GP-B Attitude and Translation Control

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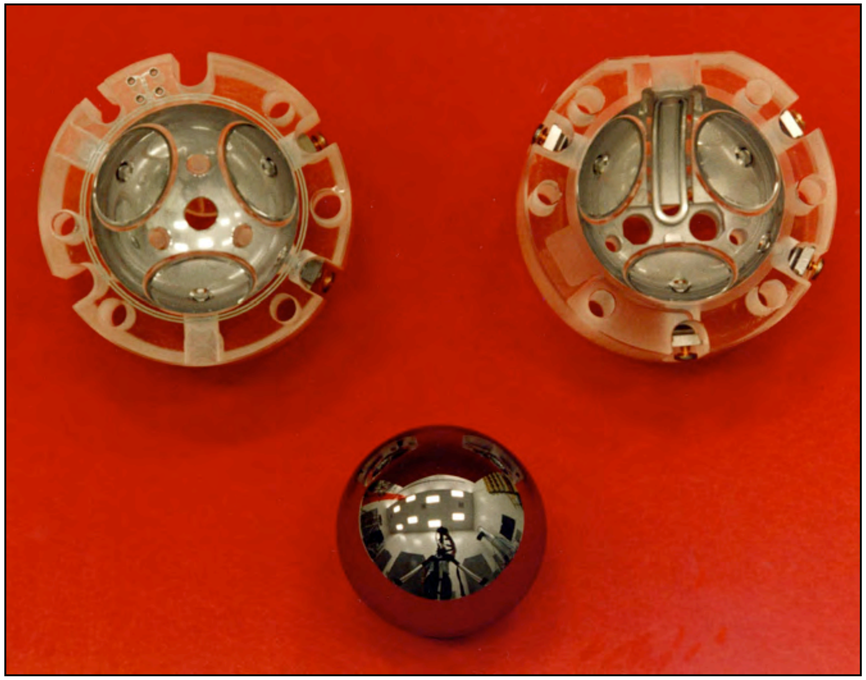
The GP-B Challenge

– Gyroscope (G)	10^7 times better than best 'modeled' inertial navigation gyros
– Telescope (T)	10^3 times better than best prior star trackers
– G – T	<1 marc-s subtraction within pointing range



Basis for 10^7 advance in gyro performance

Space

- reduced support force, "drag-free"
- roll about line of sight to star

Gyro

- sphericity and mass unbalance requirements: 10nm achieved

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LELAND STANFORD JUNIOR UNIVERSITY
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ATC Requirements

Pointing Requirement	110marcsec/√ Hz (Guide Star Valid) pitch and yaw
Roll Requirement	40 arcsec at roll rate
Acceleration Requirement	$<10^{-11}$g crass track average

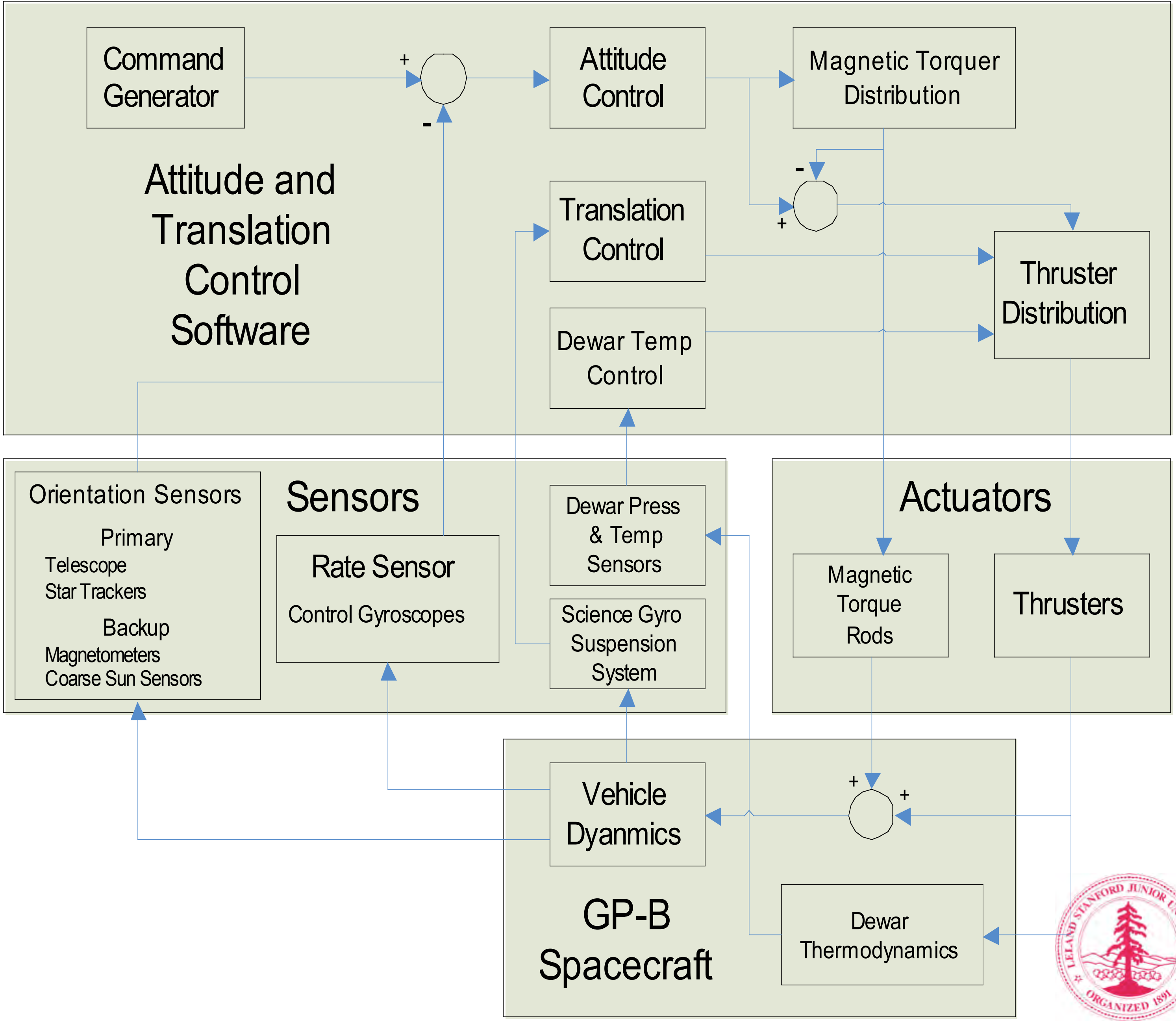
=> Active Control of all 6 dof of Spacecraft

What is the ATC system?

- First space vehicle to actively control all six degrees of freedom
  - 3 Orientation
  - 3 Translation
- 16* Cold gas proportional micro thrusters provide forces and torques
  - Fueled by helium boil-off gas from cryogenic system
  - * Two thrusters failed before science phase
- Common-mode flow rate control maintains helium bath temperature

- Pointing system controls the guide star tracking telescope and maintains roll phase
- Translation control system uses acceleration measurements from one of the science gyroscope's suspension system to null out environmental forces
- Vehicle flies in a near-perfect gravitational orbit

Block Diagram



ATC System Hardware

Sensors

Primary Sensors
- Attitude
  - Telescope
  - Star Tracker
  - Rate Gyroscopes
- Translation - One of the four science gyro suspension systems

Backup Attitude Sensors
- Magnetometers
- Coarse Sun Sensors

Backup Translation Sensors - Three more science gyroscopes

Actuators

Primary Attitude and Translation Control Actuators - 16* Proportional Micro Thrusters

Backup Attitude Actuators - Magnetic torque rods

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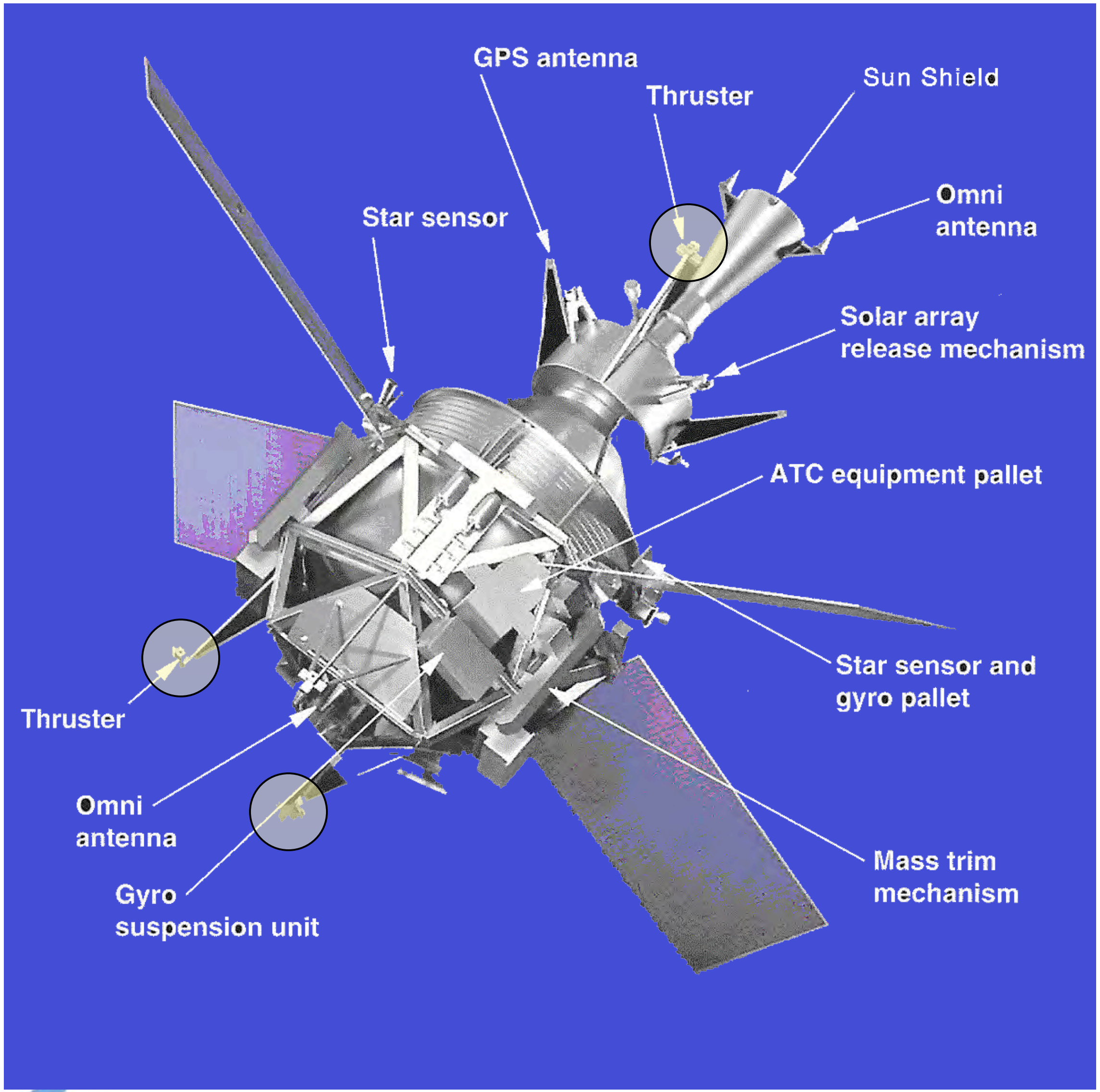
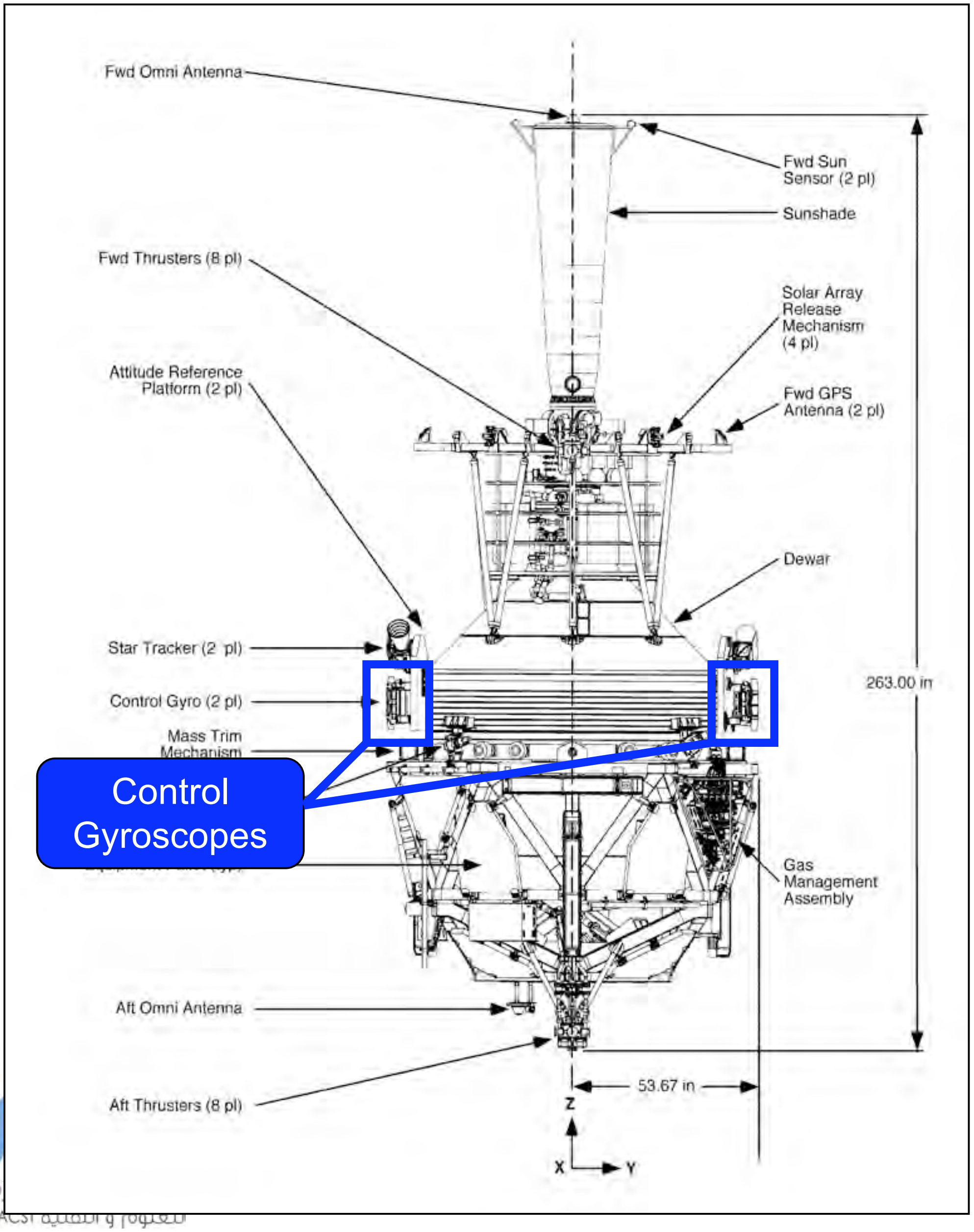
The Overall Space Vehicle



