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Gravity Probe B:

A Marriage of Physics & Engineering (1961 to 2007)

Devices, Controllers, and Spinoffs

Prof. Brad Parkinson
co-PI

Aeronautics and Astronautics
Stanford University

Acknowledgements : the Engineers

(John Turneaure has acknowledged the Physicists)

- **Stanford and Lockheed Engineers**
  - Dan DeBra (co-PI), Bill Benzce, Dick Van Patten, Gaylord Green, Bill Reeve, Richard Vassar, Hugh Daugherty, Jon Kirschenbaum, Don Davidson, Lou Herman, Dick Parmley, Jeremy Kasdin, Rob Brumley, Gregg Gutt, Clark Cohen, John Bull, Awele Ndili, Ben Lange *and many others*
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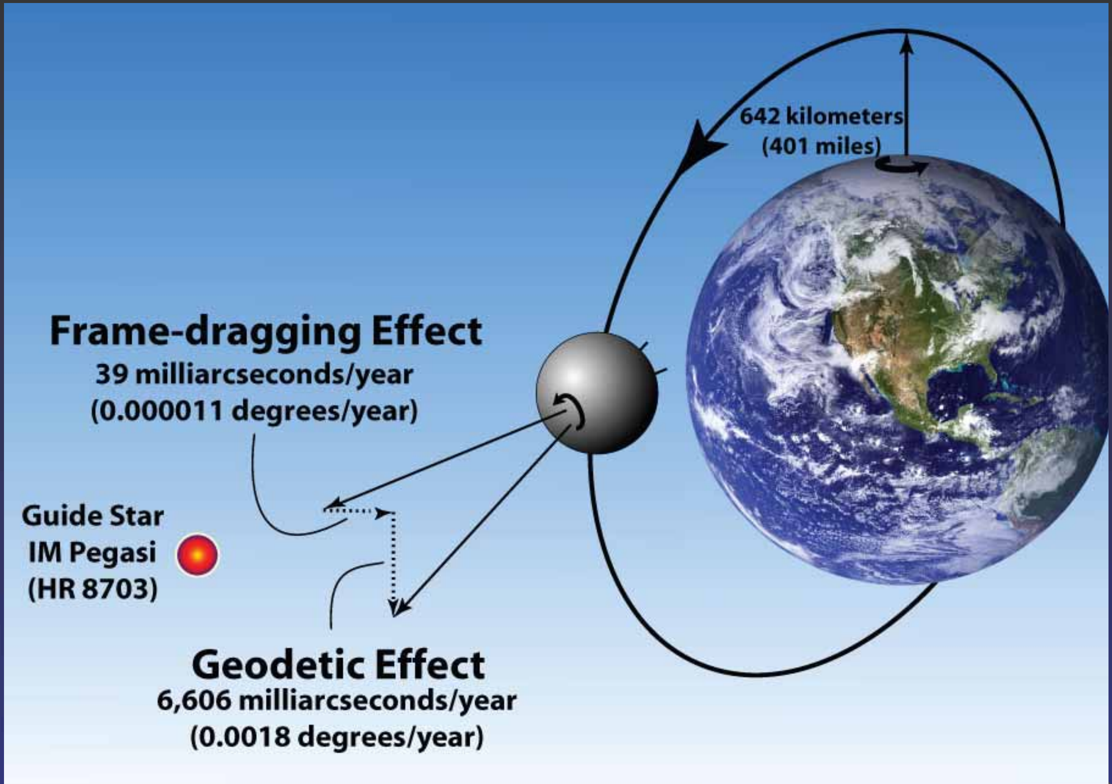
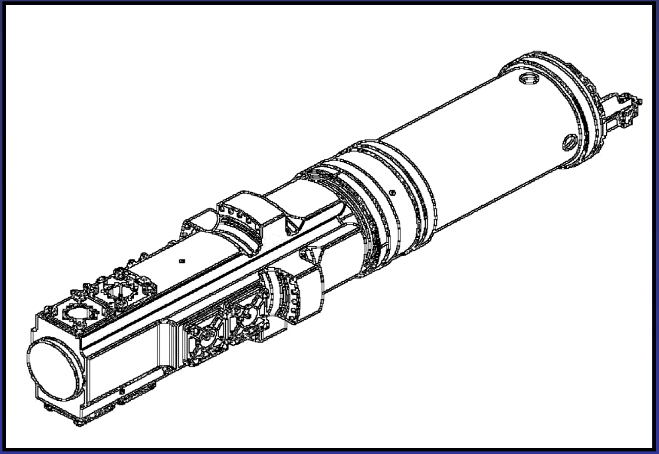
  - Rex Geveden, Tony Lyons, Buddy Randolph, Todd May, Mark West, Bill Till, Wilhelm Angele, Dick Potter *and others*
- **Support from many other individuals at various institutions**
- **GP-B funded and supported by NASA**

The Relativity Mission Concept





> *"If at first the idea is not absurd,*
> *then there is no hope for it."*
> -- A. Einstein

Short History

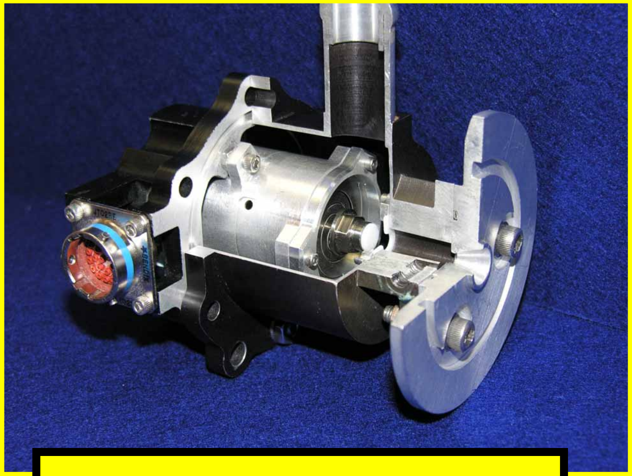

Schiff


Cannon


Fairbank

- **Conceived by Professor Leonard Schiff 1959**
- **Three Naked Professors (Len Schiff, Bob Cannon, Bill Fairbank) 1960**
- **A Marriage of Engineering and Physics for 46 years**
- ***The Near Zero philosophy of GP-B***
  - + “Natural *Averaging*” (of errors and disturbances)

Introducing Three Unique GP-B Devices



GP-B Micro Thruster

GP-B Mass-Trim Mechanism

GP-B Gyro Suspension System

Topics for This Talk

Key Engineering Devices and Controllers

- **Control Capabilities enabled by GP-B micro thrusters**
  - First 6 DOF Active Control
- **Gyro Suspension System (working range of 10^8)**
  - Essential for measuring gyro position and centering gyros
- **Spin-Offs enabled by GP-B**
  - “Einstein’s Landing System” et. al.

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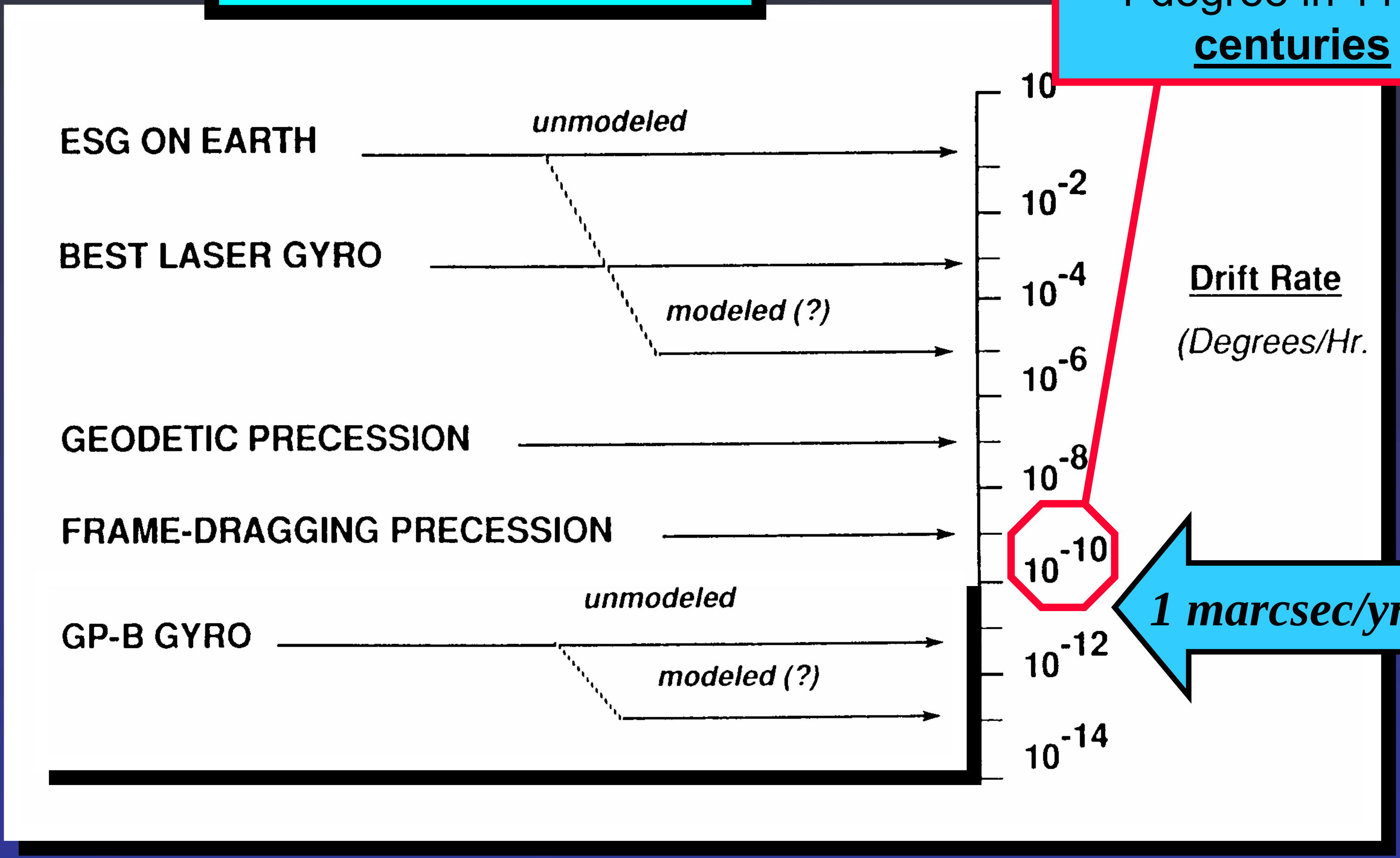
Design of Gravity Probe B Payload and Spacecraft

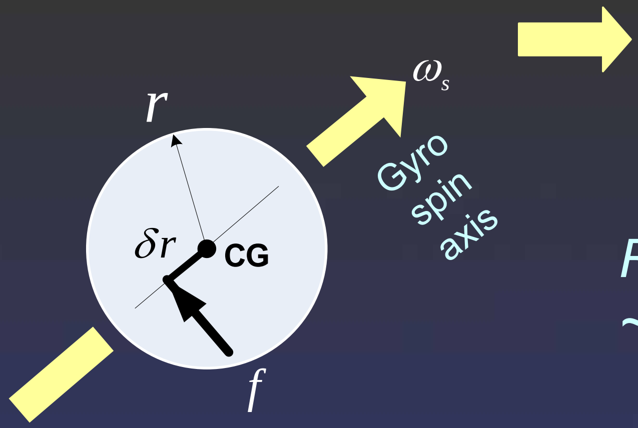
Why go to space?

