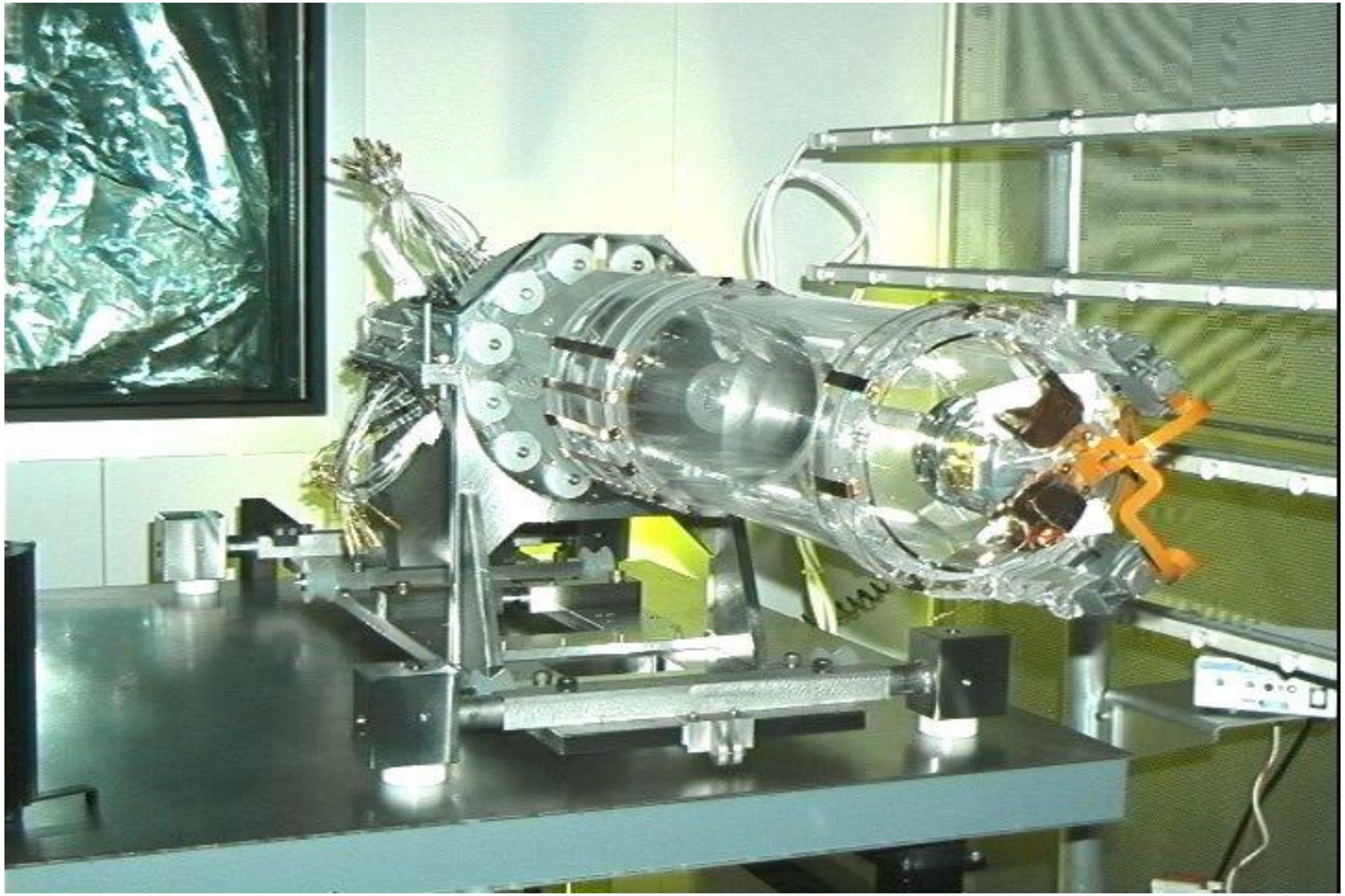
- Stanford / Rank-Taylor-Hobson
  - Roundness of the rotors measured with Talyrond (Frane Marcejla)
  - Produced topographic maps of asphericity
- Stanford (initially Marshall Space Flight Center)
  - Enhanced process for coating the fused-quartz rotors with Nb (Dale Gill)
  - Coated fused-quartz spheres with 1.5 μm thick layer of Nb (Dale Gill)
  - Measured Nb thickness variation using β–backscattering (Dale Gill)
- Nb coated gyro rotors met requirements

Property	Requirement	Achieved
Rotor asphericity ($\Delta r_a/r$)	$< 3 \times 10^{-6}$	$< 2 \times 10^{-6}$
Rotor mass unbalance ($\Delta r_m/r$)	$< 5 \times 10^{-7}$	$< 5 \times 10^{-7}$