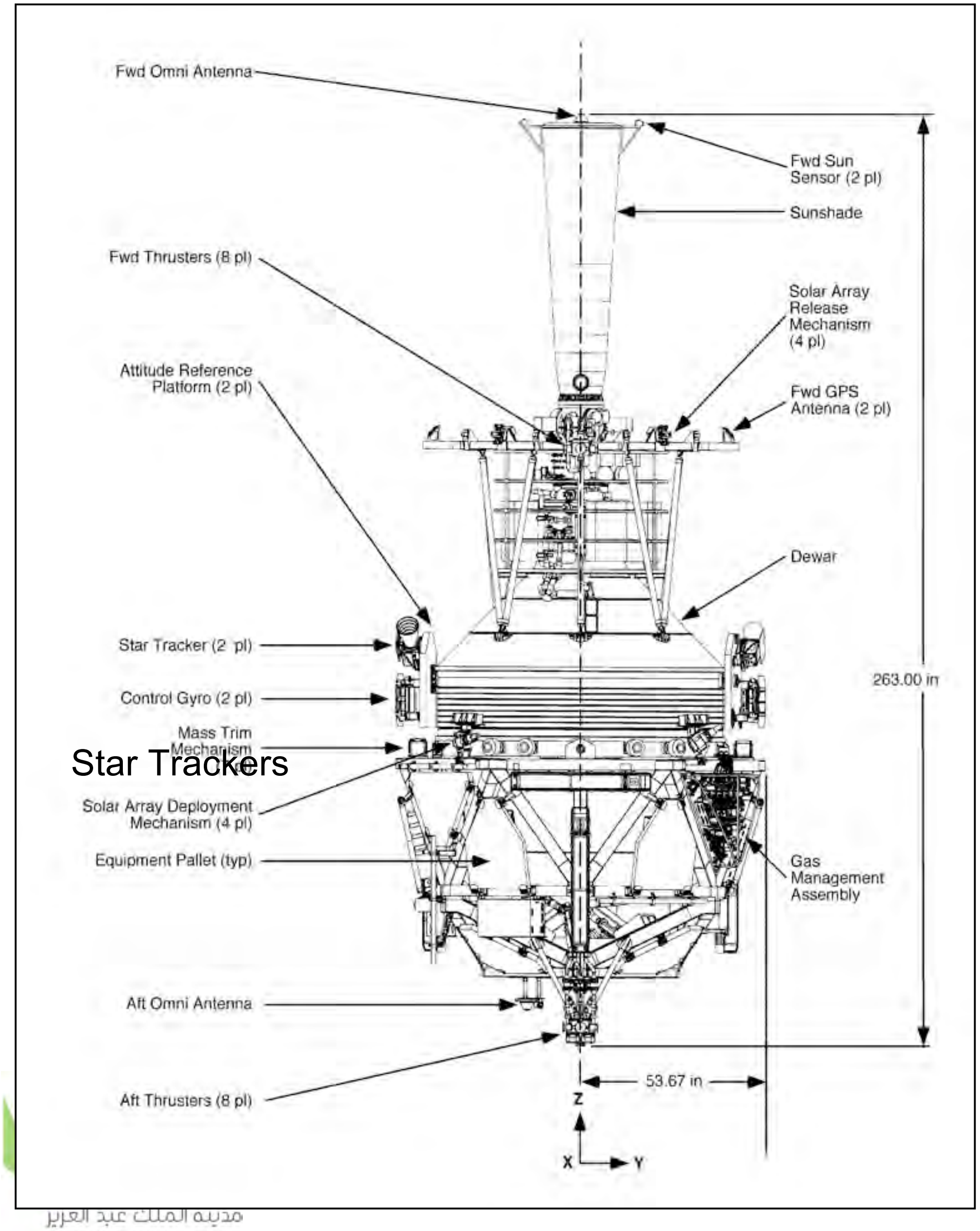
- 16 Helium gas thrusters, 0-10 mN ea, for fine 6 DOF control.
- Roll star sensors for fine pointing.
- Magnetometers for coarse attitude determination.
- Tertiary sun sensors for very coarse attitude determination.
- Magnetic torque rods for coarse orientation control.
- Mass trim to tune moments of inertia.
- Dual transponders for TDRSS and ground station communications.
- Stanford-modified GPS receiver for precise positioning. Laser ranging corner cube cross-checks GPS.
- Redundant spacecraft processors, transponders.

Control Gyroscopes

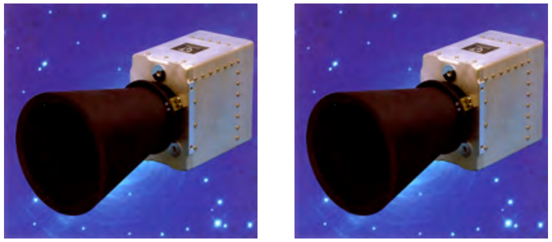


- Two gyro assemblies - one used, one backup
- Gyro mounting platform thermal distortion had a big impact on the control system performance

Star Trackers



Star Trackers



- Two star trackers - one primary, one backup
- 8 deg field of view
- Mounted at angles 10 degrees apart - different groups of stars visible

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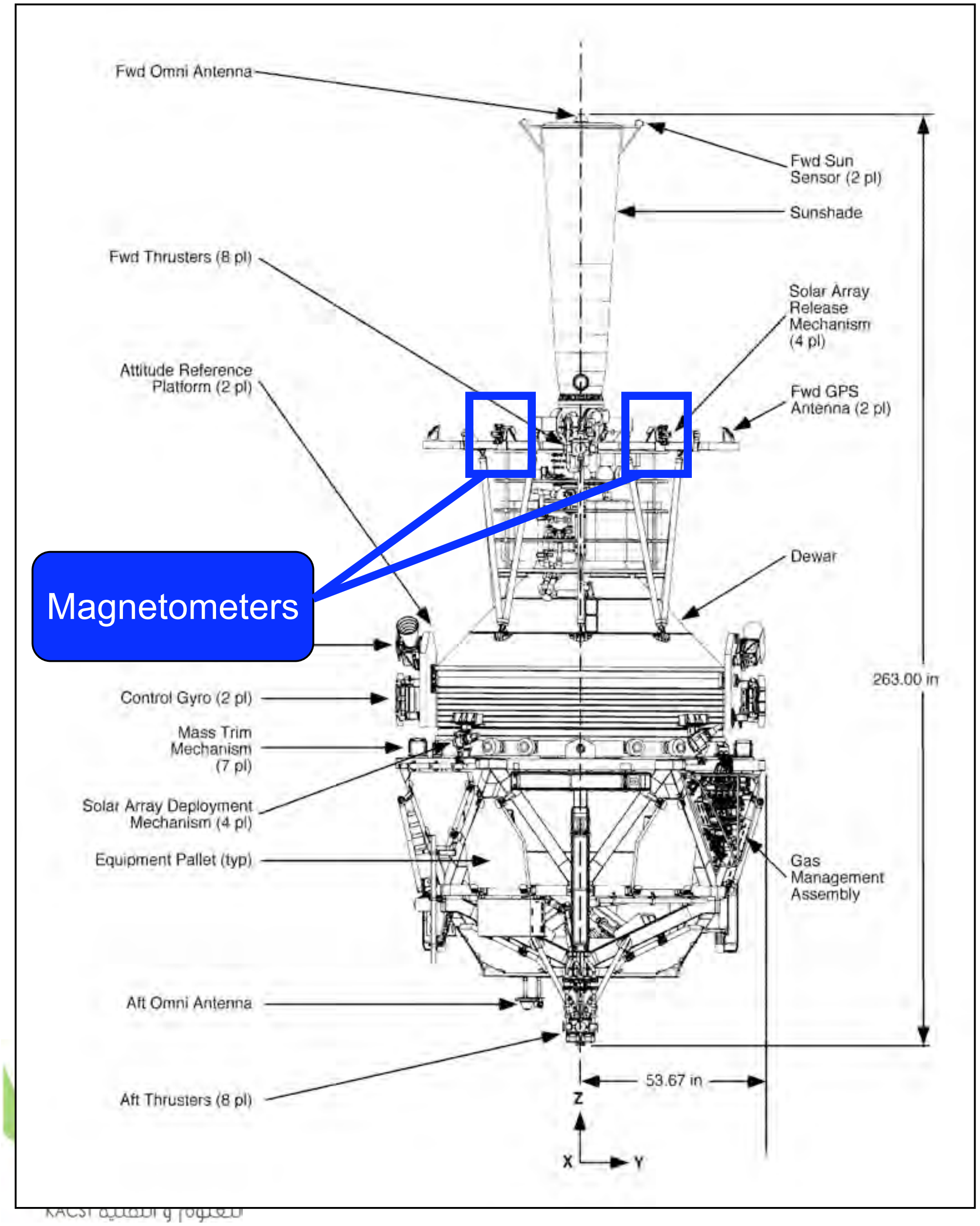
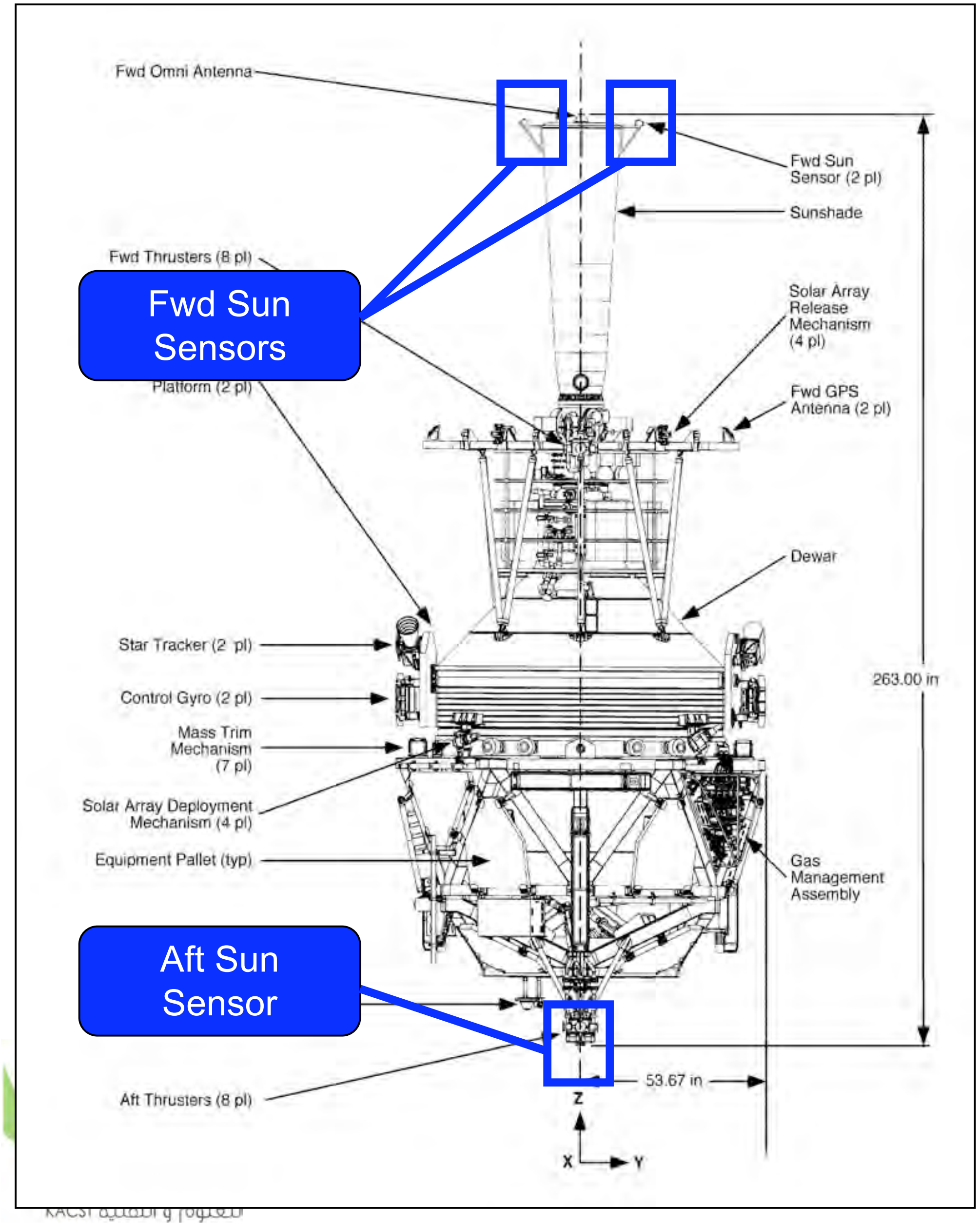
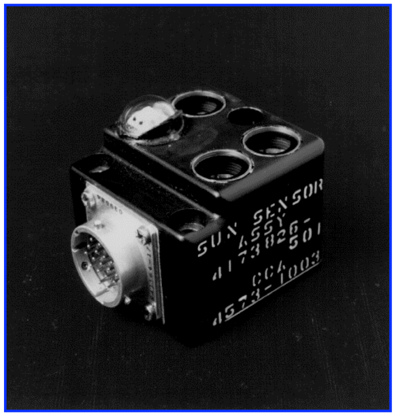
Magnetometers



- Measure vehicle orientation by comparing magnetic field reading with expected field
- Expected field depends on orbital position which is propagated onboard and updated from ground