10^{-10} deg/hr. =
1 degree in 11,400
centuries



1 marcsec/yr

Near-Zero: Mass Balance + Cross Axis Force



External forces acting through center of force, different than CM

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

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

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

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

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

Mass Balance Requirements: $$\frac{\delta r}{r} < \frac{2}{5}\frac{r\omega_s}{f}\Omega_0$$

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

(ridiculous – 10^{-4} of a proton!)

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

(unlikely – 0.1 of H atom diameter)

GP-B drag-free (f ~ 10^{-11} g cross- track average) $\frac{\delta r}{r} < 5.8 \times 10^{-6}$

(straightforward – 100 nm)

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

Selected Control Goals for GP-B

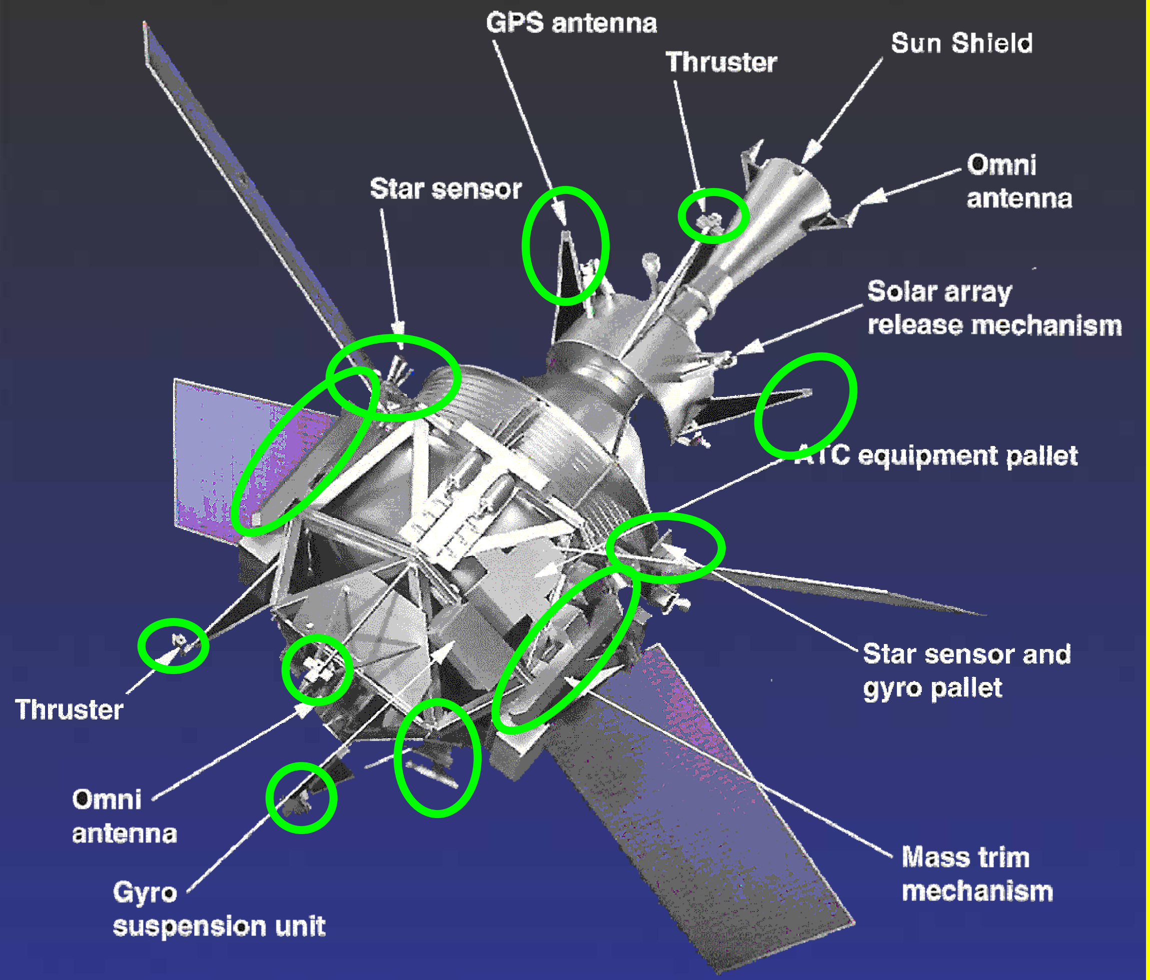
Selected Near Zeros

- Control to a ***"Drag-free" $10^{-11}g$*** on the cross axis
- Control ***Gyros to the Center*** of the Housing (avoid collisions/minimize torques)

Controlling to achieve Natural Averaging

- **Control the *Initial Orbital Plane* to contain direction to guide star and earth's spin axis**
  - Averages Gravity Gradient
  - Separates Geodetic and Frame Dragging
- **Control *Spacecraft Roll* to be Phase-Locked about guide star direction (±20 arc sec)**
  - Torque Averaging
  - Reduces Squid 1/f noise
  - Temperature Averaging
- **Control each gyro *Spin Axis* to initially point to Guide Star**
- **Control *DC Suspension* to reverse sign (chop) for less disturbance**

The Overall Space Vehicle



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

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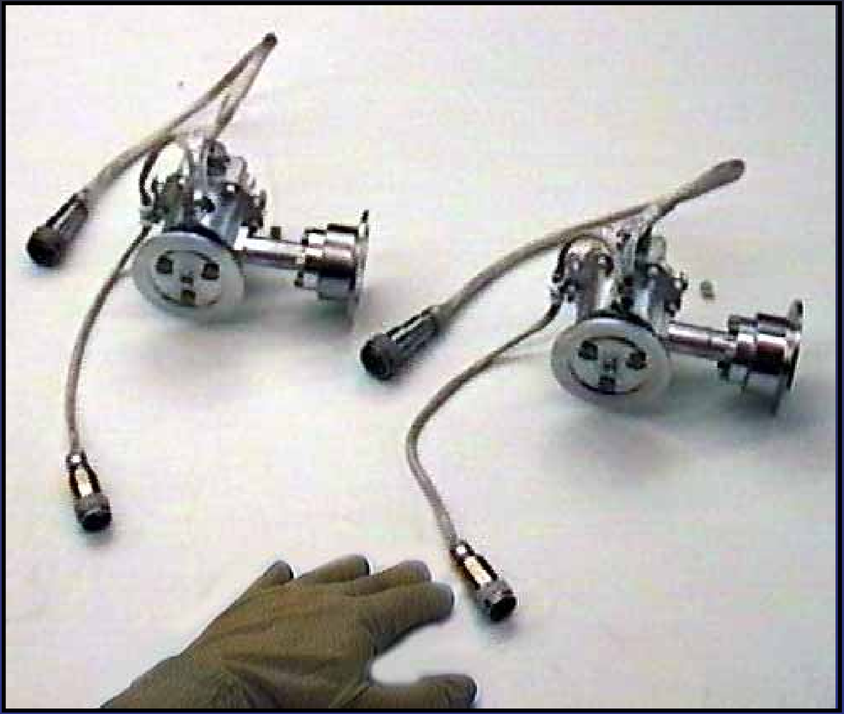
Six DOF Spacecraft Control

First *Actively* Controlled “6 DOF” Spacecraft

Controller	DOF	Reqmnt.	Sensor	Actuator	Control Computation
Pointing at Guide Star -	2	20 marcsec	Science	**Micro**	Spacecraft
“Drag Free” Gyro	3	10^{-11} g RMS			
Other Gyros “Centered”		0.3 nano-m at roll			
Spacecraft Roll Phase-locked	1	20 arcsec rms			
Initial Orbit		< 500 m from Pole			
Axis of Maximum Inertia		Thruster Capability			
Spacecraft CM on Drag Free Gyro Spin Axis		0.3 mm			

Micro-Thrusters

Capture the He Boil Off and chase the drag-free Gyroscope



- Controls orbital cross axis component to < 0.0003 in.
- Drag free pioneered at Stanford by Dan DeBra
  - First demo in 1972 (Transit)
- Unusual “proportional” control (not on/off)

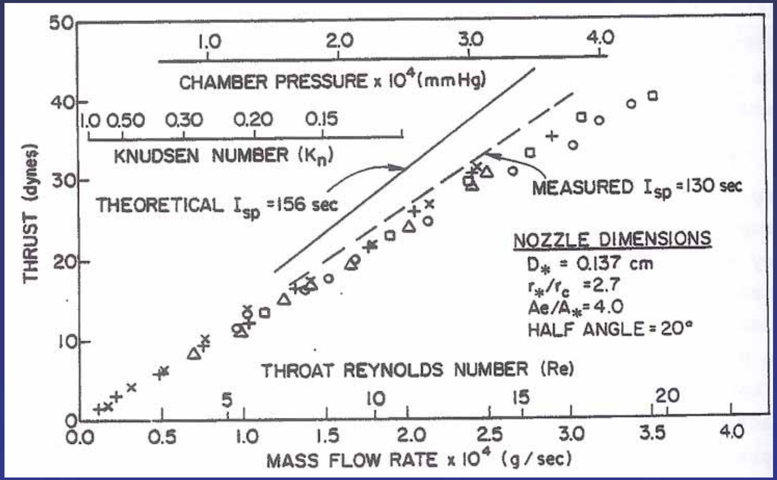
Six Degree of Freedom Control

Helium Boil-off = Propellant

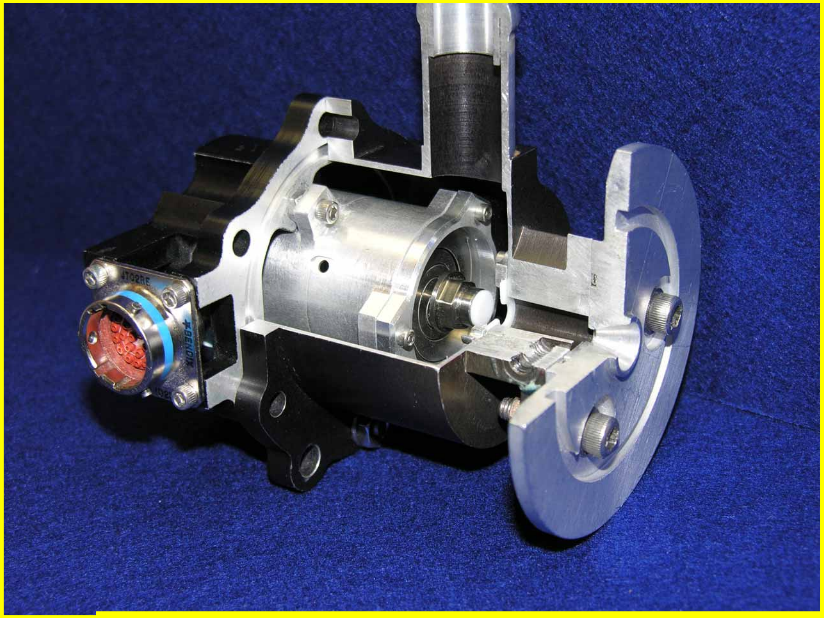
- **A very different control system**
  - 16 proportional cold gas thrusters.
  - Propellant: Helium boil-off @ 12 torr
  - Isp = 130 sec; 6.5 mg/sec flow