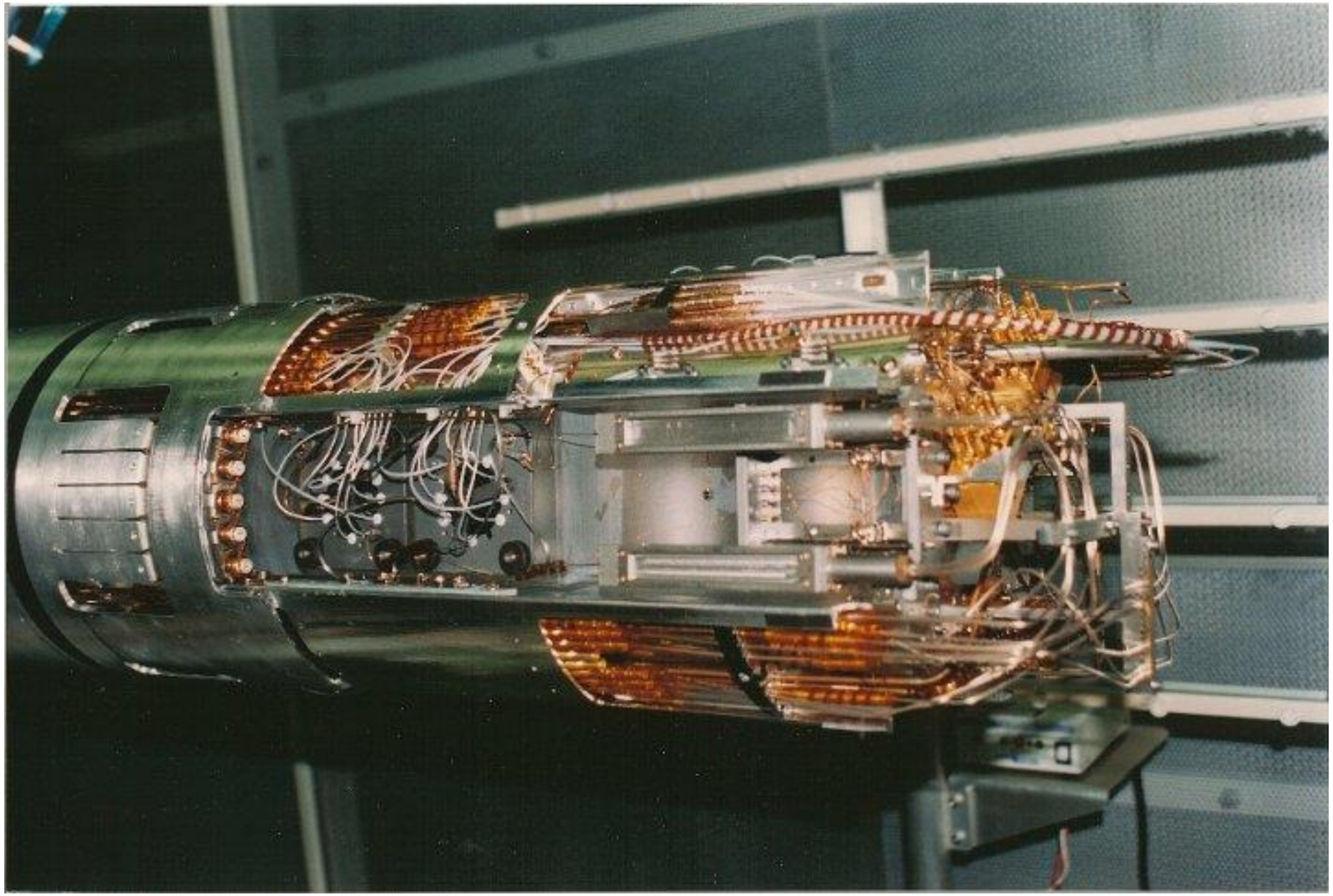
Assembled gyro ready for installation in QB