Coarse Sun Sensors

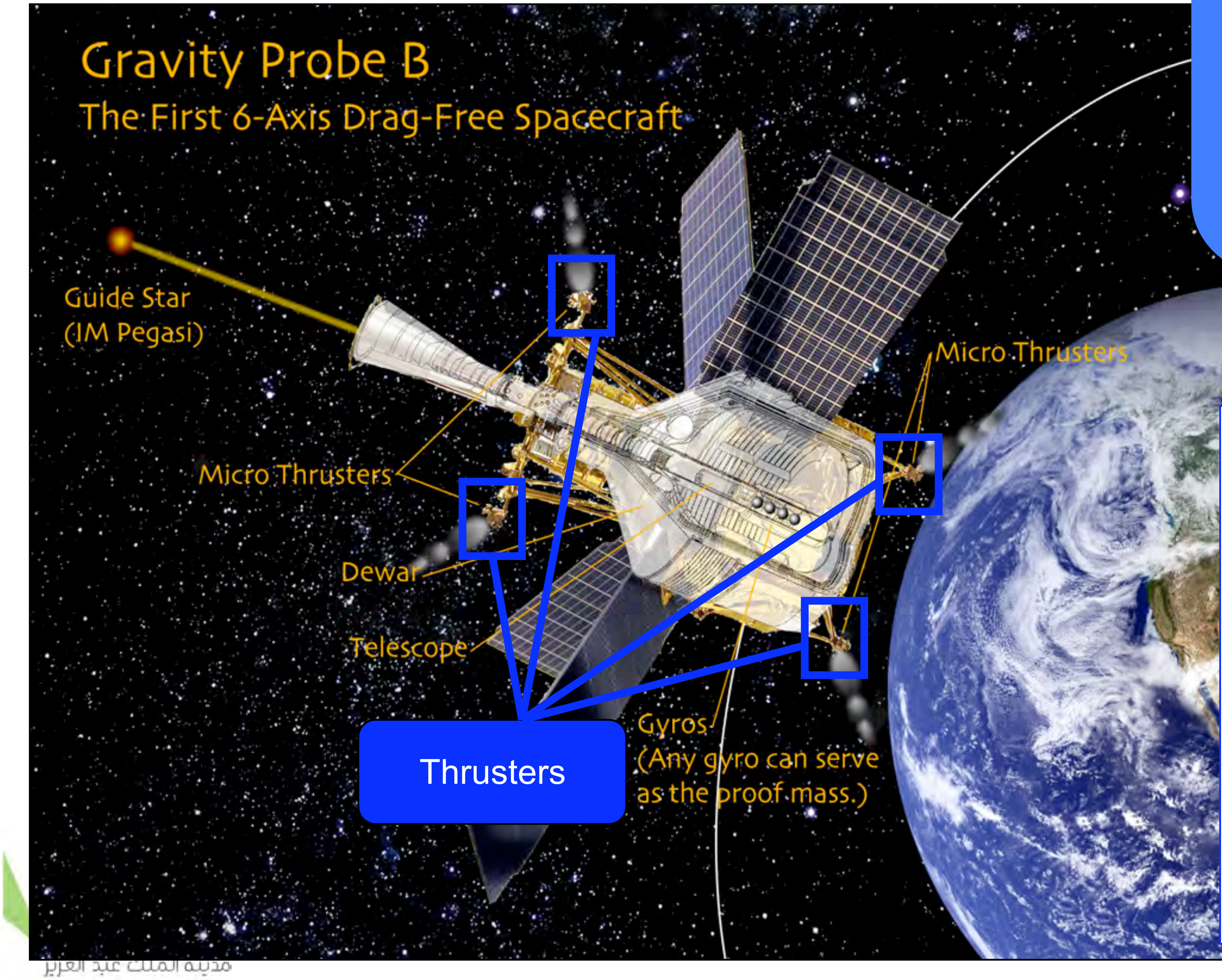




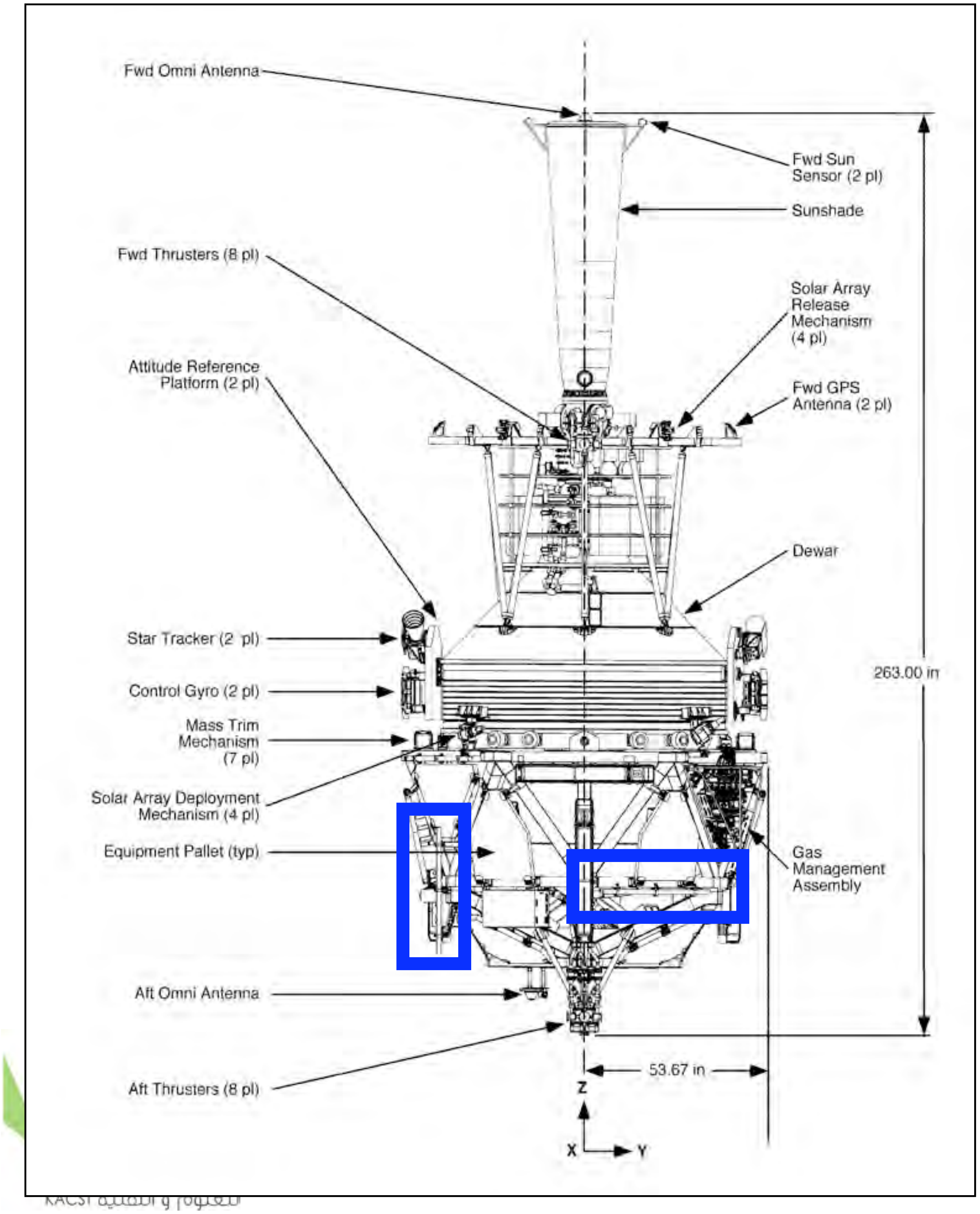
- Backup coarse orientation sensors
- Rough estimate of vehicle orientation
- Only used if star trackers and magnetometers fail

Thrusters

- Vehicle has a nominal mass flow rate of ~8 mg/s
- Maximum thruster force: 8mN



Magnetic Torque Rods



- 3 Orthogonal torque rods
- Two axis control depending on magnetic field geometry
- Orbit position propagated onboard and updated with ground processed GPS data
- Thruster failure backup
- Used during science to increase fuel margin
- Still used today to control satellite to ~5 deg

Attitude Control

- Science Mode
  - Pitch/Yaw Pointing
    - Telescope
    - Control gyroscopes
  - Roll Control
    - Star tracker
    - Control gyroscopes

- Coarse Control
  - Pitch/Yaw Pointing
    - Star tracker
    - Control gyroscopes
    - (Magnetometers)
    - (Coarse sun sensors)
  - Roll Control
    - Star Tracker
    - Control Gyroscopes
    - (Magnetometers)
    - (Coarse sun sensors)

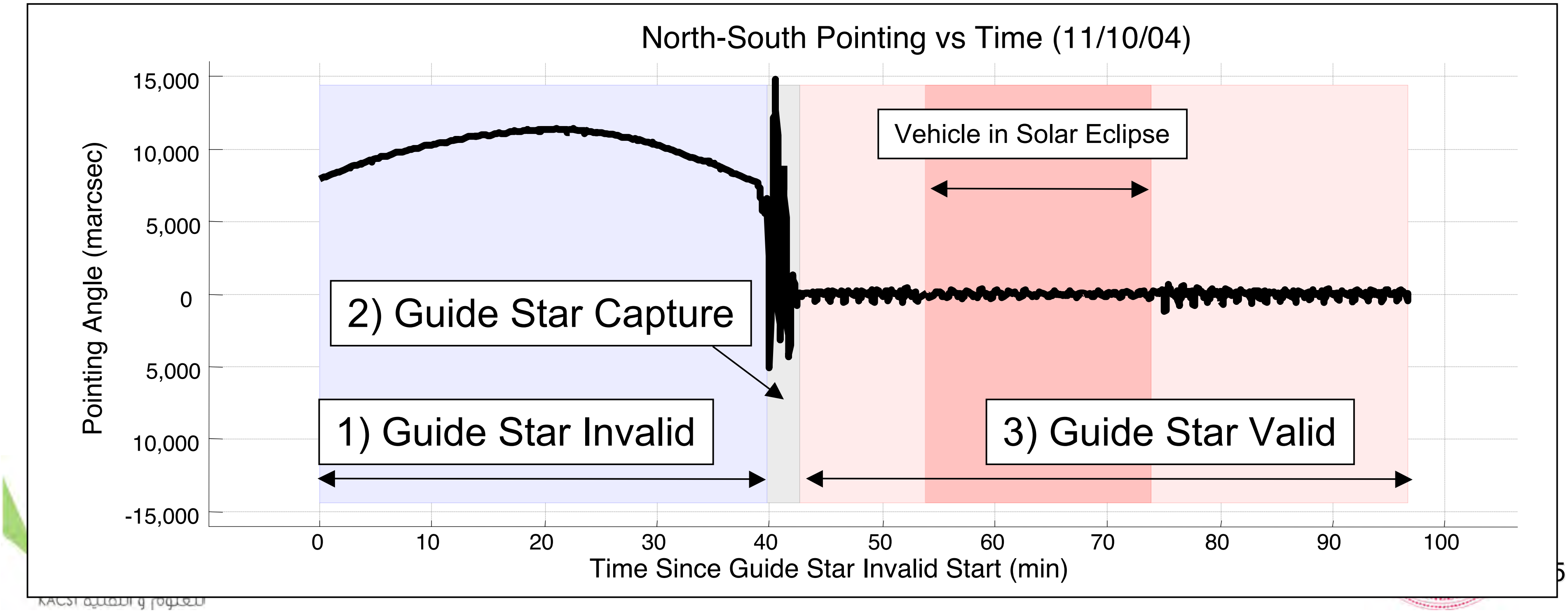
Single Axis Pointing Error

The attitude control goes through three different phases each orbit:

1) Guide Star Invalid – Guide star is blocked by Earth

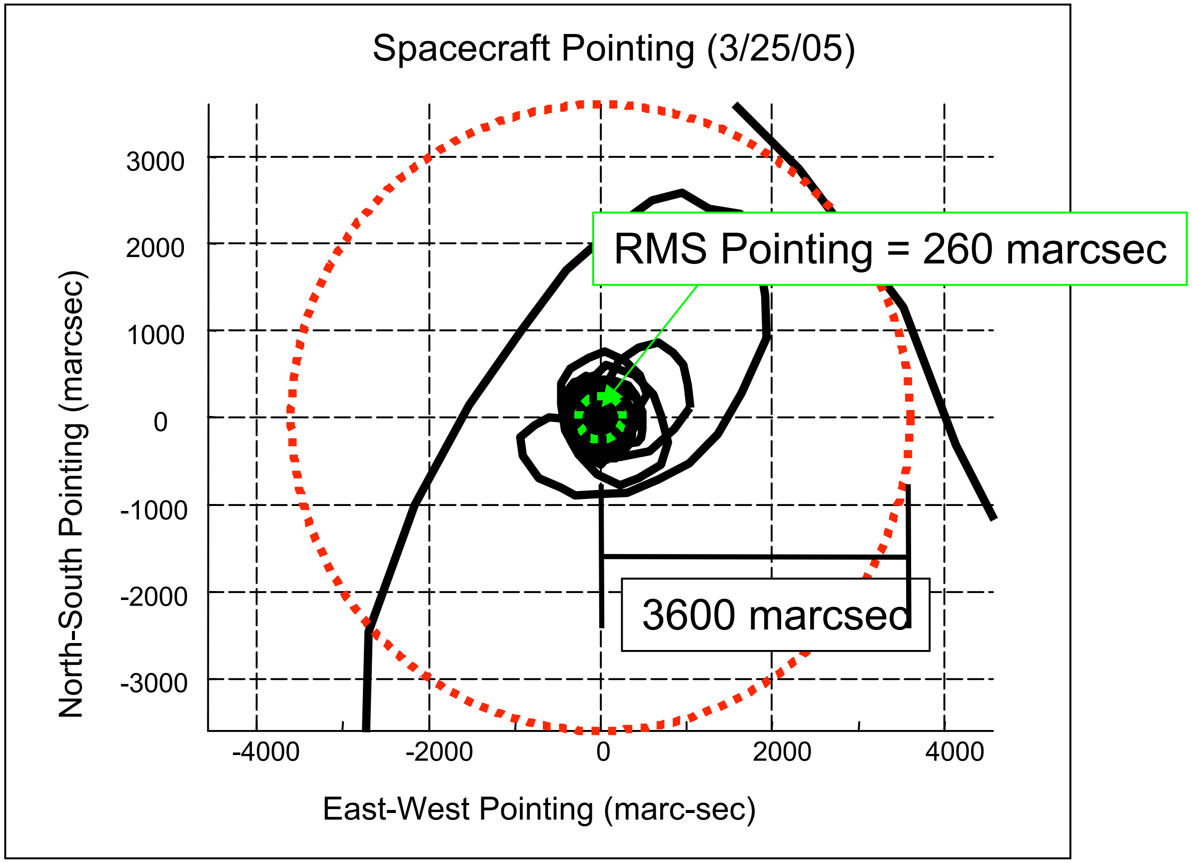
2) Guide Star Capture – Guide star is re-centered in the telescope field of view

3) Guide Star Valid – Nominal telescope pointing



Target Plot

- Nominal guide star capture times range from 30 to 90 seconds
- The RMS vehicle pointing is controlled to less than 320 marcsec (1.55 microrad)