ATC Performance:

- Inertial Pointing to <20 marc-s
- Translation to < 10^{-11} g average
- 6 DOF control

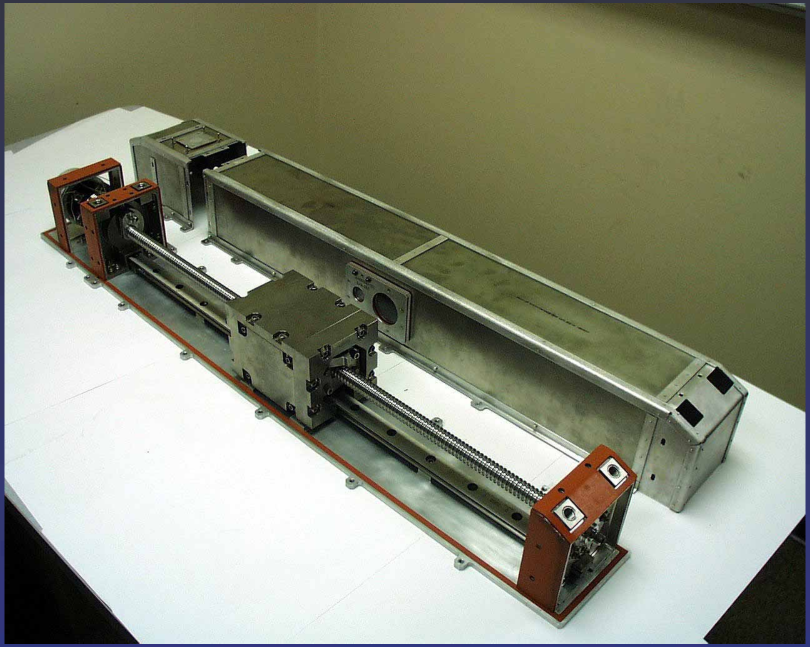


Specific impulse vs. mass flow rate



Prototype thruster cutaway view

Mass Trim to adjust CM and Axis of Inertia



7 Mass Trim Mechanisms

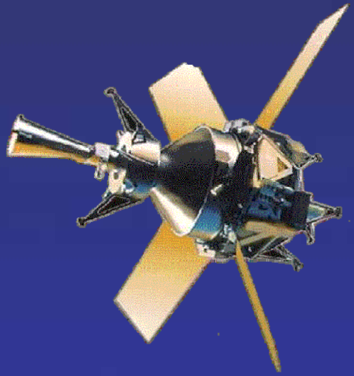
(Lockheed Martin and Litton Poly-Scientific)

GP-B Launch - 20 April 2004

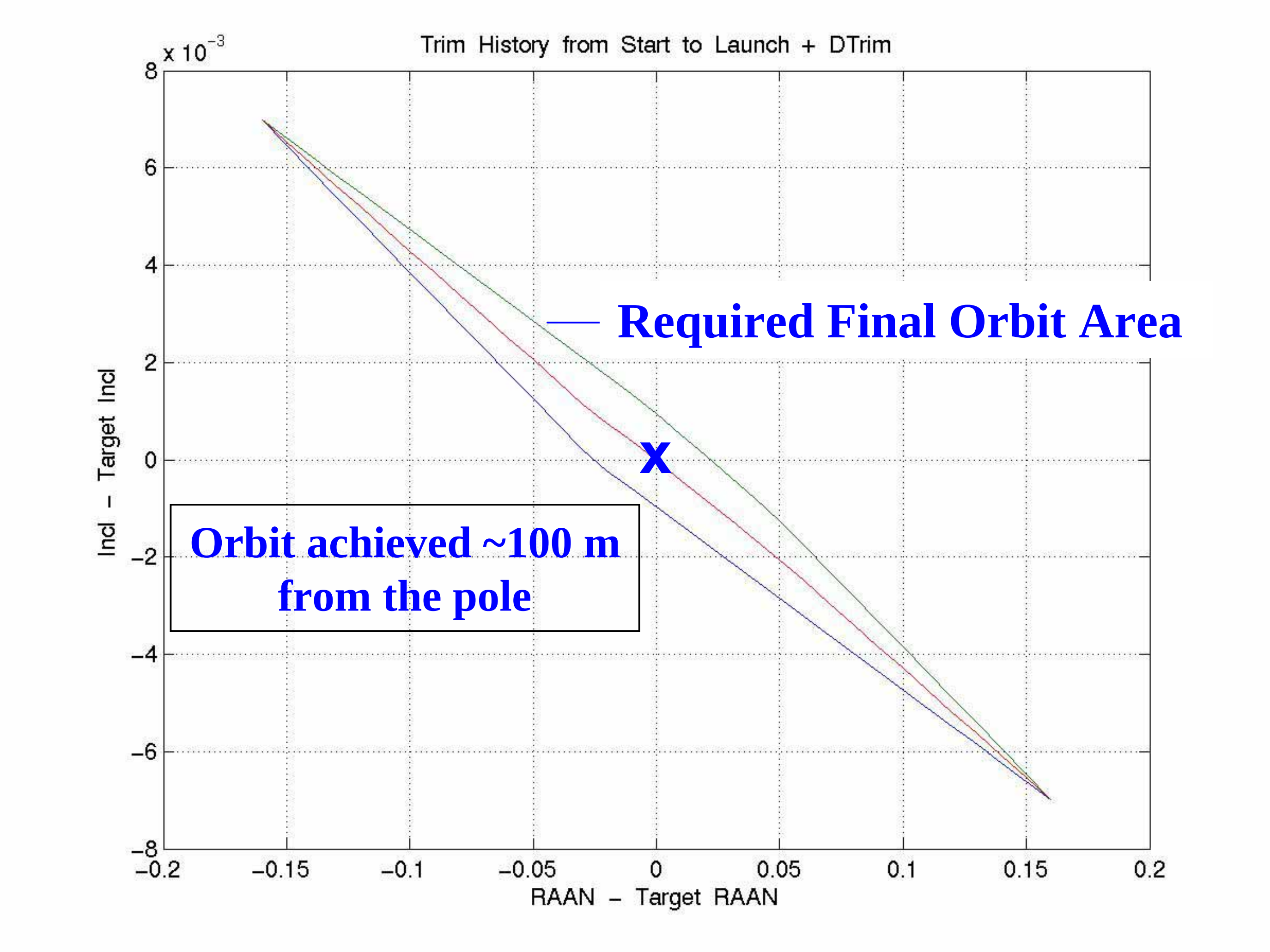
Fairing Installation

Launch!

Release from booster.



Boeing & Luck -- A Near Perfect Orbit



Required Final Orbit Area

Orbit achieved ~100 m from the pole

Delta II Nominal Accuracy

Gyro Suspension System

Schizophrenic *requirements = a challenging design!*

“Do Nothing”:

Minimize Torques

- Slow response
- Low voltages
- SQUID compatible – low EMI.
- “Zero force” drag-free control.

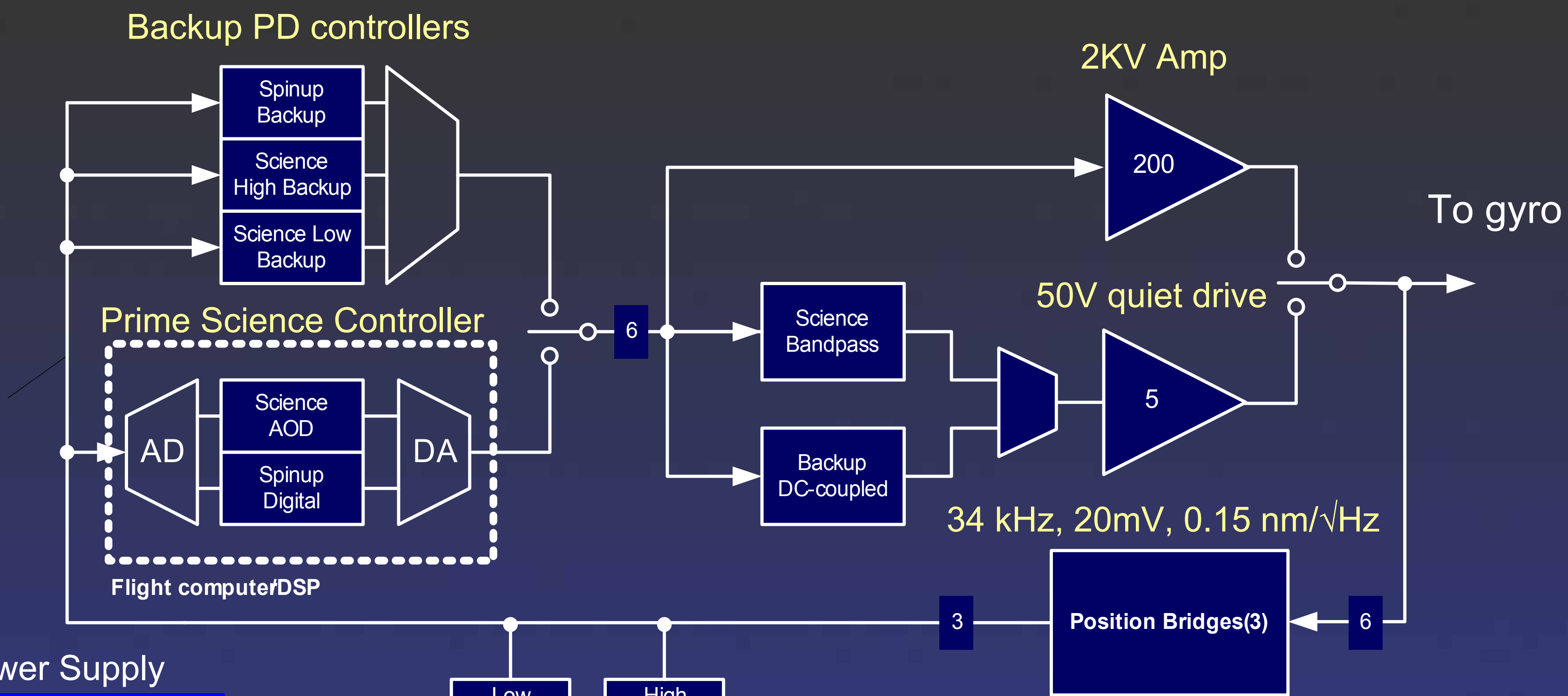
“DO NOT let the rotor crash”:

Protect the Rotor

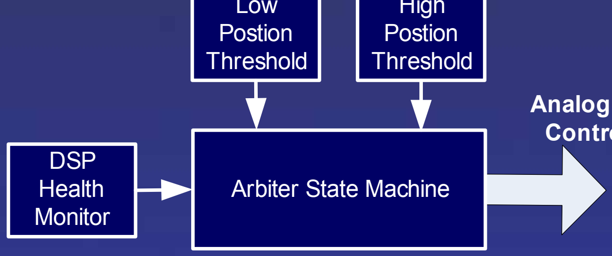
- Ground test and spinup control.
- Fast response/bandwidth.
- High suspension voltages.
- High position bridge SNR
- Robust control algorithm.