Gyros & Telescope mounted to Quartz Block



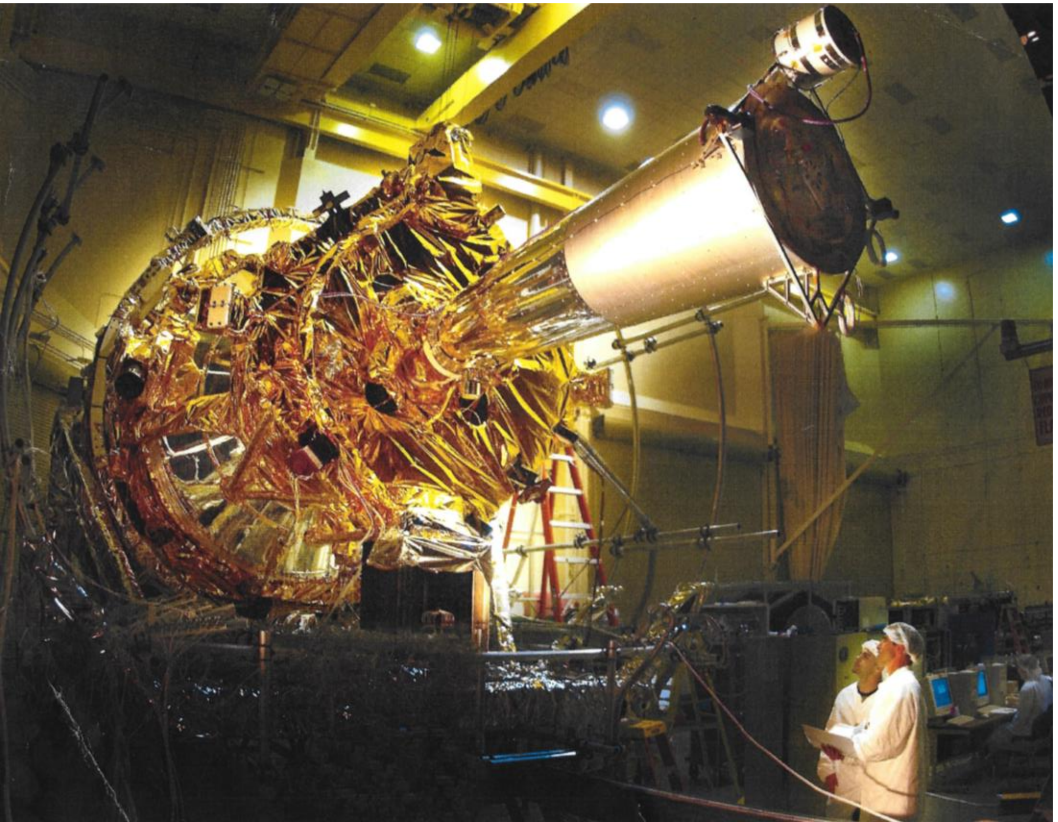
Science Instrument Assy Mounted in Probe



Probe in Vacuum Can

Instrument under test in flight dewar

Assembled Spacecraft



Spacecraft mounted on Delta II launch vehicle

Launch of GP-B on
April 20, 2004

Mission operations center at Stanford

On-Orbit Success

- All four gyroscopes were suspended and spun up to > 60 Hz
  - Gyros spun freely for entire mission
  - Gyro SQUID readout systems functioned well
  - Trapped flux in gyros met requirements (lead bag survived launch)
- Telescope and its electronics worked as designed
- ATC system provided needed attitude and drag-free performance
  - Guide star was acquired
- Dewar lifetime exceeded 16-month design requirement

Data analysis issues & results





- Data analysis surprises complicated analysis (patch effect)
    1. Larger polhode damping than expected
    2. Larger misalignment torques than expected
    3. Large torques at roll-polhode resonances
- Data analysis model was adapted to account for these surprises
- Final results for the ensemble of the four gyroscopes

Precession	GR Prediction (mas/yr)	GP-B Result (mas/yr)
Geodetic NS	-6606.1	-6601.8 ± 18.3
Frame-Dragging WE	-39.2	-37.2 ± 7.2

GP-B results published in PRL in 2011

Gravity Probe B: Final Results of a Space Experiment to Test General Relativity

C. W. F. Everitt, D. B. DeBra, B. W. Parkinson, J. P. Turneaure, J. W. Conklin, M. I. Heifetz, G. M. Keiser, A. S. Silbergleit, T. Holmes, J. Kolodziejczak, M. Al-Meshari, J. C. Mester, B. Muhlfelder, V. G. Solomonik, K. Stahl, P. W. Worden, Jr., W. Bencze, S. Buchman, B. Clarke, A. Al-Jadaan, H. Al-Jibreen, J. Li, J. A. Lipa, J. M. Lockhart, B. Al-Suwaidan, M. Taber, and S. Wang

Volume 106, Number 22, 3 June 2011
221101-1–221101- 4

GP-B results published in Classical and Quantum Gravity, 2015

The Gravity Probe B test of general relativity

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We remember absent colleagues

• Leonard Schiff	The GP-B concept
• Bill Fairbank	The inspiration for GP-B
• Bob Cannon	Strong supporter of GP-B from the beginning
• Yueming Xiao	Gyro testing, low-flow low-temperature He gas spin-up, observation of London Magnetic Moment of gyro rotor
• Bob Farley	Telescope electronics
• Don Davidson	Telescope design, gyro housing design and much more
• Dan DeBra	Micro-thruster development, gyro metrology & advanced polishing machine design, integrated telescope testing & artificial star
• Dick Parmley	Complex flight superfluid Dewar & instrument probe
• Bill Reeve	Restoration of thermal contact of probe to Dewar heat stations
• Dei-Yu Pan	Rotor polishing & metrology