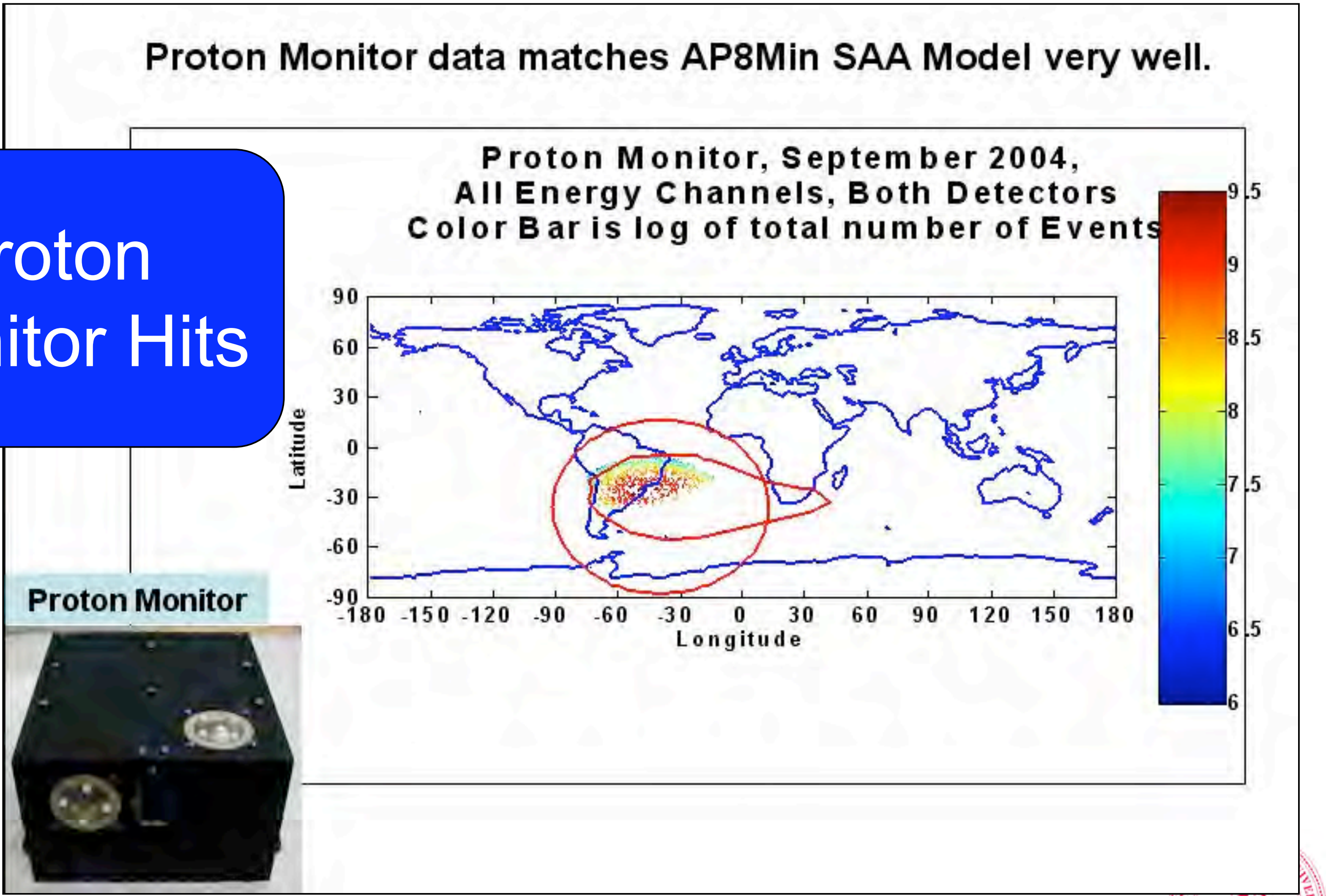

Spacecraft Pointing (3/25/05)

RMS Pointing = 260 marcsec

3600 marcsec

Proton Monitor Data

Proton Monitor Hits



Proton Monitor data matches AP8Min SAA Model very well.

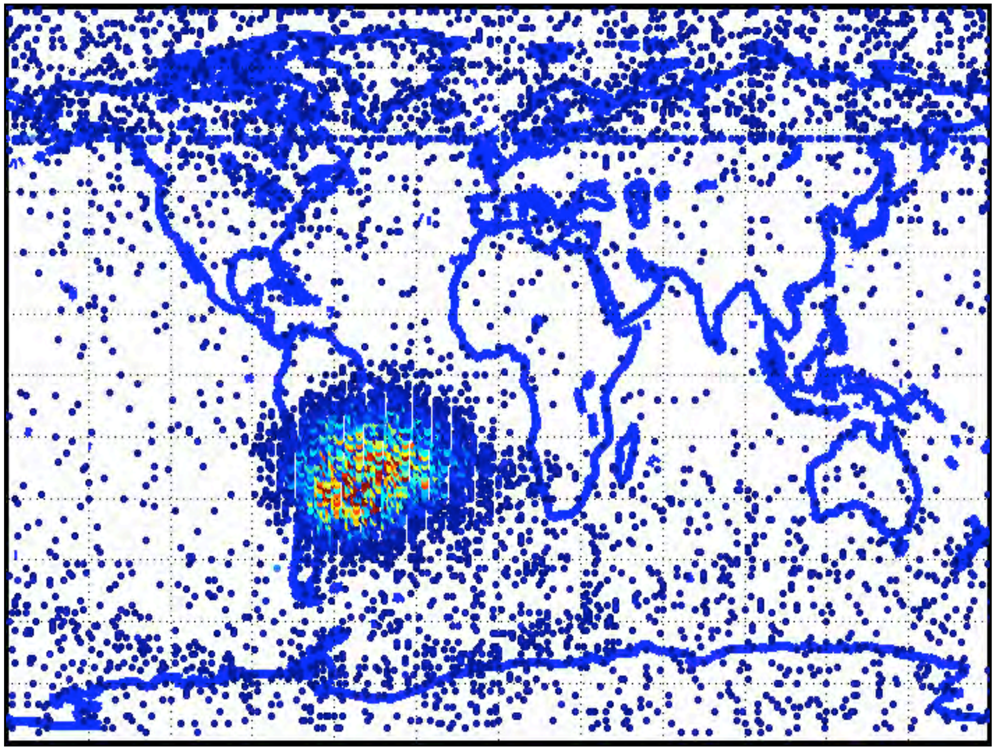
Proton Monitor, September 2004,
All Energy Channels, Both Detectors
Color Bar is log of total number of Events

Proton Monitor

Telescope Detector Data

Particle hits also affected the telescope detectors

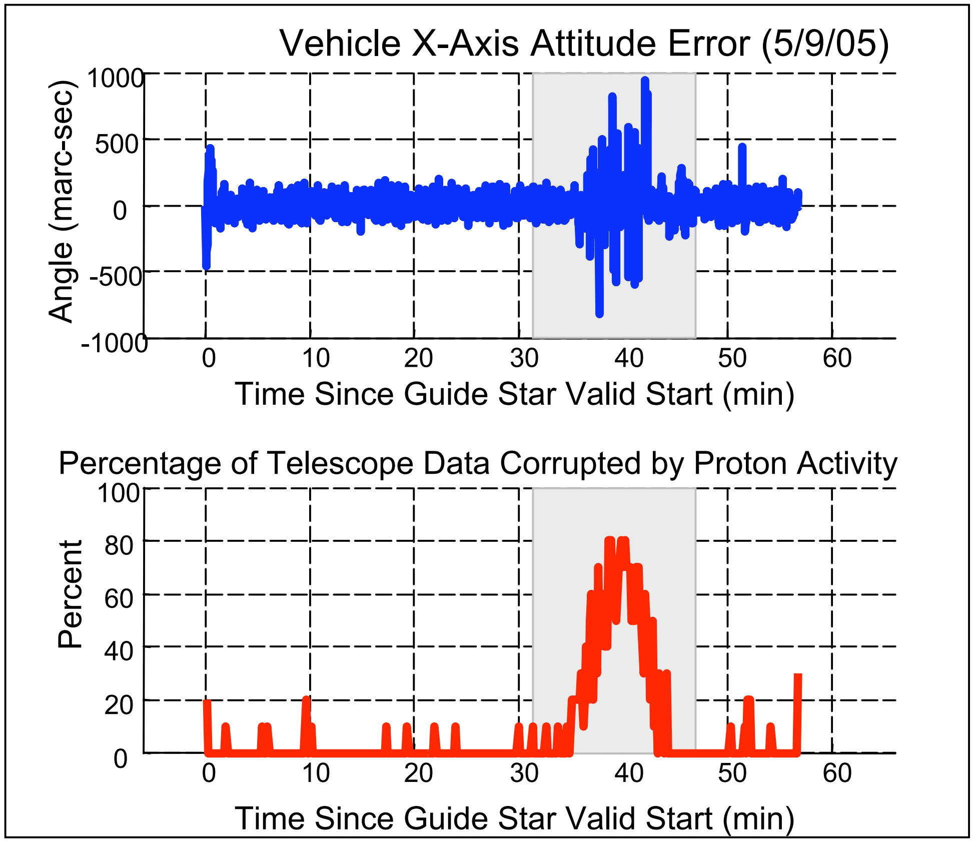
A plot of the number of hits in the telescope clearly shows the South Atlantic Anomaly region



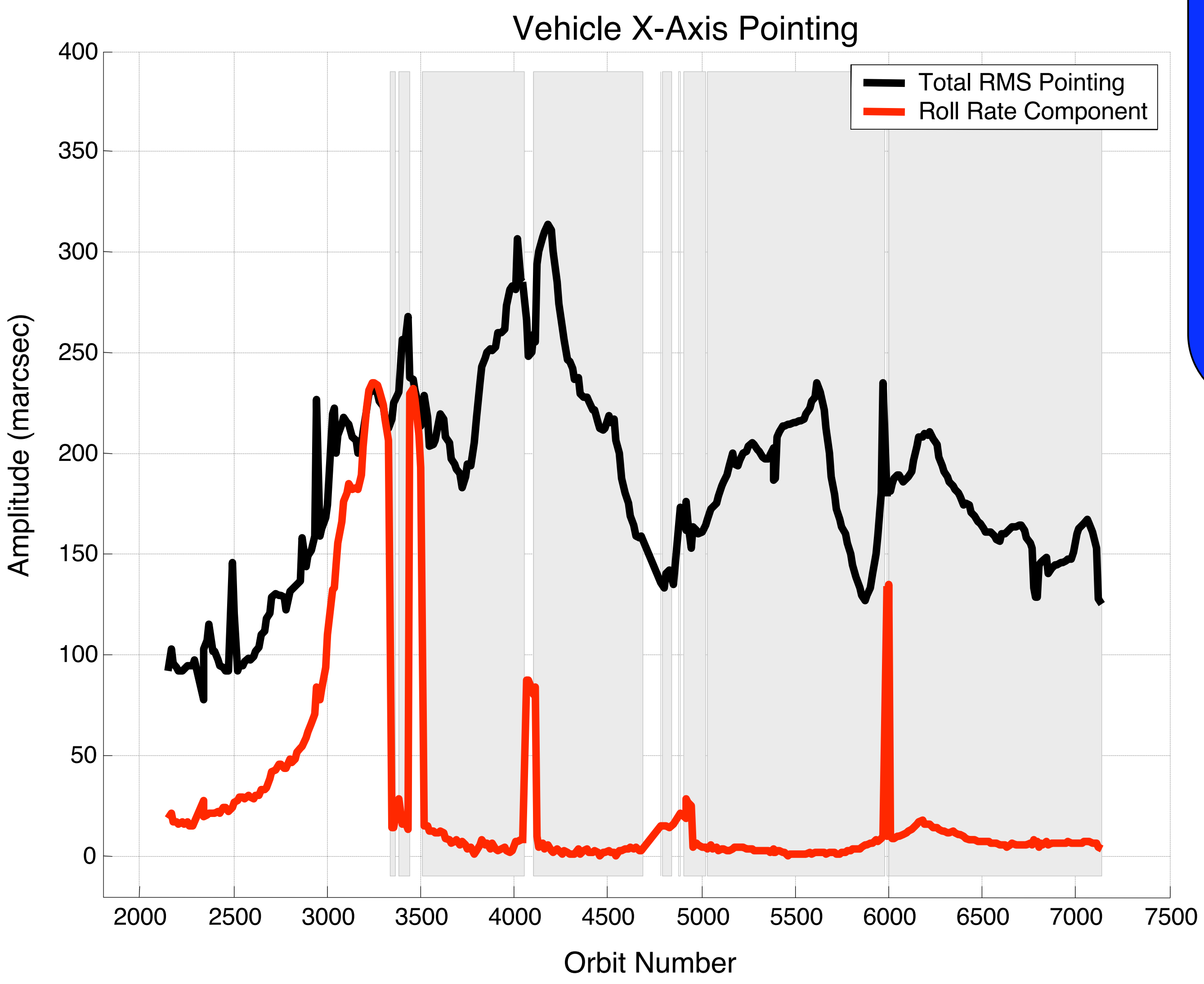
Telescope Detector Proton Hits

SAA Data Plot

GP-B flies through the SAA at least three out of every fifteen orbits losing, at times, up to 80% of the telescope data to proton corruption



Roll Rate Plot

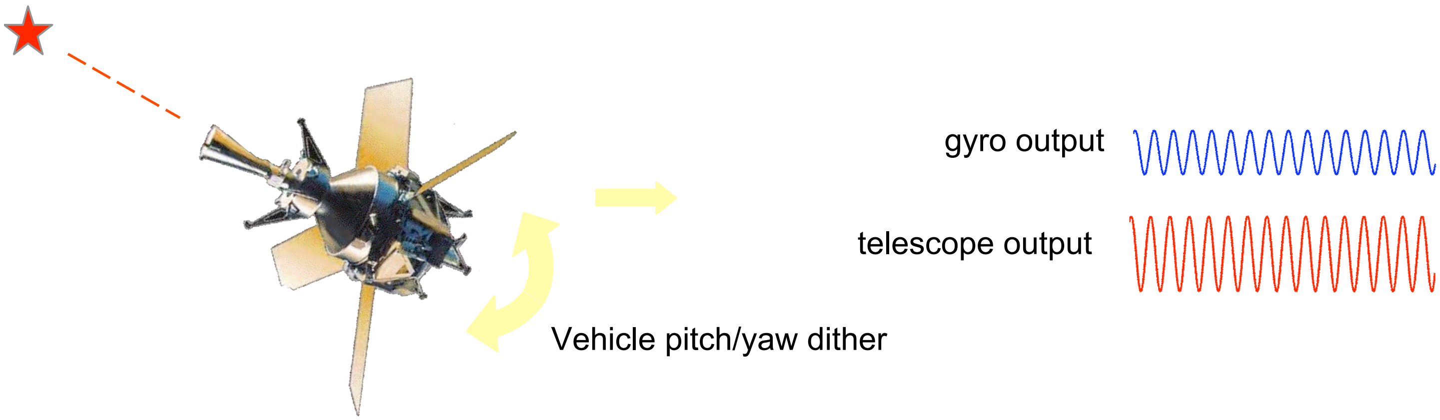


- Mission-long pointing performance

- Shaded Regions - Roll Rate Notch Filter Turned ON

Pitch/Yaw Attitude Dither

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



gyro output

telescope output

Vehicle pitch/yaw dither

Scale factors matched for accurate subtraction

Once telescope/gyroscope scale factor is known, vehicle motion can be subtracted out of the gyroscope signal

Roll Phase Control

There are two star trackers onboard the GP-B satellite.