- Spaceflight compatible
  - **Slow computing resources.**
  - **Endure environment vibration, shock, radiation, thermal, vacuum**
  - **Operate semi-autonomously with low drift and tight power budget.**

Suspension System Hardware



34 kHz, 20mV, 0.15 nm/√Hz



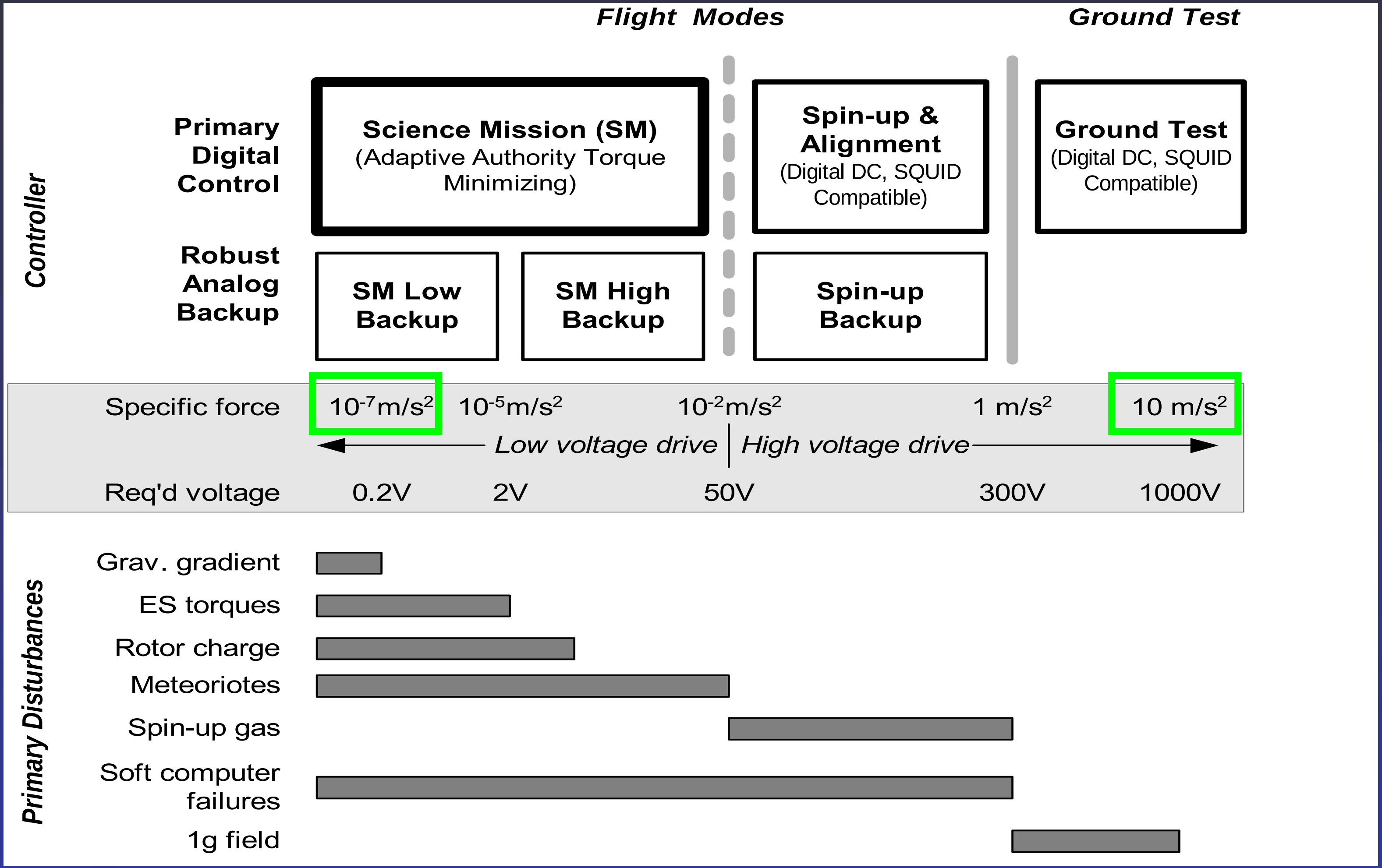
Autonomous control system Arbiter

DSP + Power Supply

Analog drive, Backup control

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**	**Spin-up Backup**	

Specific force	10^{-7}m/s^2	10^{-5}m/s^2	10^{-2}m/s^2	1 m/s^2	10 m/s^2
	Low voltage drive			*High voltage drive*	
Req'd voltage	0.2V	2V	50V	300V	1000V