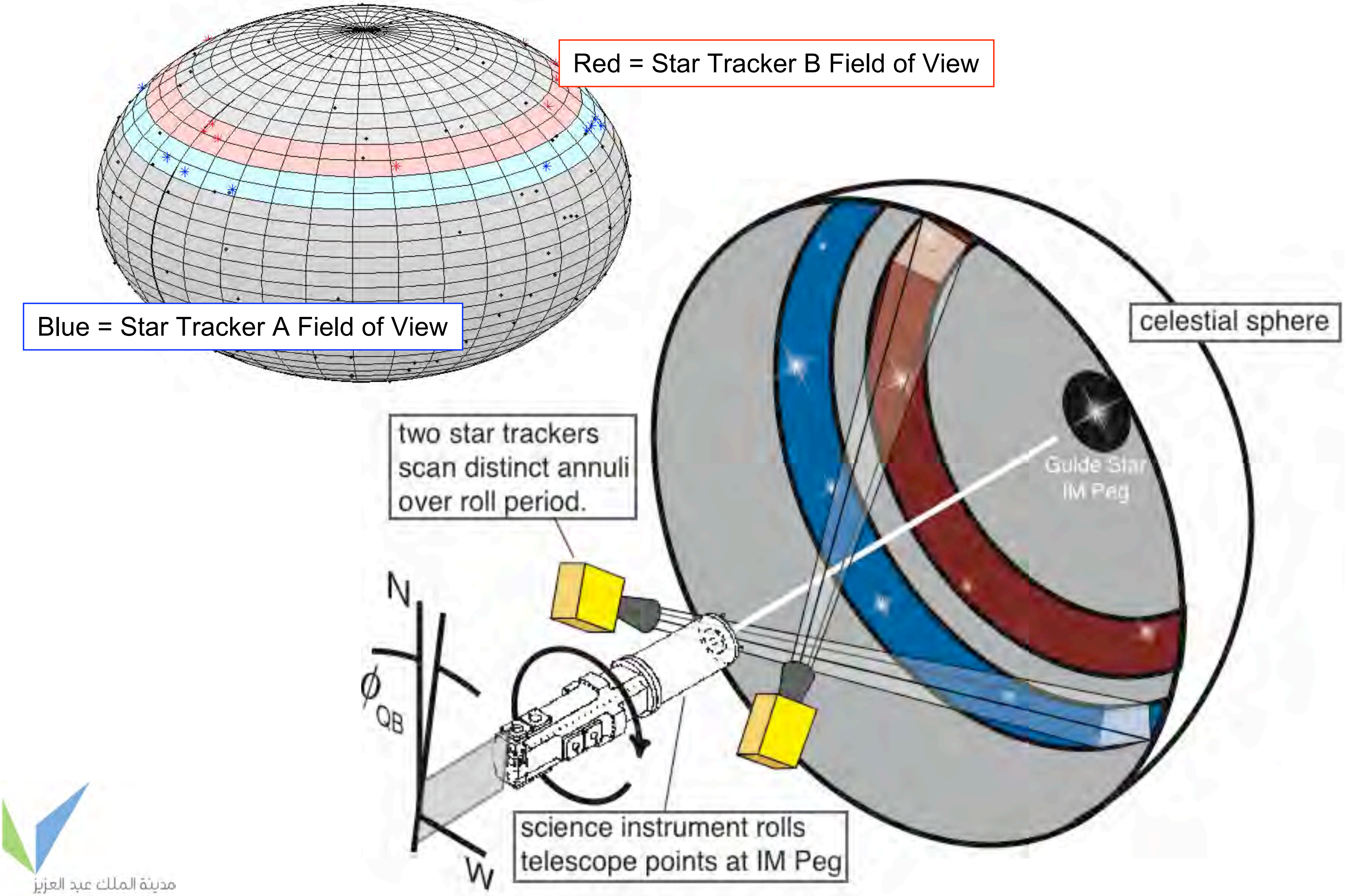
- Field-of-view: 8^{o}x8^{o}
- Boresight axes are 50^{o} and 60^{o} away from the satellite roll axis, out of phase by 180^{o}

Two Attitude Reference Platforms (ARPs) are mounted on the graphite ring around the dewar of the satellite.

One control gyroscope package and one star tracker are mounted on each ARP

Close-loop control of the roll phase is implemented with 16 proportional cold gas thrusters by the Attitude and Translation Control (ATC) system.

Star Tracked Fields of View



Red = Star Tracker B Field of View

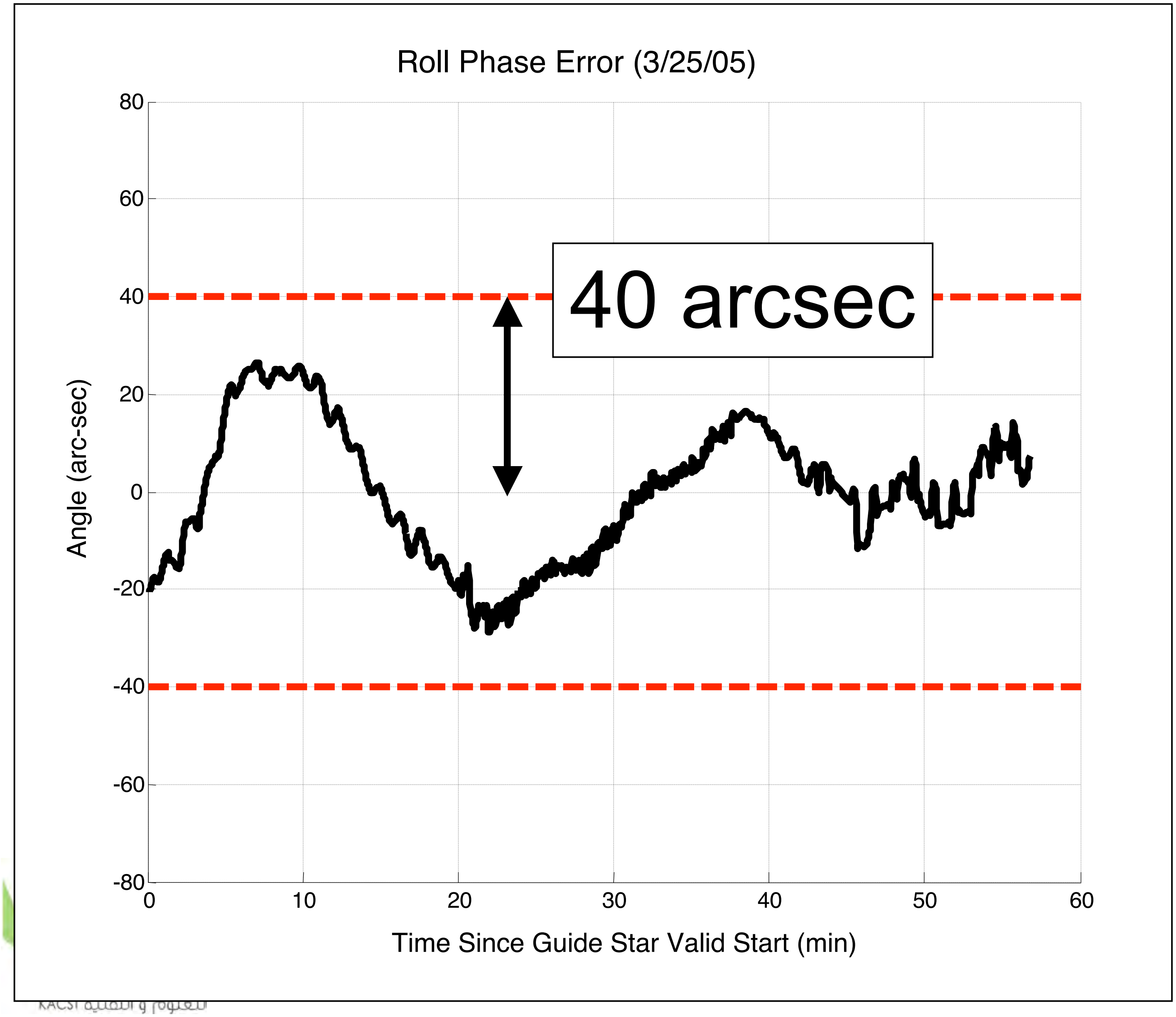
Blue = Star Tracker A Field of View

celestial sphere

two star trackers scan distinct annuli over roll period.

science instrument rolls telescope points at IM Peg

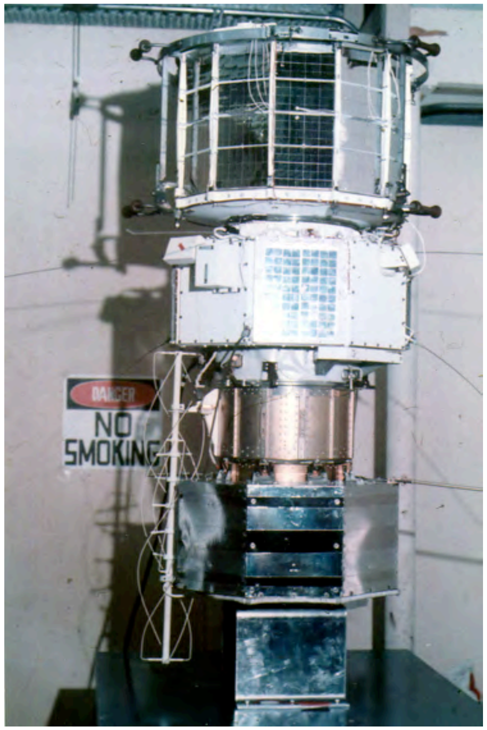
Roll Angle Plot



- The control gyroscopes and star trackers are used to control the spacecraft roll angle to an error less than 40 arcsec at a constant roll period of 77.5 sec

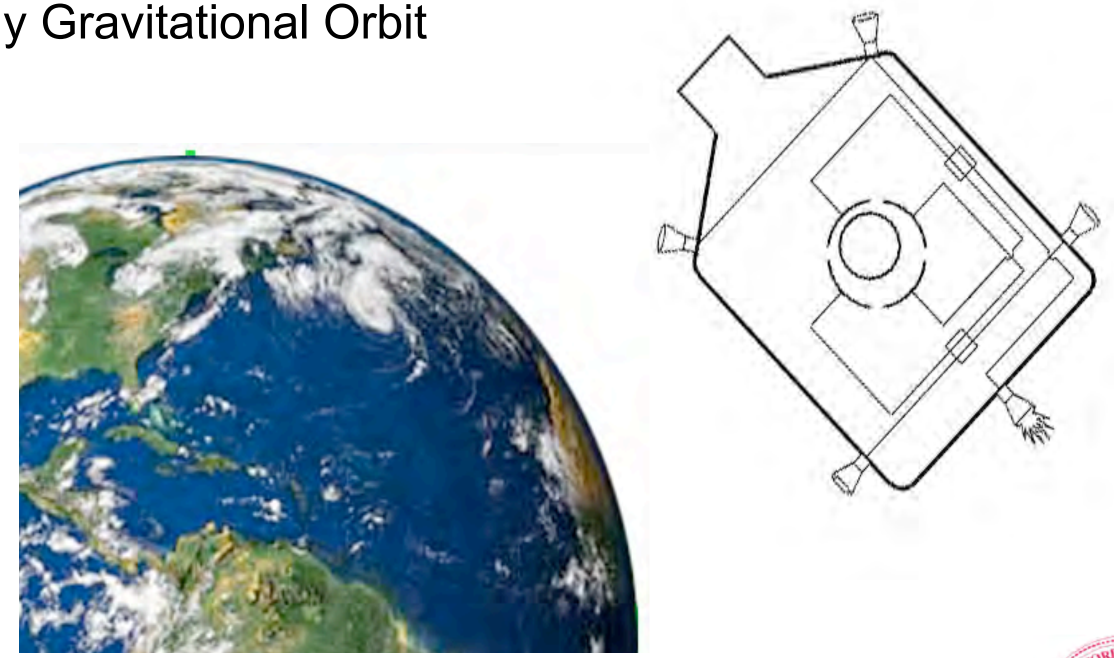
Drag-free Satellite Technology

- 1959 – George Pugh envisioned a “tender satellite” for first proposed test of General Relativity.
- 1964 – Ben Lange (Stanford) provided first detailed study of issues surrounding drag-free satellites.
- 1972 – Flight of a Disturbance Compensation System (DISCOS) on *Transit I* (experimental US Navy navigation satellite)
- 2004 – Flight of Gravity Probe B



Drag Free Concept

- Control Spacecraft to follow an inertial sensor
- Reduce disturbances in measurement band
  - Aerodynamic drag
  - Magnetic torques
  - Gravity Gradient torques
  - Radiation Pressure
- Spacecraft Follows a purely Gravitational Orbit



Drag Free History

Drag-Free Satellites have flown successfully

TRIAD I : Johns Hopkins Applied Physics Laboratory
Navy Transit Navigation System

- Launched September 2, 1972
- Polar Orbit at 750 km
- Mission Lifetime over one year
- DISCOS - Disturbance Compensation System - Stanford
  - 3 axis translation control

And Now Also GP-B

- 3 axis translation control
- 3 axis attitude control

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DISCOS Performance

- Electrostatic Sensing of Proof Mass
- Pressurized gas “On-Off” Thrusters
- 3 Axis Translation Control
- Acceleration levels were below 5 x 10^{-12} g averaged over 3 days
  - limited by tracking data and earth gravity model

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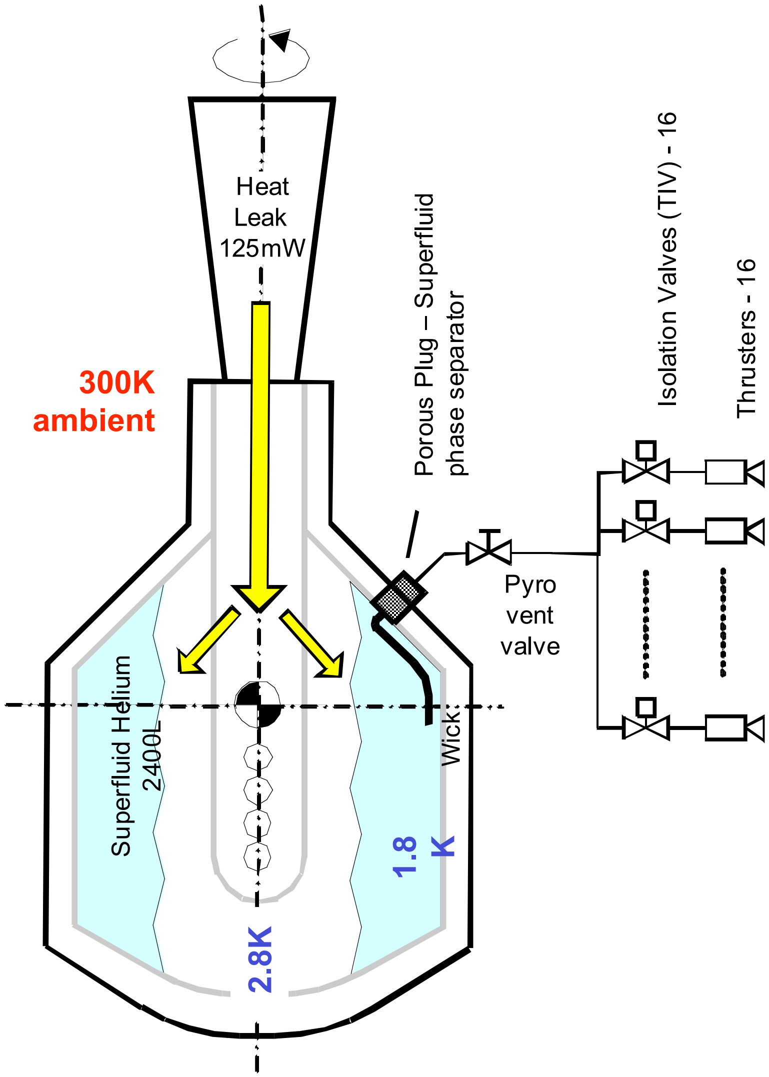
Propellant Source: Helium Boil-off



- **Superfluid phase separator "porous plug" permits gaseous Helium to leave main tank while keeping superfluid He inside.**
- **Mass Flow: 4 - 16 mg·s^{-1} over plug temperatures of 1.6K to 2.0K without choke or breakthrough.**
- **Provides supply pressure of 660 to 2300 Pa (5 to 17.5 torr) to thrusters.**
- **Each thruster is provided a dedicated isolation valve (TIV) to disable unit if a failure occurs.**

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Flight Proportional Thruster Design

Thrust: 0 – 10 mN
I_{SP}: 130 sec
Mdot: 6-7 mg·s^{-1}

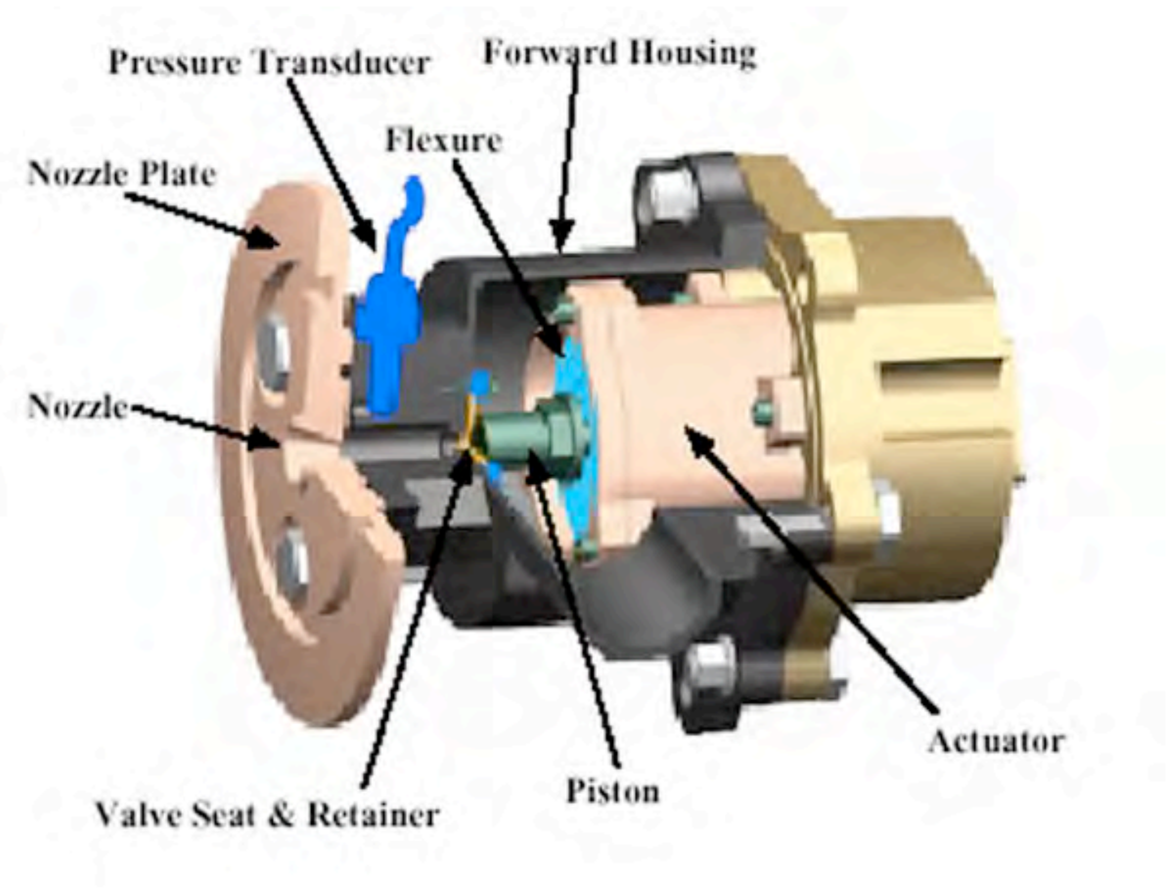
Scale factor variation: 6%

Bias variation: 0.2 mN

Noise: 25 μN·Hz$^{-1/2}$

Operates under choked flow conditions

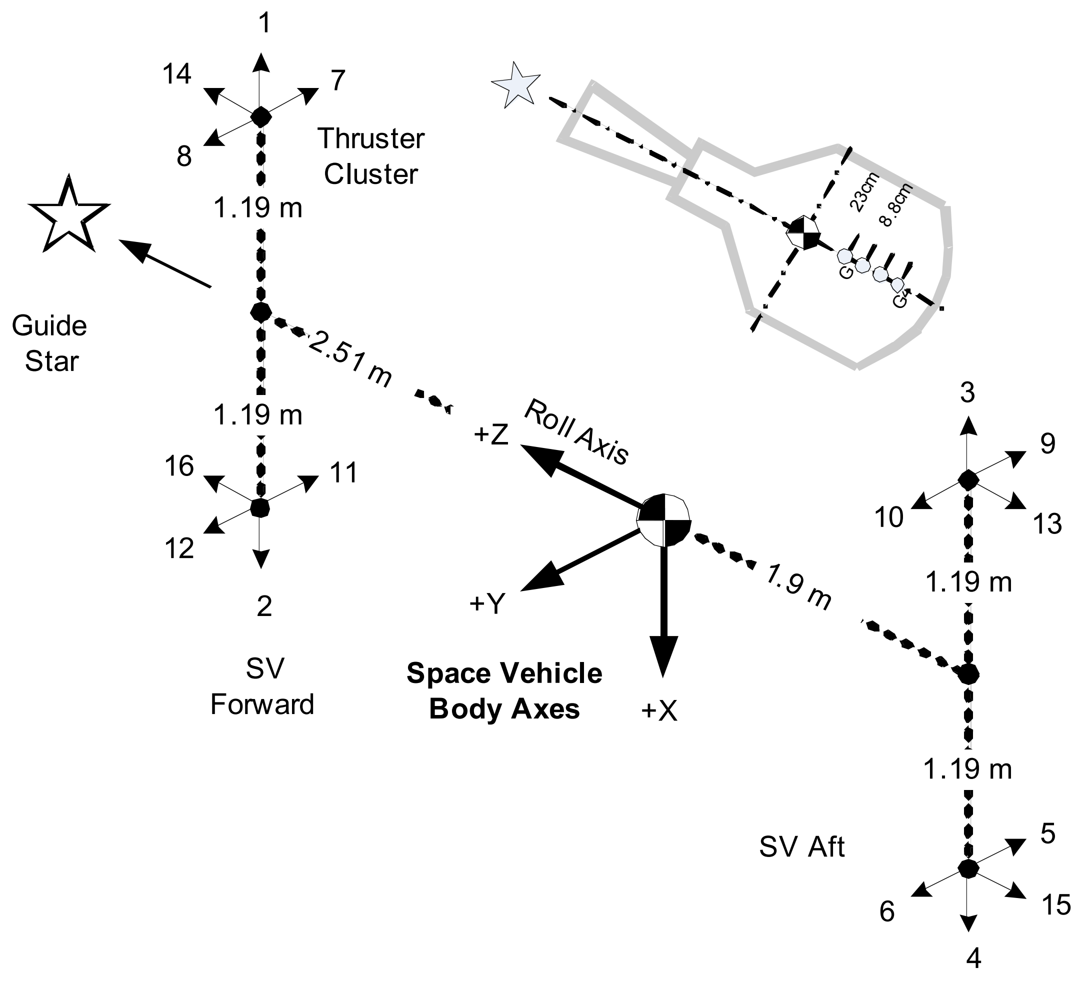
Pressure FB loop makes thrust independent of unit temperature



Supply: 5 to 17.5 torr

Re ~10 – Laminar flow!

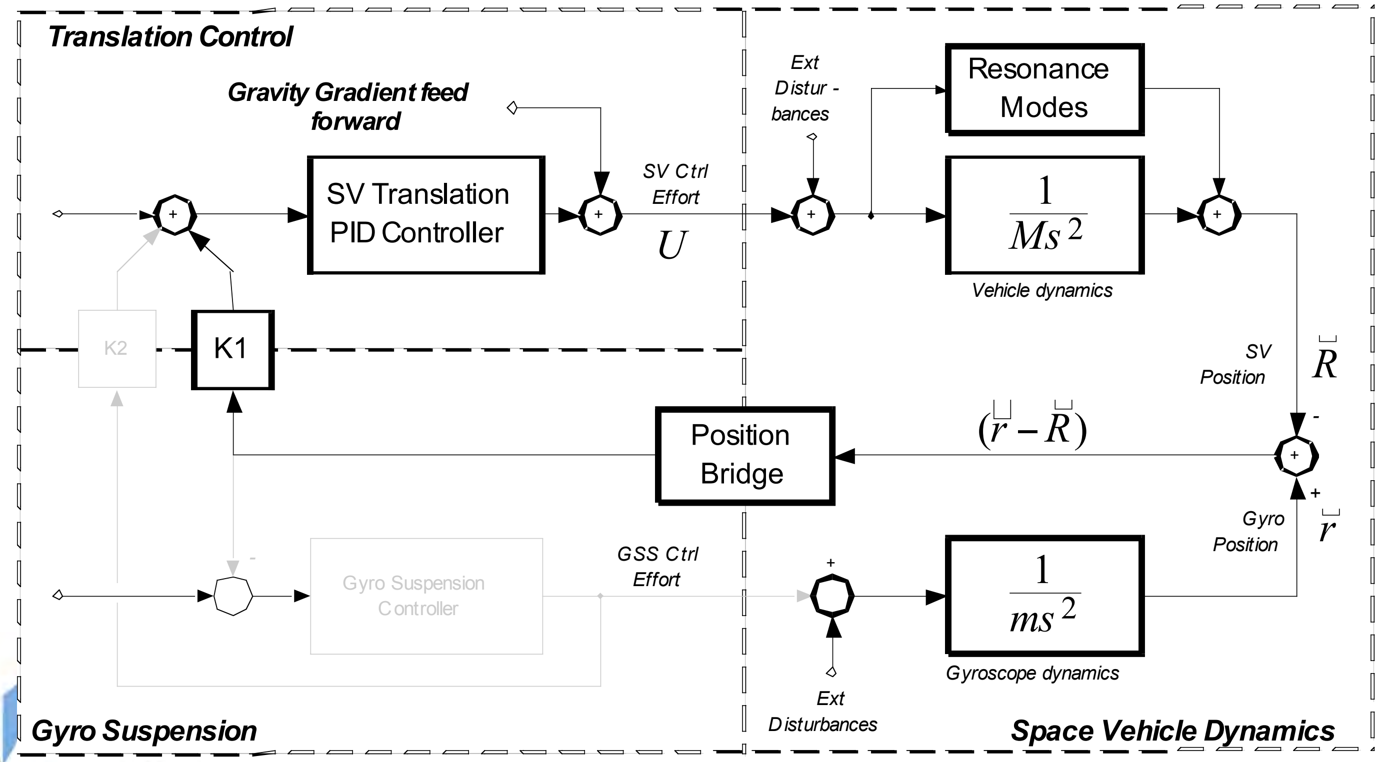
Thruster Arrangement on Vehicle

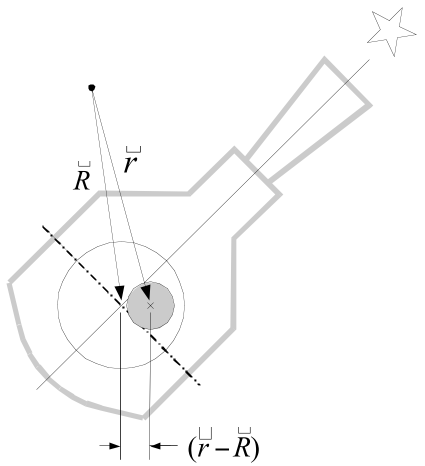


- Thrusters are arranged in 4 clusters of 4 units each.
- Each cluster has thrust authority along 3 axis.
- Arrangement chosen to be robust to thruster failures.
- Provides 3DOF of attitude and 3DOF of translation control for the space vehicle.

“Prime” Drag-free Operation

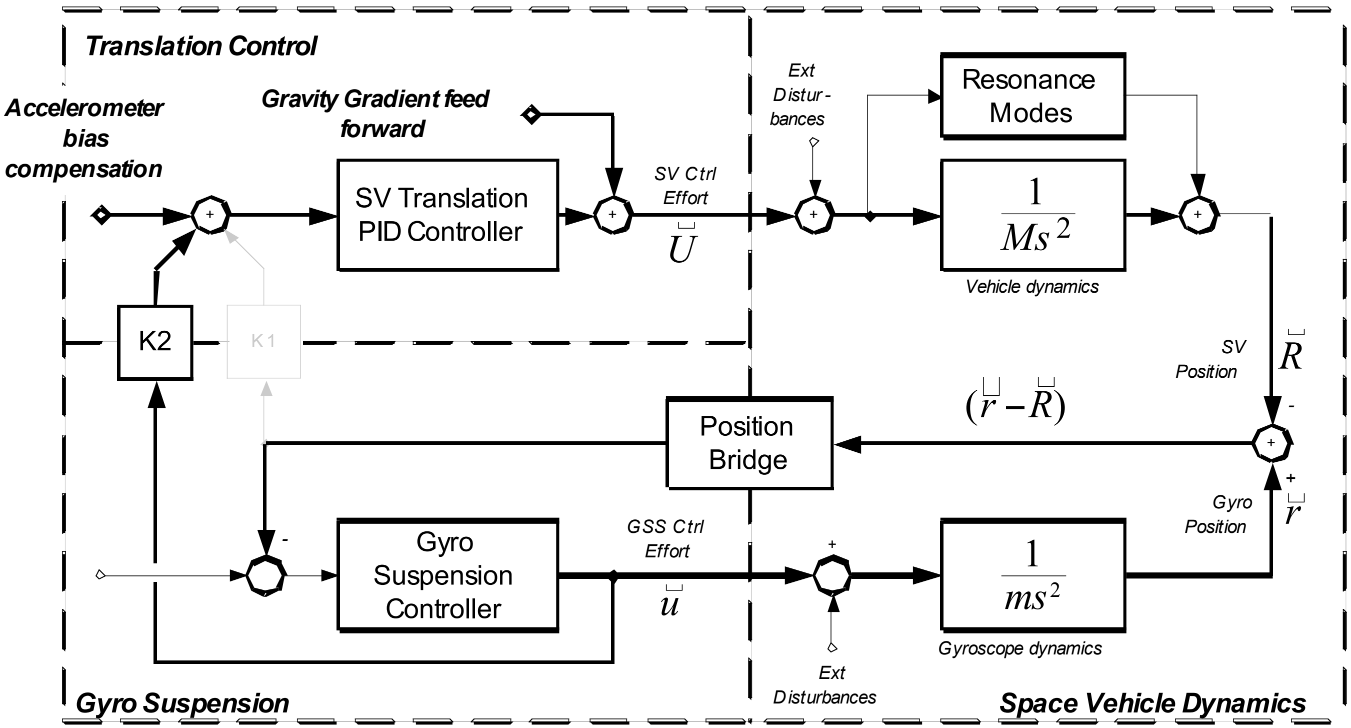
- In prime drag-free, the ATC system flies the SV around the position of the proof mass
  - Suspension control is turned “off” (up to a given safety radius)
  - **Advantage**: Suspension forces/torques minimized (somewhat)
  - **Disadvantages**: 1) unsuspended spinning “bomb”, 2) cannot correct for accelerometer biases