Primary Disturbances

Grav. gradient

ES torques

Rotor charge

Meteoriotes

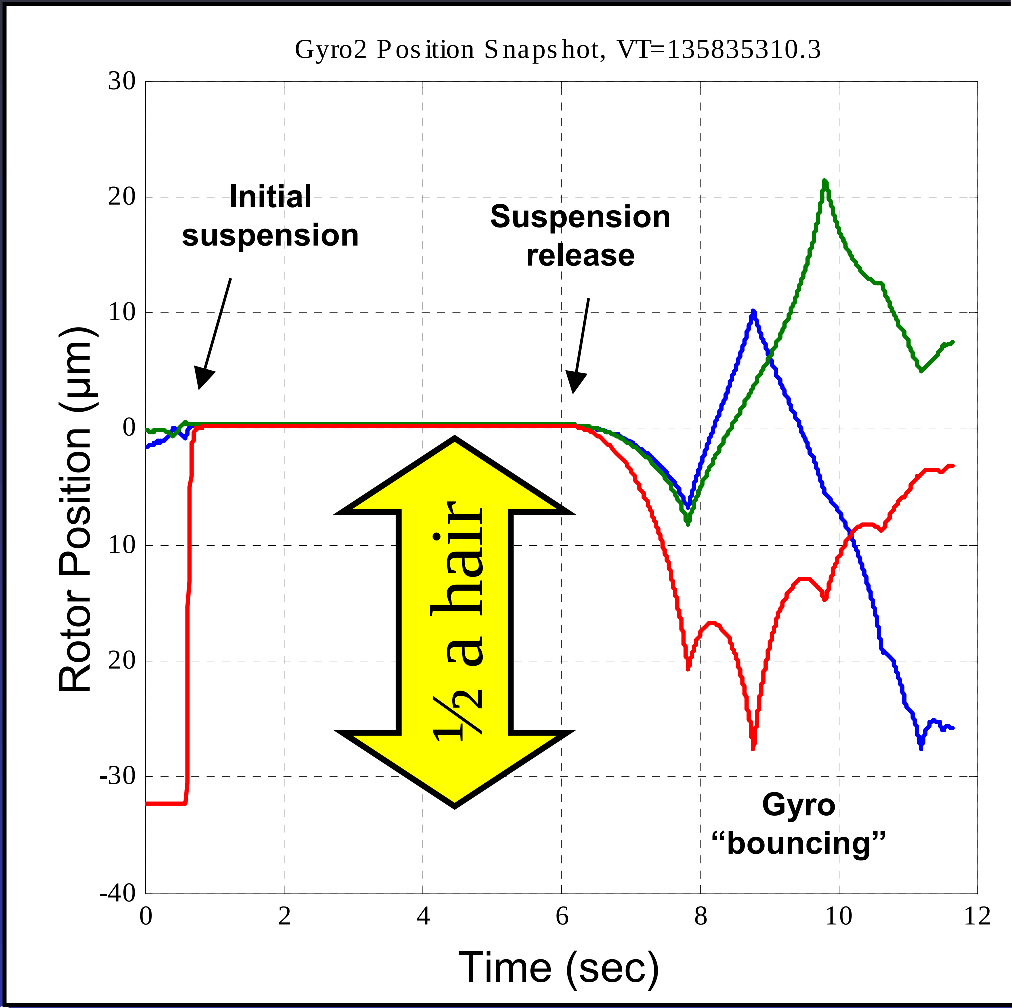
Spin-up gas

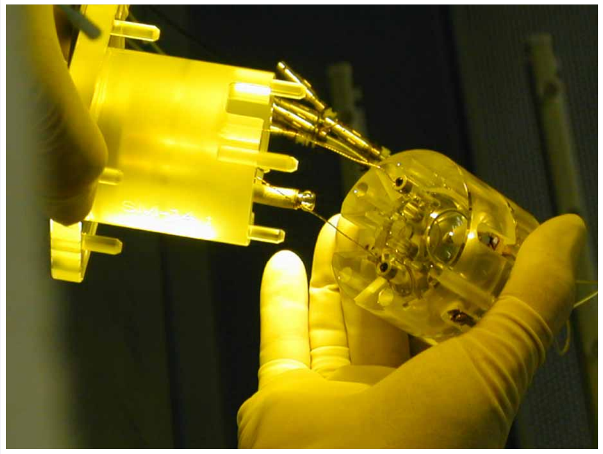
Soft computer failures

1g field

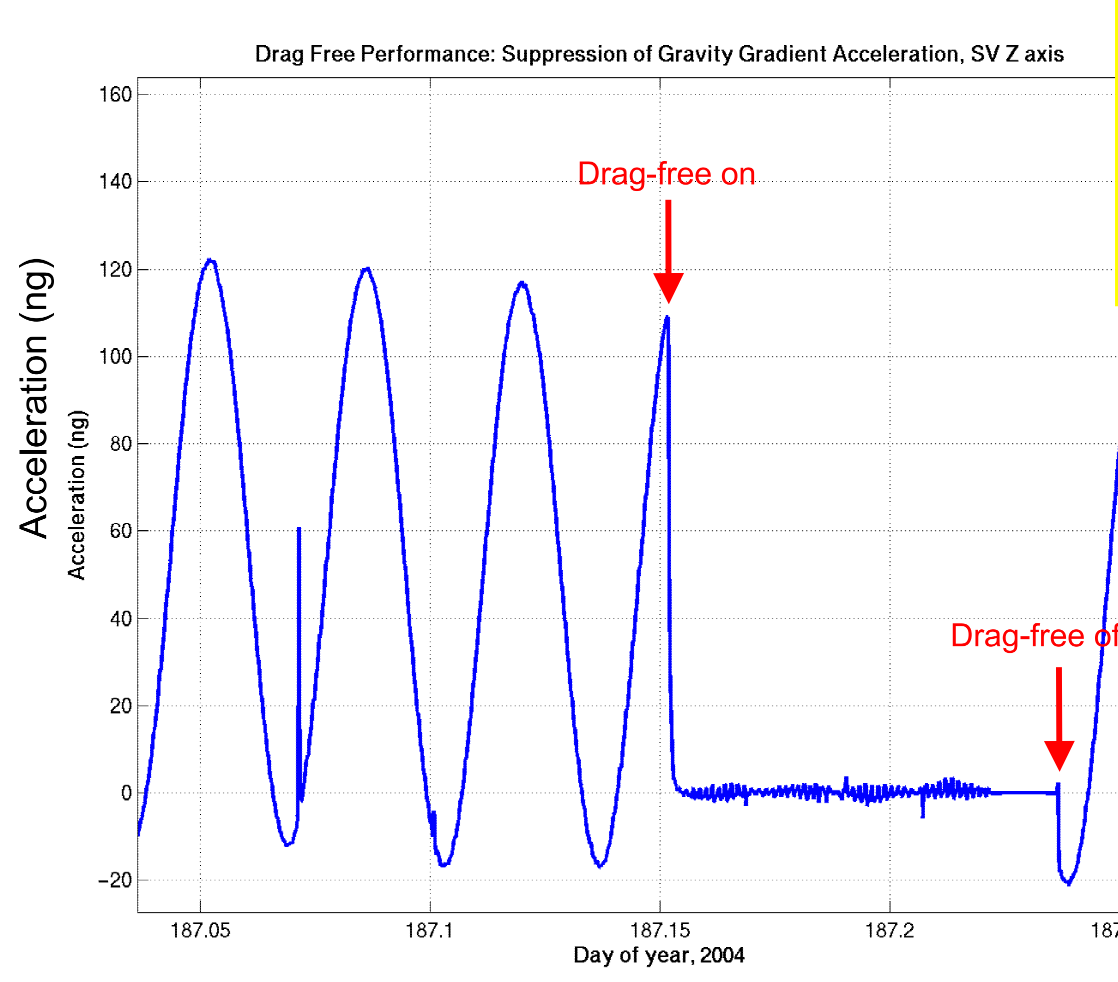
GP-B Gyro On-Orbit Initial Liftoff

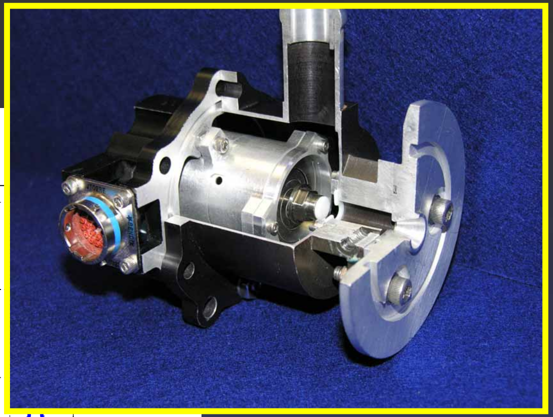
Initial Gyro Levitation and De-levitation using analog backup system





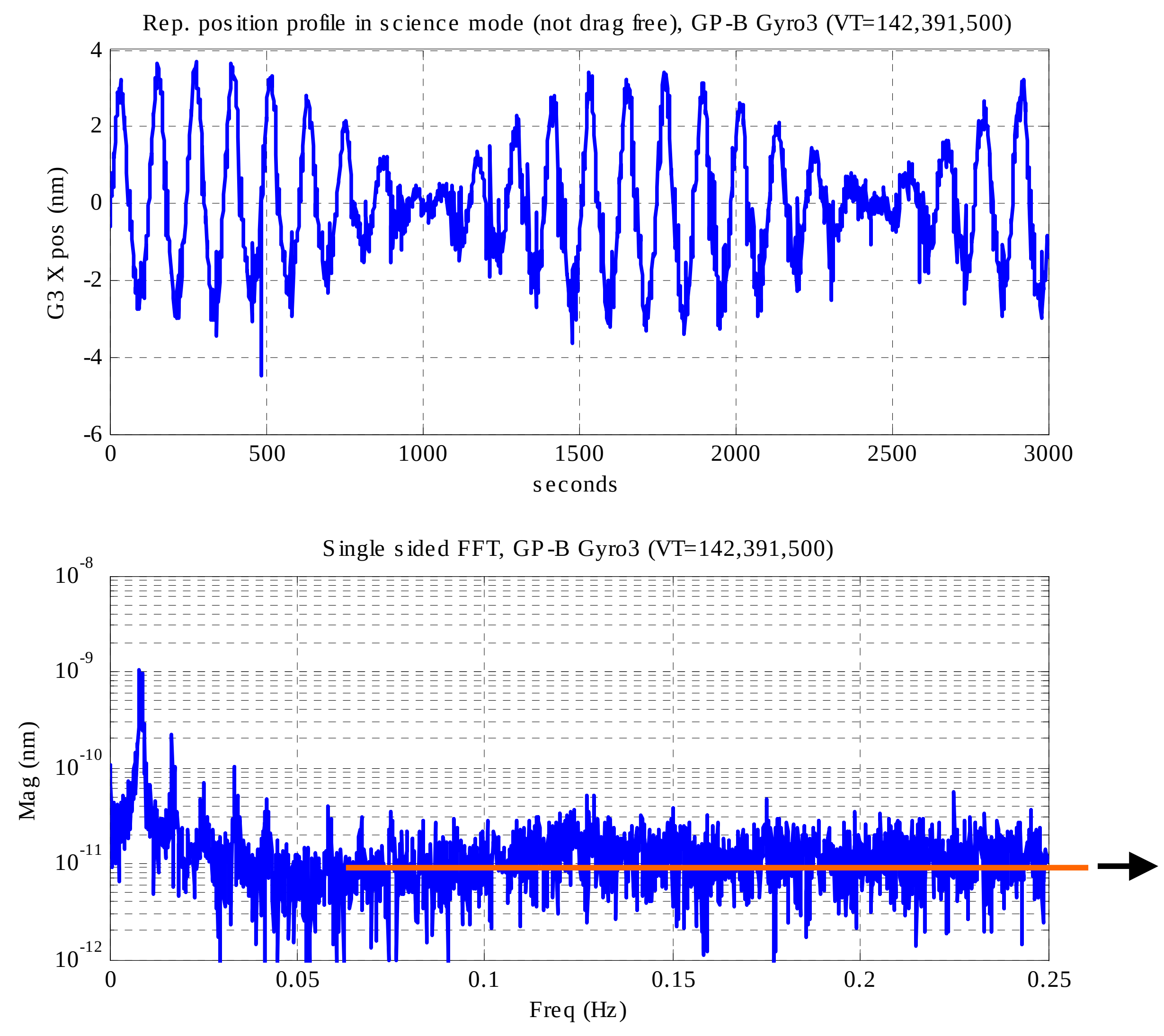
Drag-Free:





Demonstrated accelerometer (drag free) performance better than 10^{-11} g DC to 1 Hz

Suspension Performance On-Orbit



Rep. position profile in science mode (not drag free), GP-B Gyro3 (VT=142,391,500)

Single sided FFT, GP-B Gyro3 (VT=142,391,500)

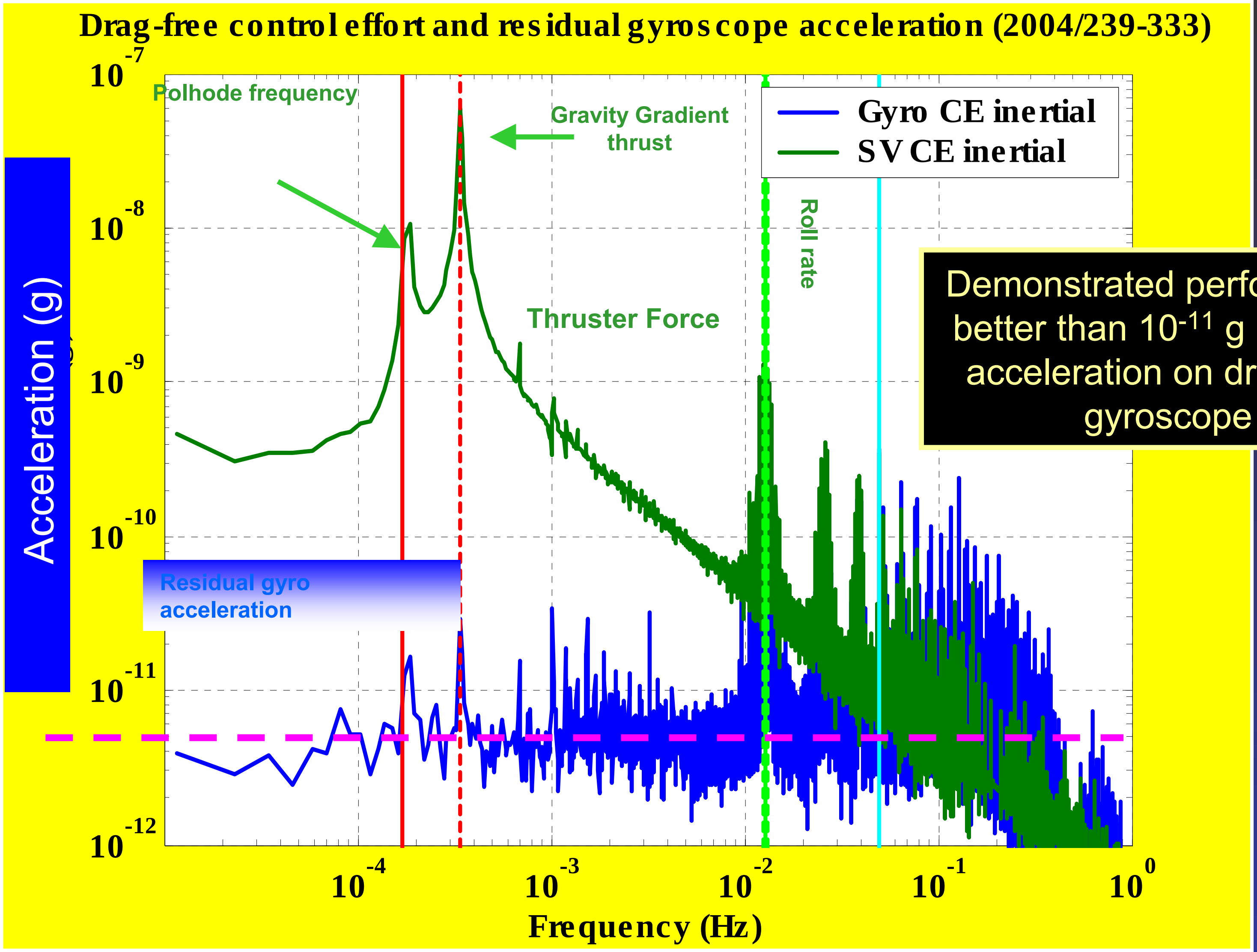
<u>Gyro position</u> – non drag-free gravity gradient effects in Science Mission Mode

<u>Measurement noise </u>– 4.5 Angstroms rms

- About1 Silicon Atom

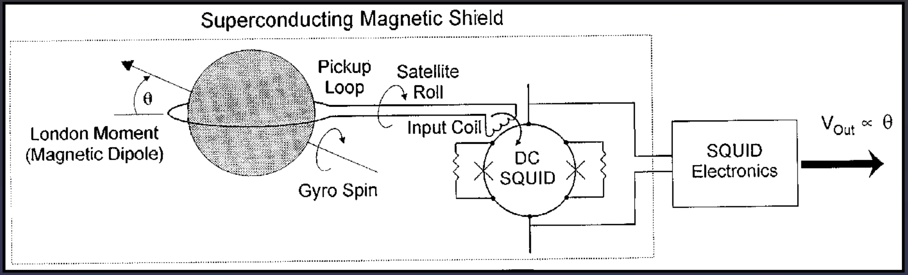
→ *Noise floor*

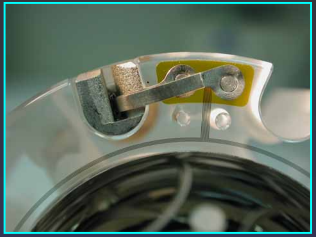
Drag Free Control


Drag-free control effort and residual gyroscope acceleration (2004/239-333)