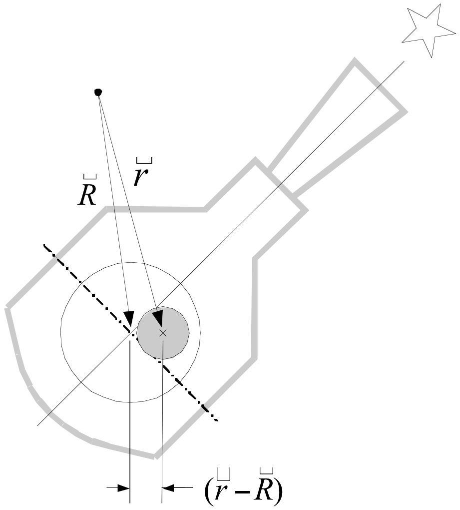




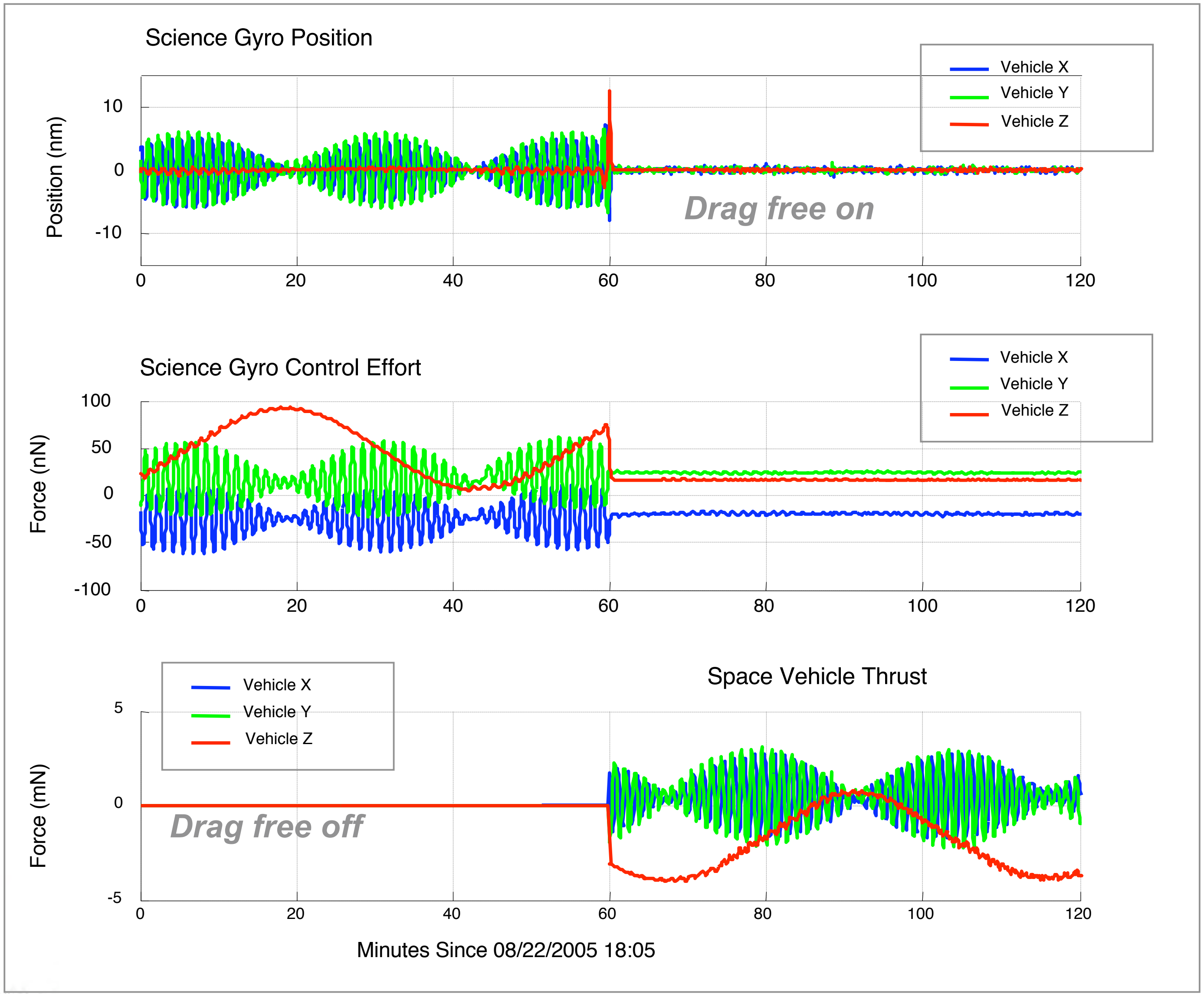
“Backup” Drag-free Operation

- In suspended (backup) drag-free, the ATC system nulls the gyro suspension control effort.
  - **Advantage**: Gyro “always” suspended; 2) Accelerometer biases can be removed.
  - **Disadvantage**: Suspension forces and torques reduced to preload minimums.





Example Drag-free Transitions



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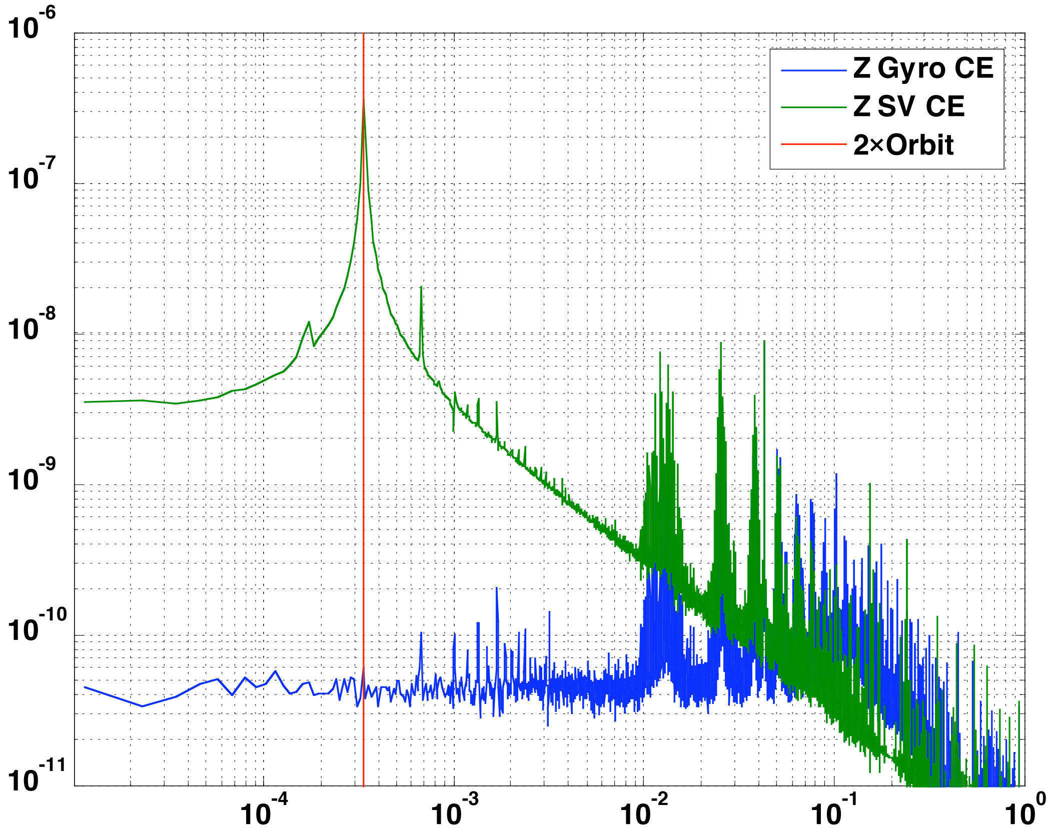
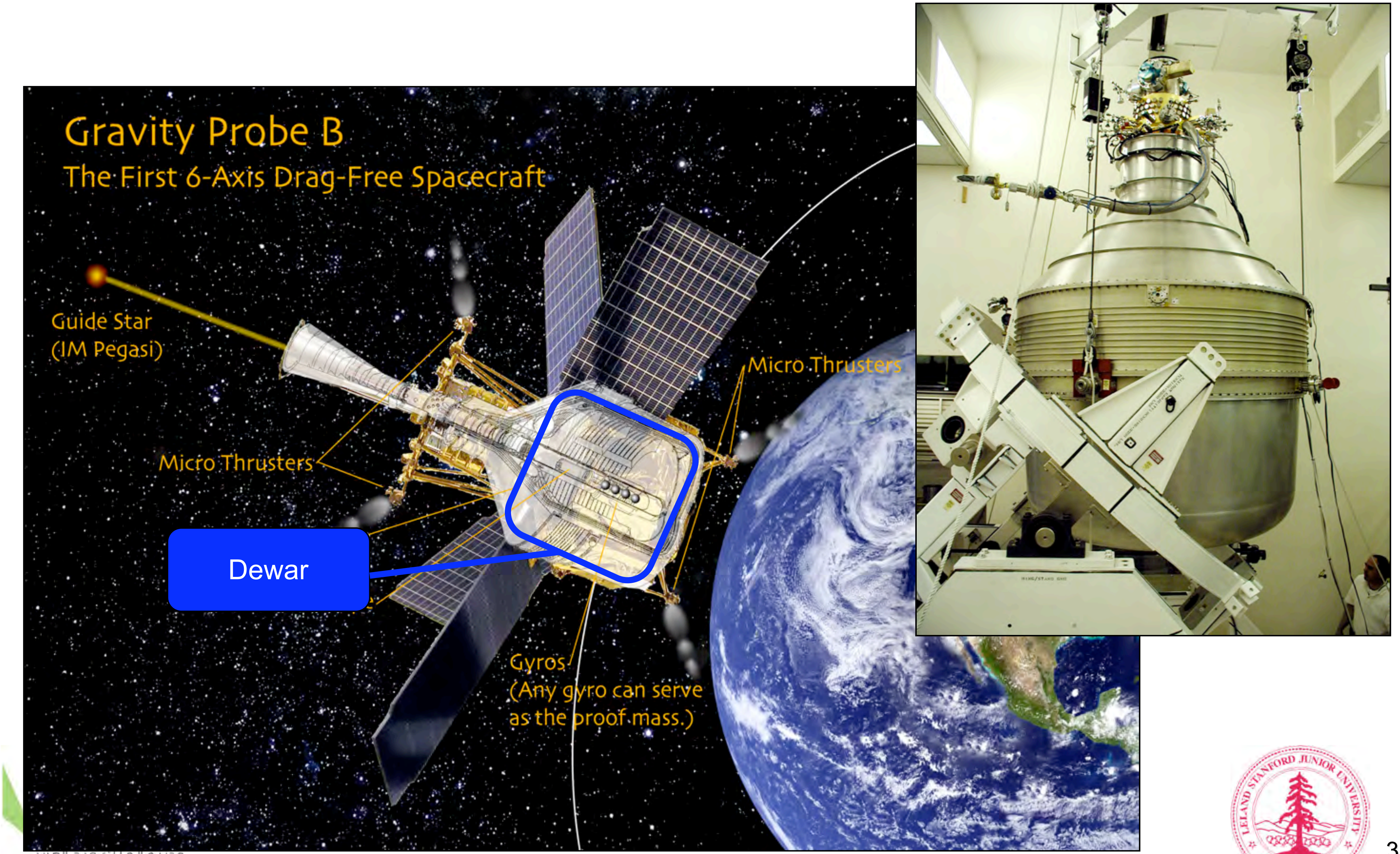
Overall Drag-free Performance

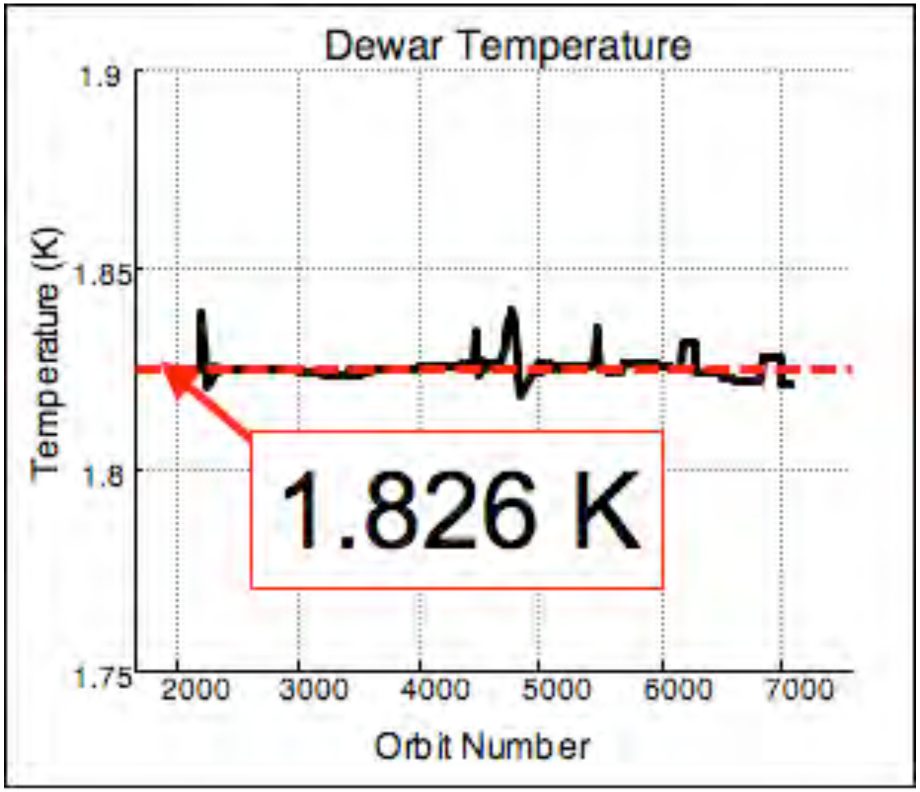


- **Performance at $4x10^{-12}$ g level between 0.01 mHz and 10 mHz in inertial space.**
- **Suppression of gravity gradient acceleration by a factor of ~10,000.**
- **Meets needs of experiment to minimize support forces on gyroscope.**

Dewar


Gravity Probe B
The First 6-Axis Drag-Free Spacecraft
Guide Star
(IM Pegasi)
Micro Thrusters
Micro Thrusters
Dewar
Gyros
(Any gyro can serve
as the proof mass.)

Dewar control plots



- The ATC system maintains a constant dewar temperature of ~1.83 K by controlling the flow rate of helium boil-off from the dewar

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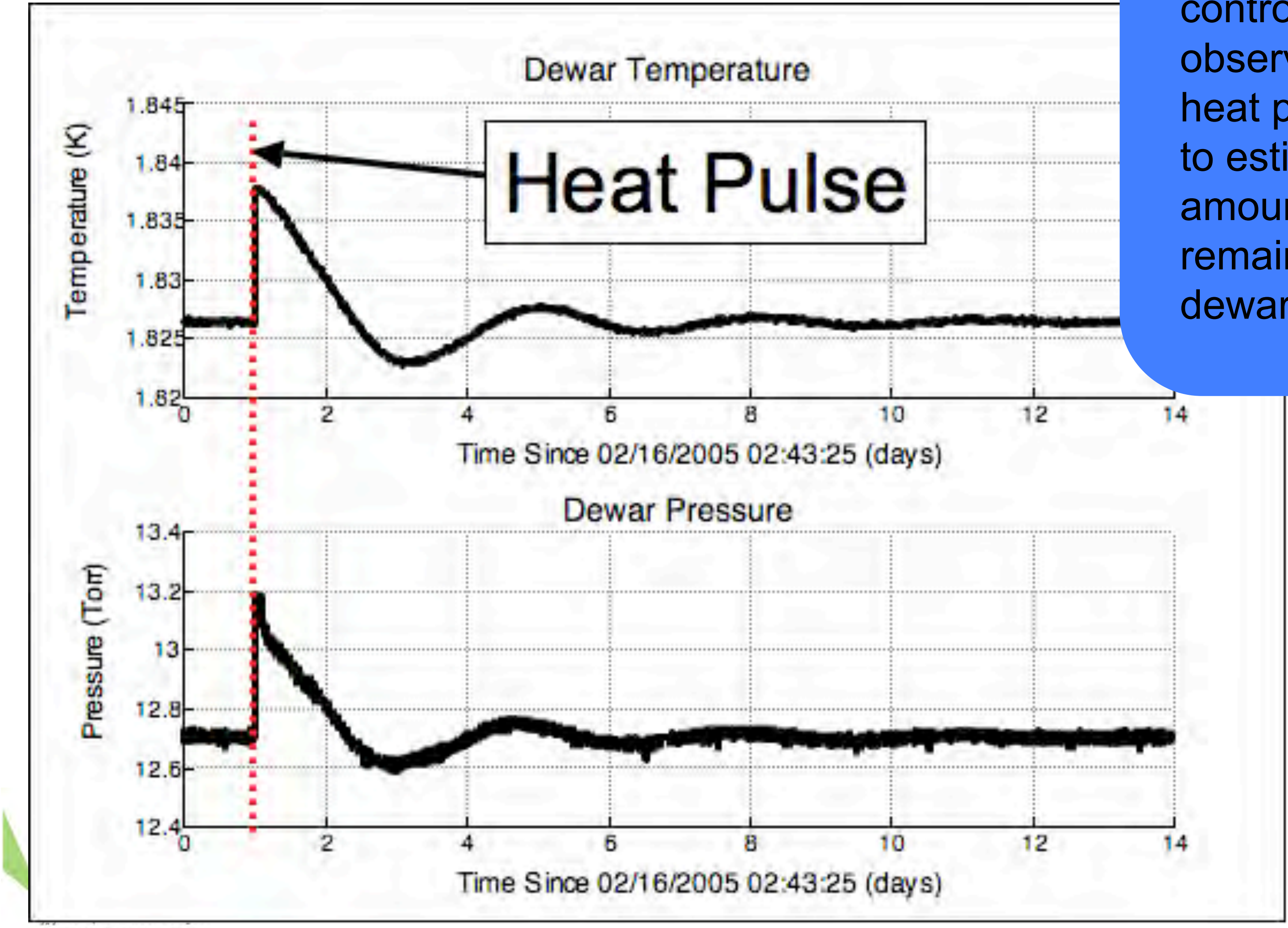
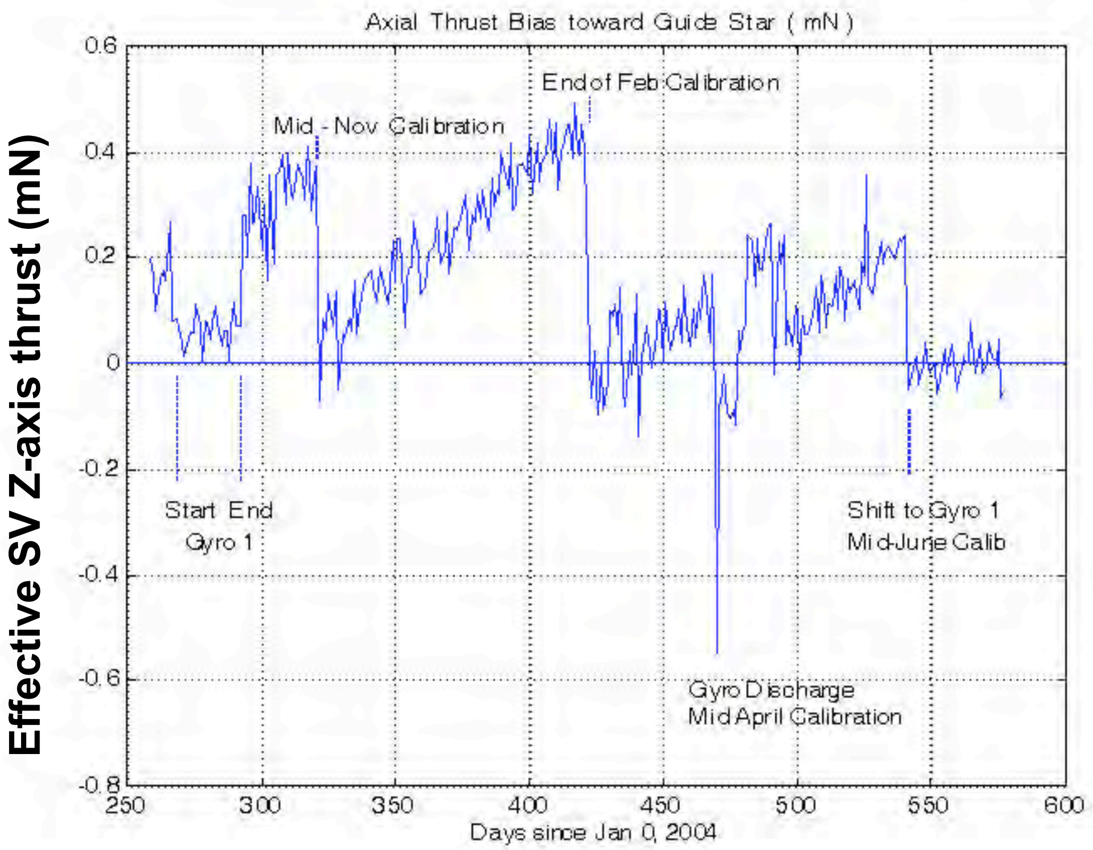
Dewar Heat Pulse



- The temperature control behavior is observable during a heat pulse test (used to estimate the amount of helium remaining in the dewar)

Lesson: Accelerometer biases Bends Orbit



- Accelerometer bias due to small patch charges generate drag-free force bias on vehicle.
- Bias identified via GPS and laser ranging; removed via parameter update.
- Necessitated backup drag-free operation to compensate for biases; no ability to compensate in prime drag-free.

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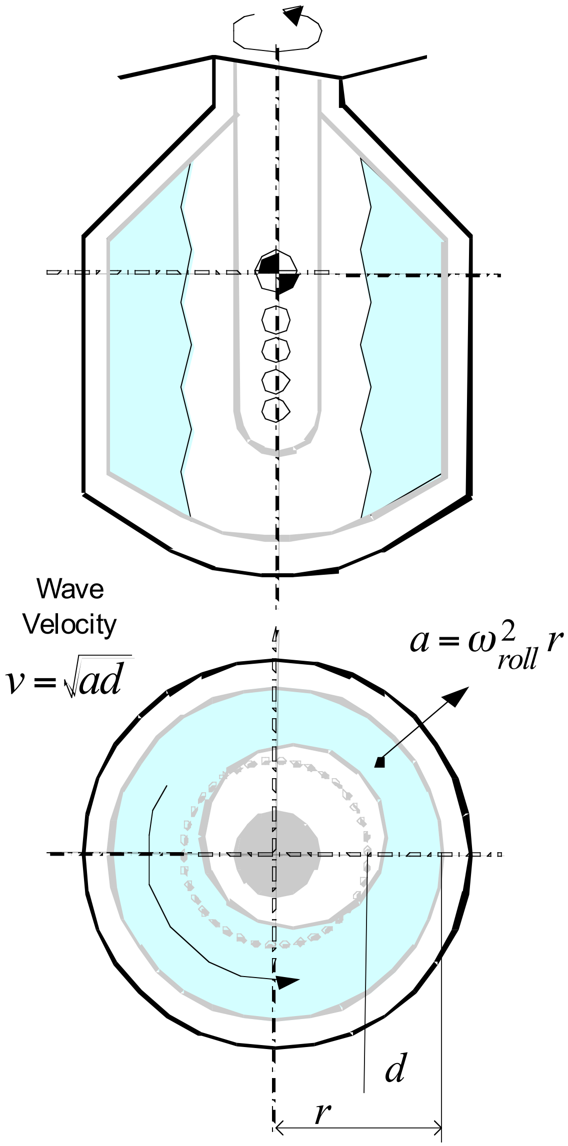
Lesson: Dewar slosh mode coupling



Dewar slosh mode resonance peak pumped by drag-free controller

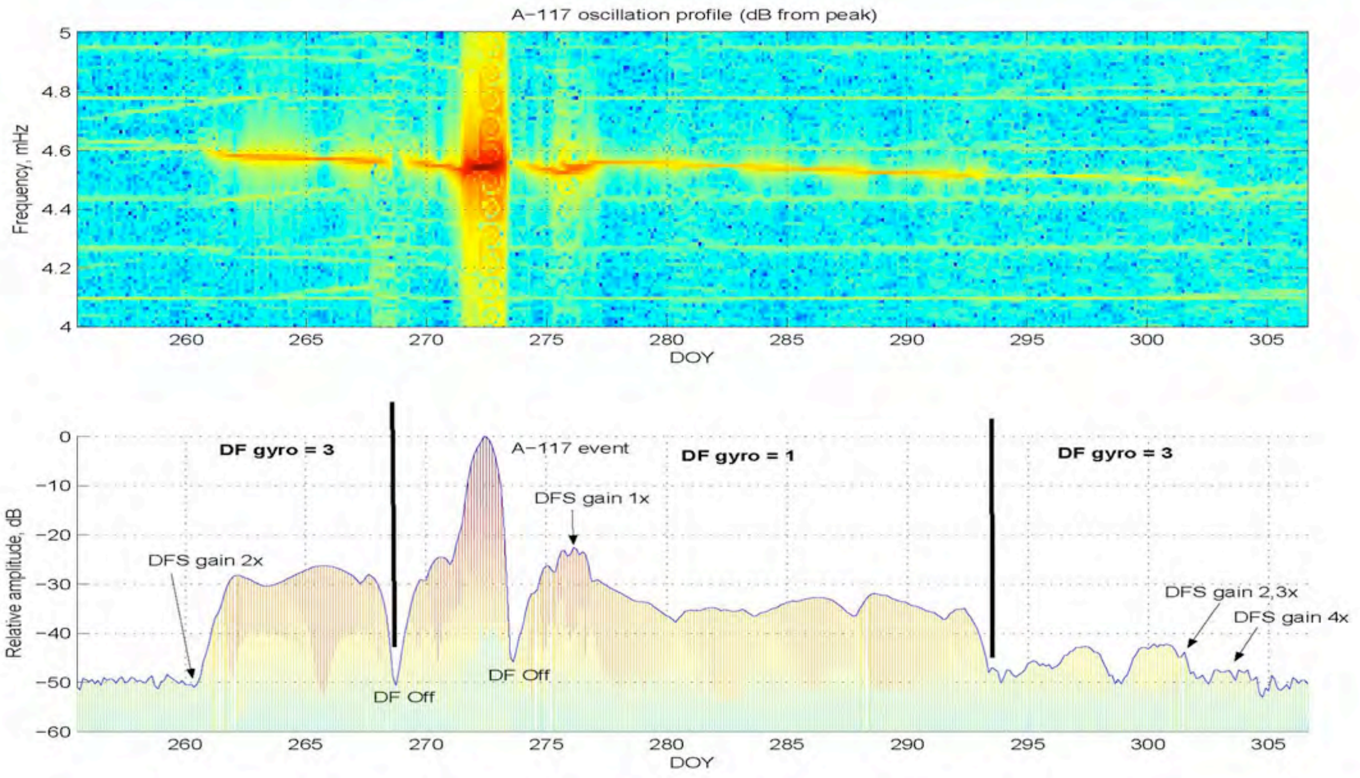
Managed via drag-free loop gain setting and crossover phase margin.

Simple fluid wave model predicts period with high accuracy:

$$T_{slosh} = \frac{l}{v} = \frac{2\pi r}{\sqrt{ad}}$$
$$= T_{roll}\sqrt{\frac{r}{d}}$$

Periods:
100 to 200 sec
(without the addition of SV roll period, 77.5 sec)

Slosh Mode Evolution



Peak at 1.2x10^{-7} g

217 sec period

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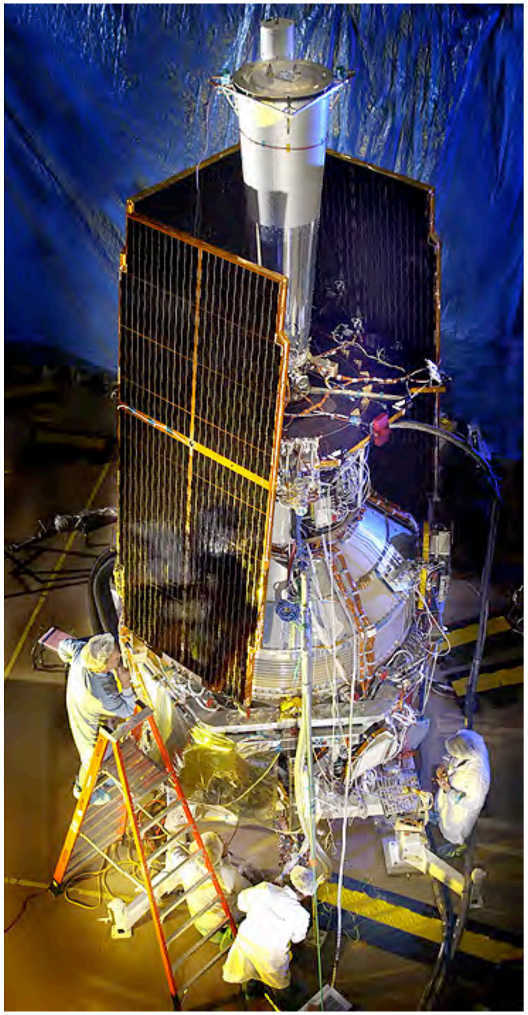
Conclusions



- 100marcsec/√ Hz pointing Achieved
  - 5marcsec at roll frequency
- Roll phase controlled to <40arcsec
- Drag-free performance on orbit established at the 4×10^{-12} g level.
- Reduced the gravity gradient accelerations on the proof mass by a factor of ~10,000.
- Proportional cold gas thrusters fueled from Helium boil-off worked well to control the space vehicle in 6DOF.
- Both prime and backup drag-free modes were demonstrated on orbit.
- Accelerometer biases were corrected in backup drag-free mode to keep the orbit constant.
- **6 Degree of Freedom Control Works**

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