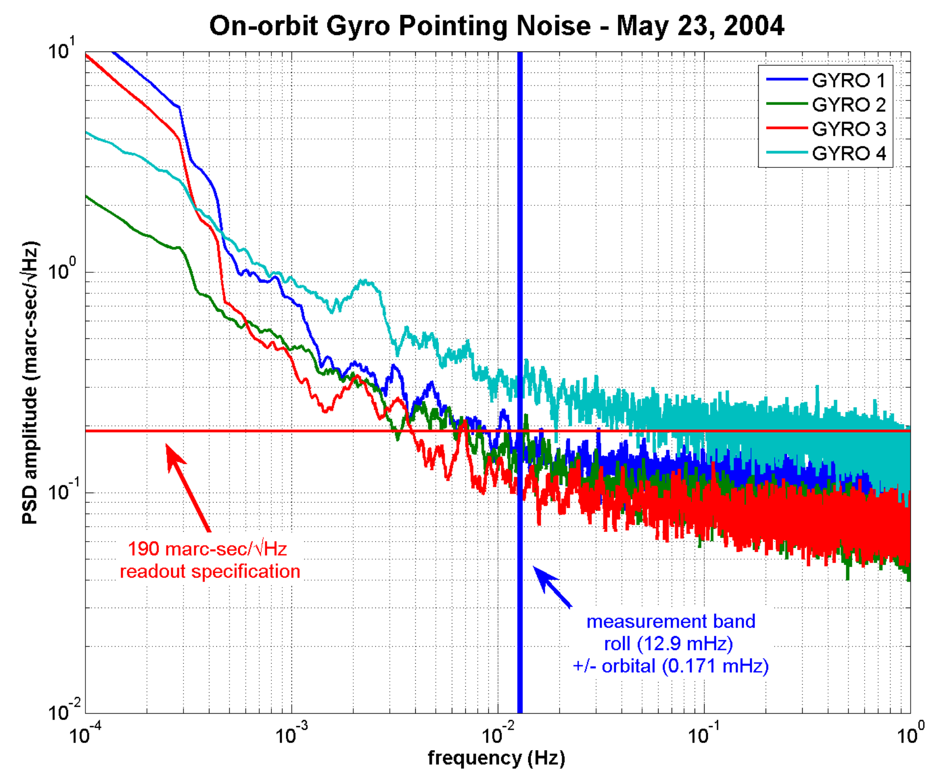
Demonstrated performance better than 10^{-11} g residual acceleration on drag free gyroscope

Rolling reduces low frequency squid noise (and helps in many other respects)





“SQUID” 1 marcsec in 10 hours

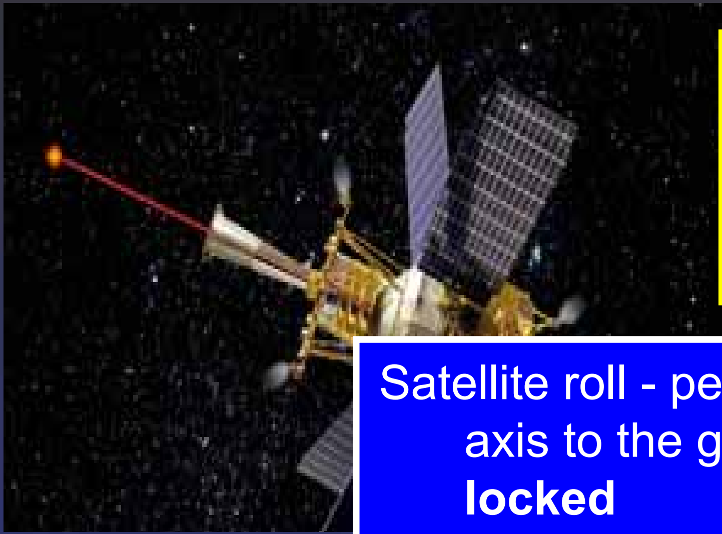


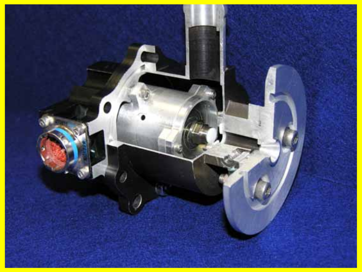
On-orbit Gyro Pointing Noise - May 23, 2004

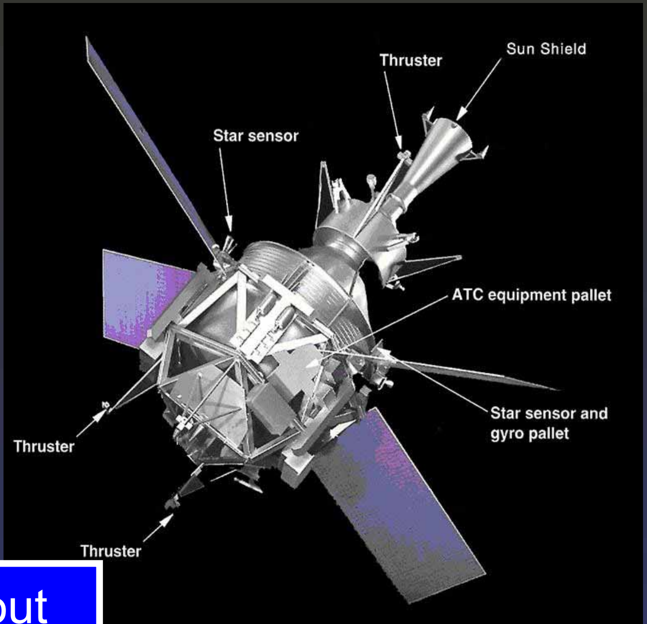
190 marc-sec/√Hz
readout specification

measurement band
roll (12.9 mHz)
+/- orbital (0.171 mHz)

GP-B Roll Phase



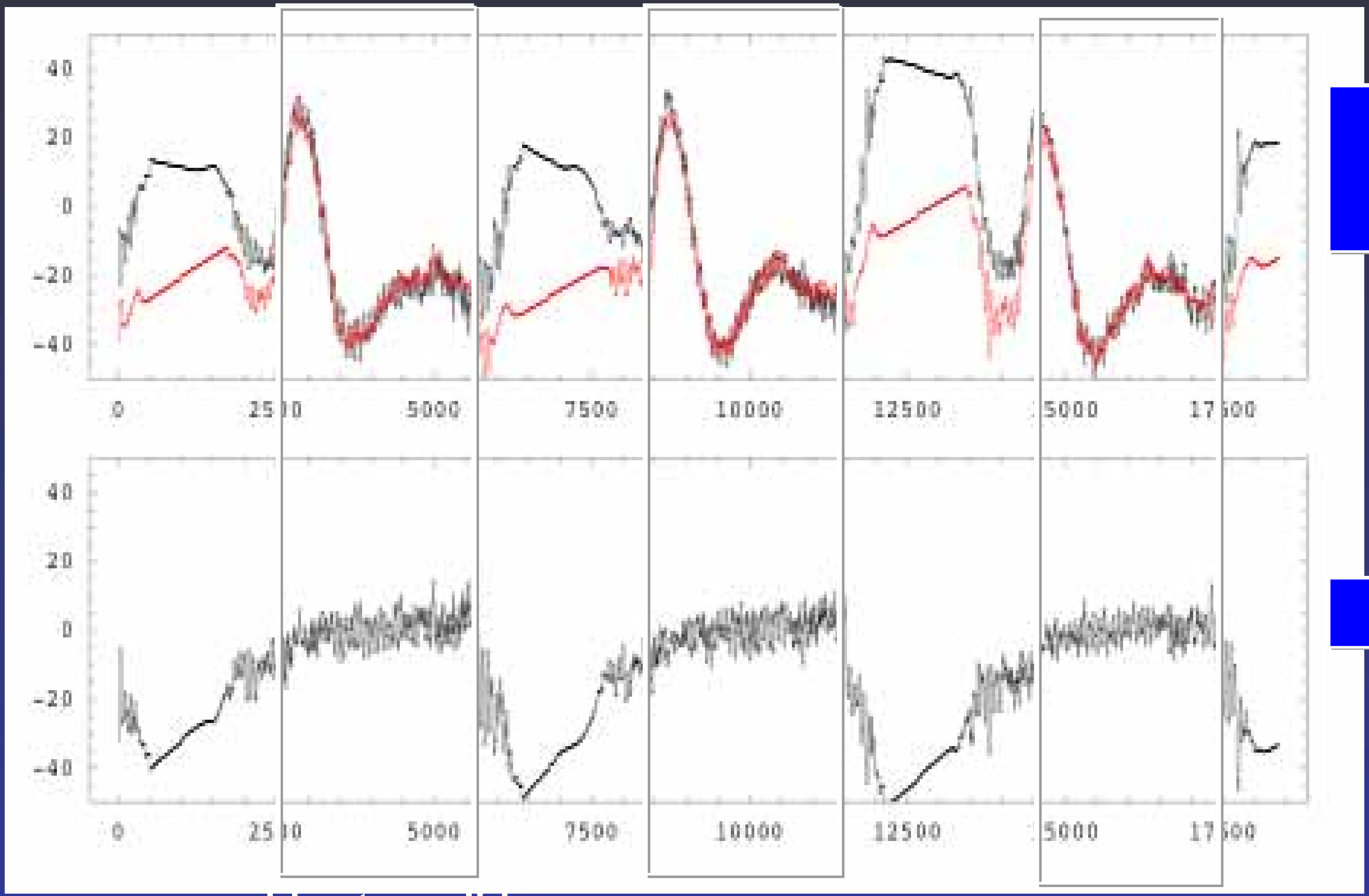




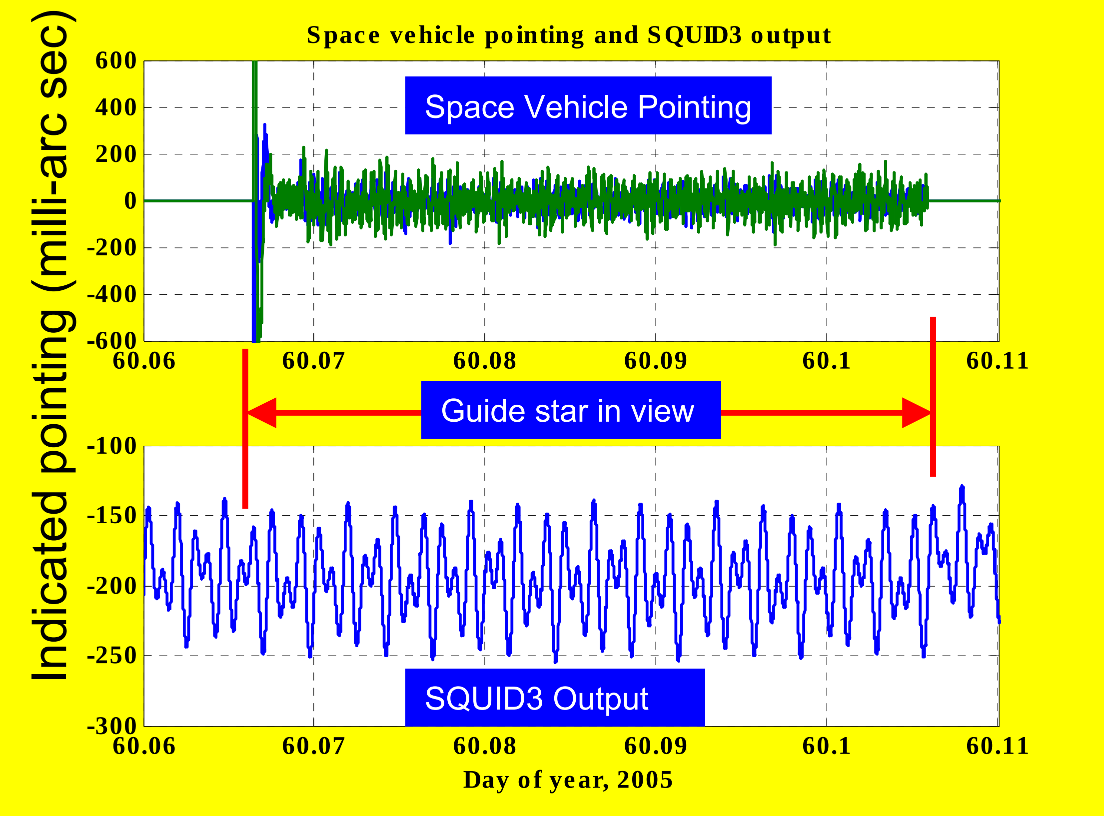
- Satellite roll - period of 77.5 sec about axis to the guide star –**phase locked**
- Body fixed disturbance torques are averaged out.
- Gyroscope readout noise (1/f) is reduced.
- The roll phase used to separate Einstein’s predicted gyroscope spin-axis drifts.
- The roll phase is determined by star trackers.

Star Tracker
Roll Phase Instrument

Tracker A: Black, Tracker B: Red (May 3, 2005)



One Orbit of Science Data



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

<u>Data processing:</u>

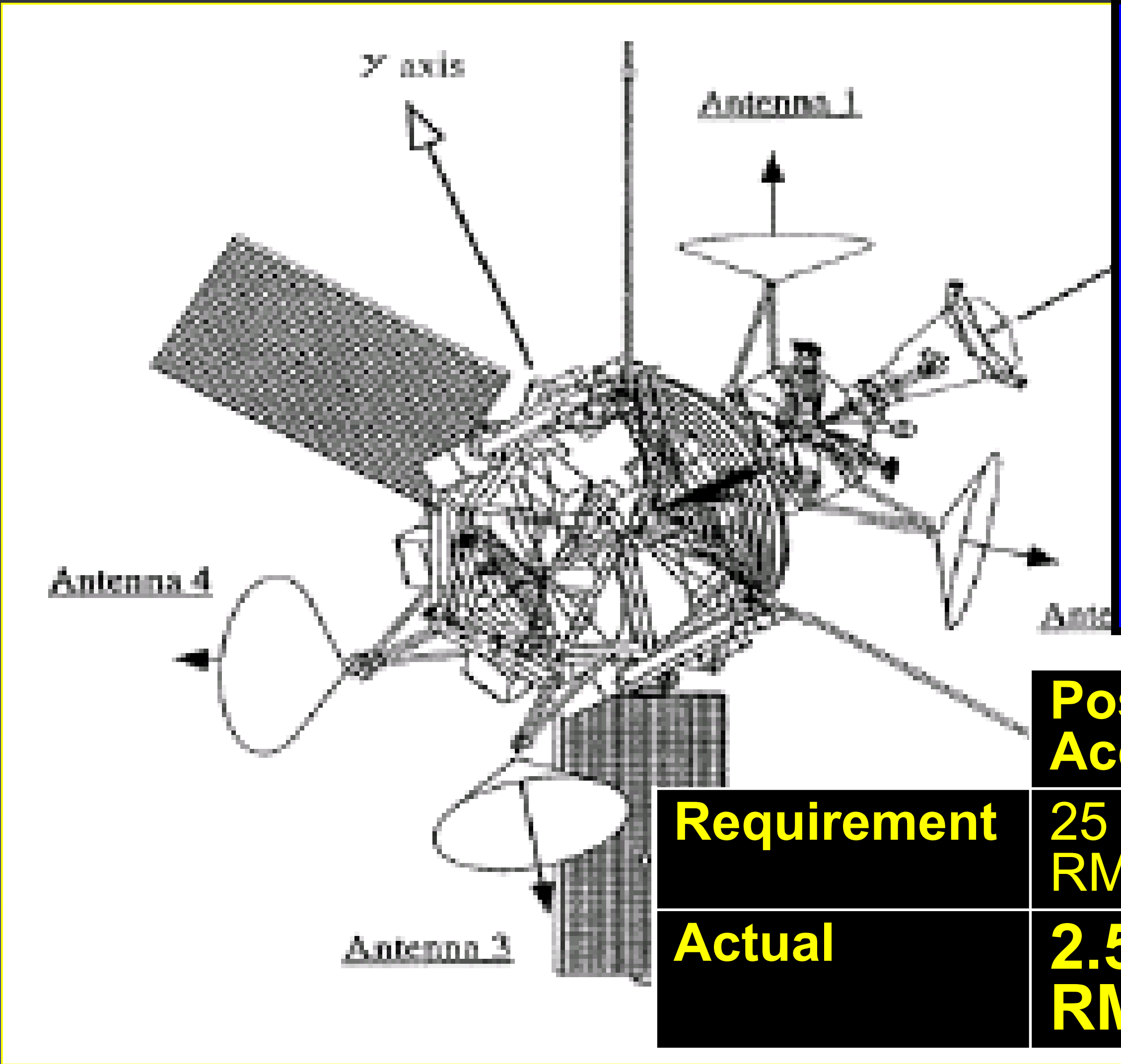
- Remove known (calibrate-able) signals from SQUID signal to get at gyro precession.

<u>Remove effects of:</u>

- 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.

Gravity Probe B's GPS system

(a Commercial system modified by Stanford)



- GPS data sole data source for orbit determination
- Two fully redundant sets: receiver + four antennas
- Data (position, velocity, time) every 10 seconds
- More than 5000 points per day

	Position Accuracy	**Velocity Accuracy**
Requirement	25 m RMS	7.5 cm/sec RMS
Actual	**2.5 m RMS**	**2.2 mm/sec RMS**

Cannon's Law of Consequence

-why does everything happen?

"One Thing Leads to Another"

Spinoffs from GP-B

Five Major Categories and a few examples

- **Precision Machining, Assembly, and Bonding**
  - Gyros, housings, Coatings, catalyzed optical contacting
- **Cryogenics**
  - Porous plug, Space Dewar, payload probe, instruments
- **Ultra – low magnetic field and shielding**
  - 10^{-6} Gauss, 10^{13} isolation
- **Drag Free and Pointing Technologies**
- **New Spacecraft Technologies**
  - Micro thrusters (changing a disturbance into a control mechanism)
  - Satellite Dynamical Balancing in Space (CG and Inertia Axes)
  - GPS Attitude measurements
  - GPS Blind Landing System

Flight Tests of Attitude Determination Using GPS Compared to an Inertial Navigation Unit

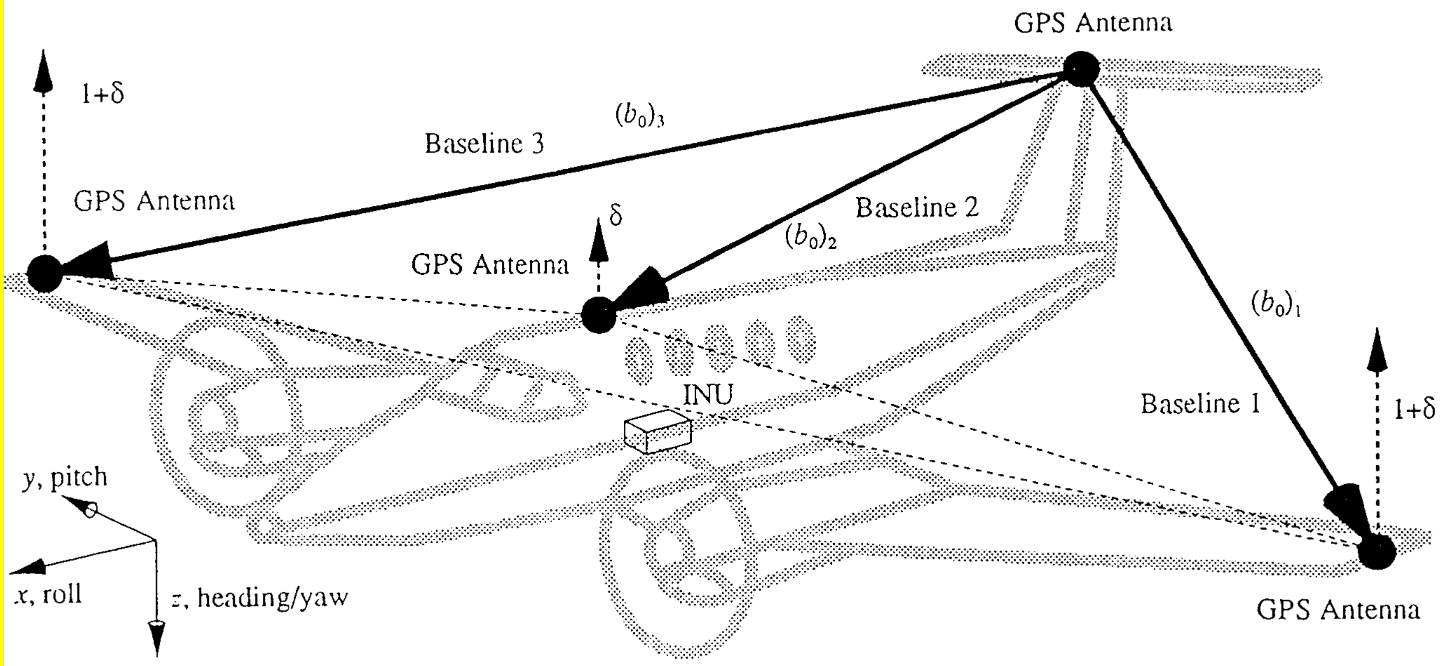
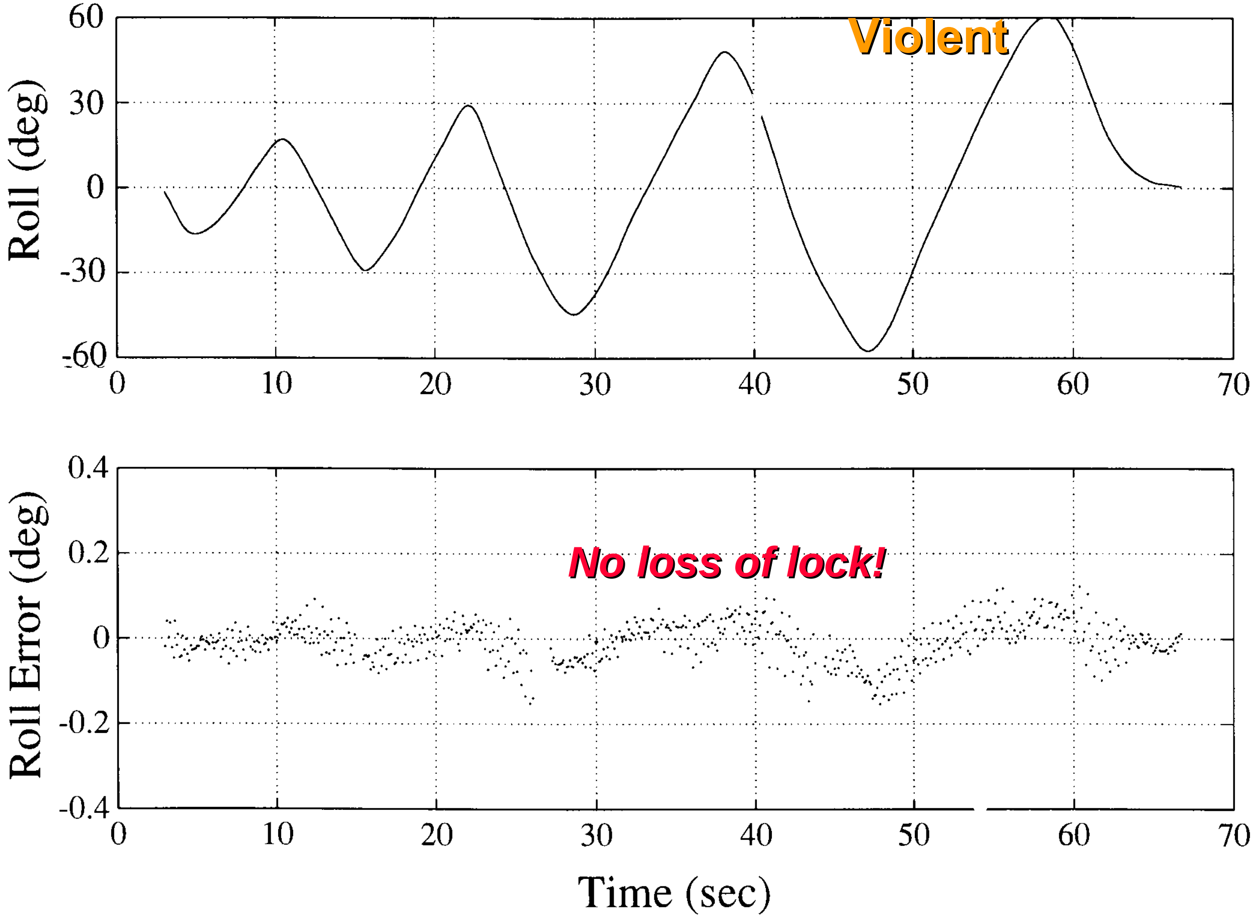


Figure 5: Antenna Baseline and Wing Flexure Definitions

Clark Cohen, Stanford University
B. David McNally, NASA/Ames
Brad Parkinson, Stanford University

Roll Reversals

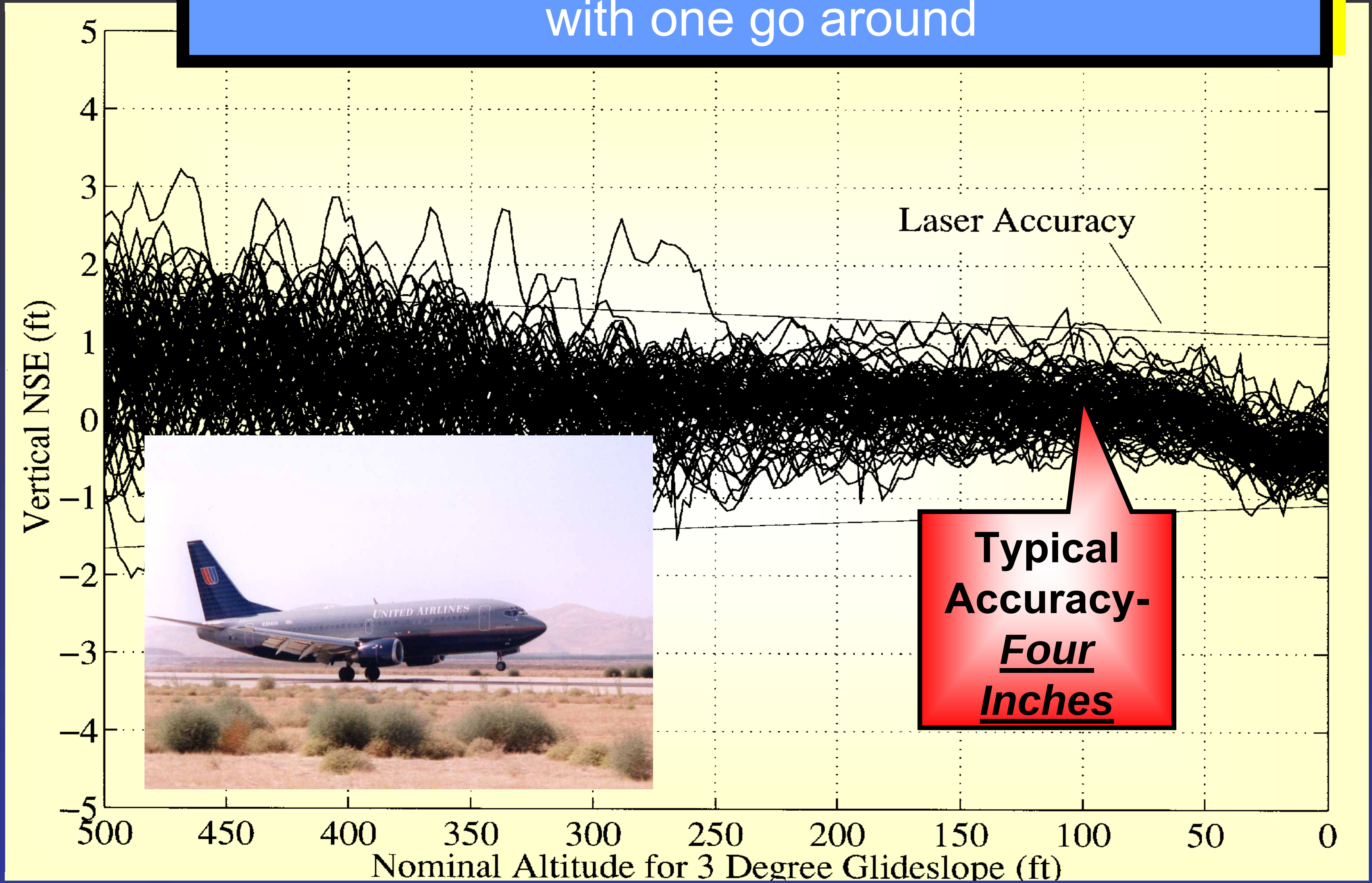


Violent

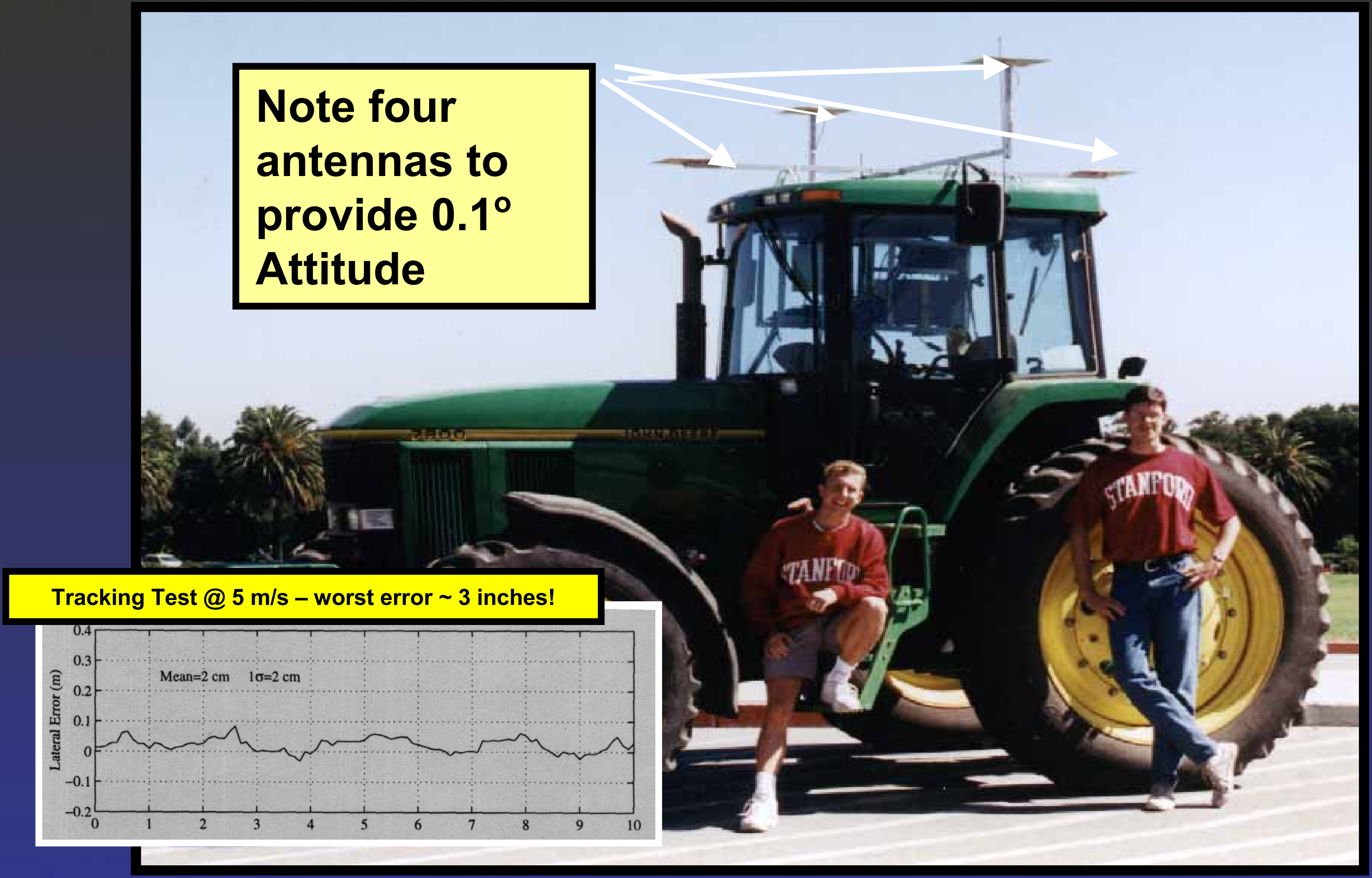
No loss of lock!

IMU Spec

Einstein's Landing System: Blind Landing Tests – 110 straight successes with one go around



Typical Accuracy- *__Four Inches__*



Note four antennas to provide 0.1° Attitude

Tracking Test @ 5 m/s – worst error ~ 3 inches!

Stanford Robot Tractor

Observations

(Simple in Concept ≠ Simple in Execution)

- **Marriage of Physics and Engineering Essential**
- **Critical Components and Controllers met the Goals of GP-B**
  - These Devices also enable the next generation of experiments
- **Spinoffs are not surprising**

  - but the spin direction is sometimes unexpected…

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