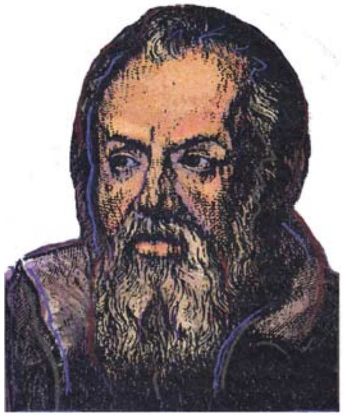
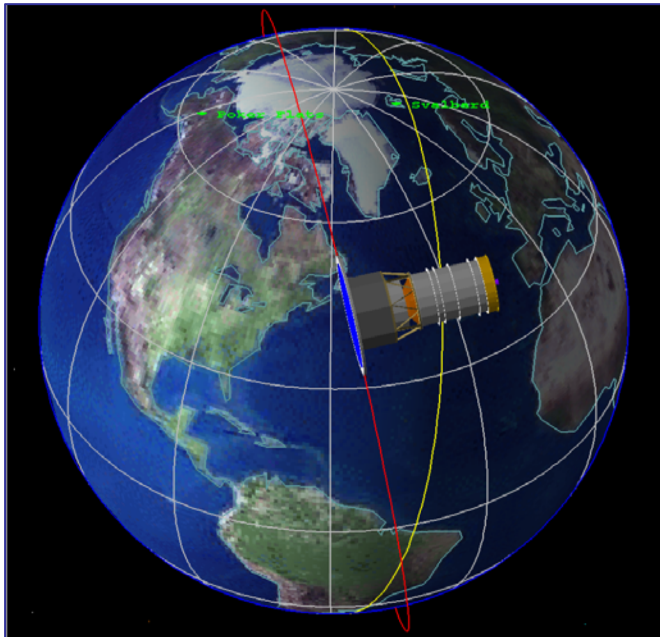


Satellite Test of the Equivalence Principle (STEP)

John Mester

MAY 2009



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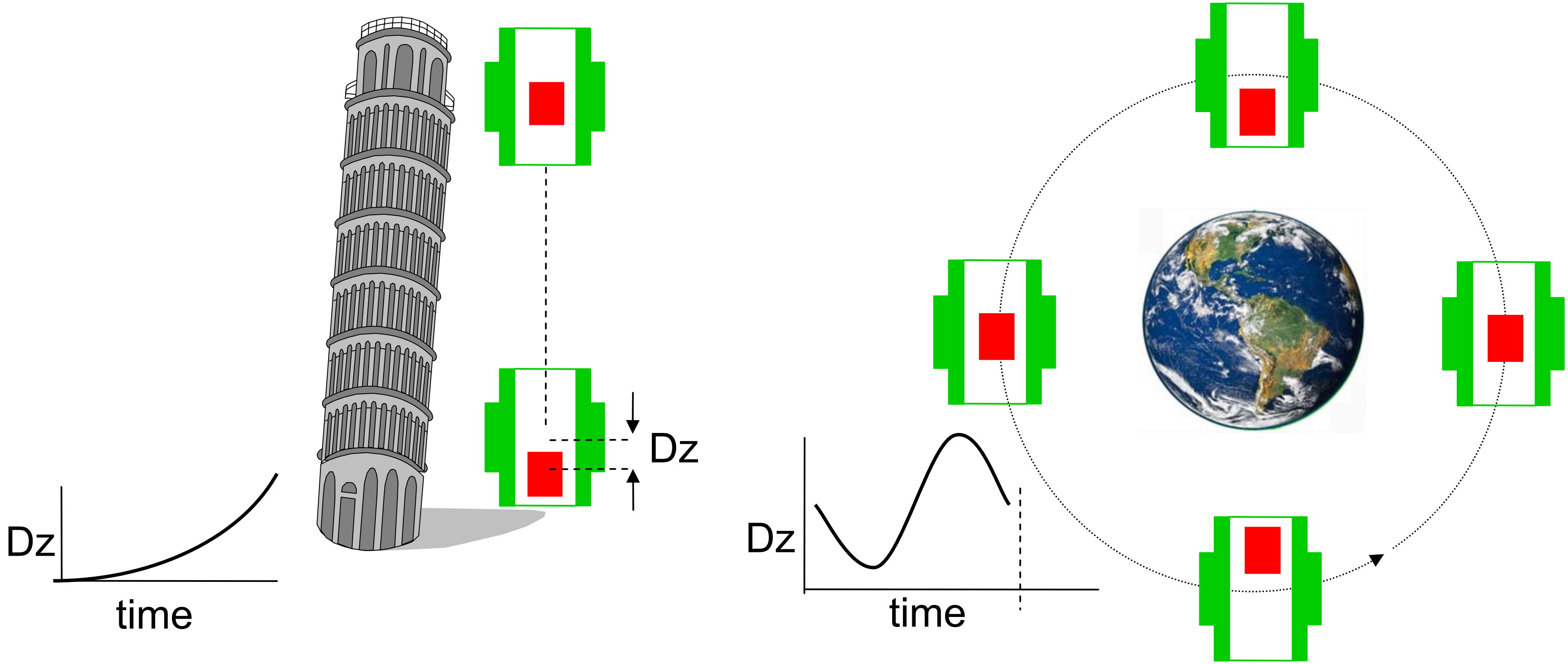
Satellite Test of the Equivalence Principle

Newton's Mystery {
- $F = ma$ — mass - the receptacle of inertia
- $F = GMm/r^2$ — mass - the source of gravitation

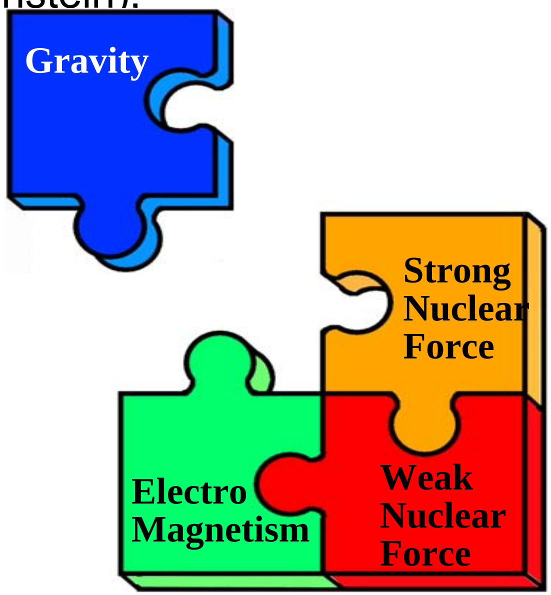


Orbiting drop tower experiment {
- * More time for separation to build
- * Periodic signal

"Equivalence" not true of any other forces (e.g. magnetism)

Can Gravity Be Made to Fit?

- **Unification in physics** – through fields (Maxwell), geometry (Einstein), symmetries and gauge invariance (electroweak theory)…. and now (?) supersymmetry and strings



- **The problems of gravity** – quantization; hierarchy -10^{-42}; cosmological constant Λ (10^{-120}!); equivalence

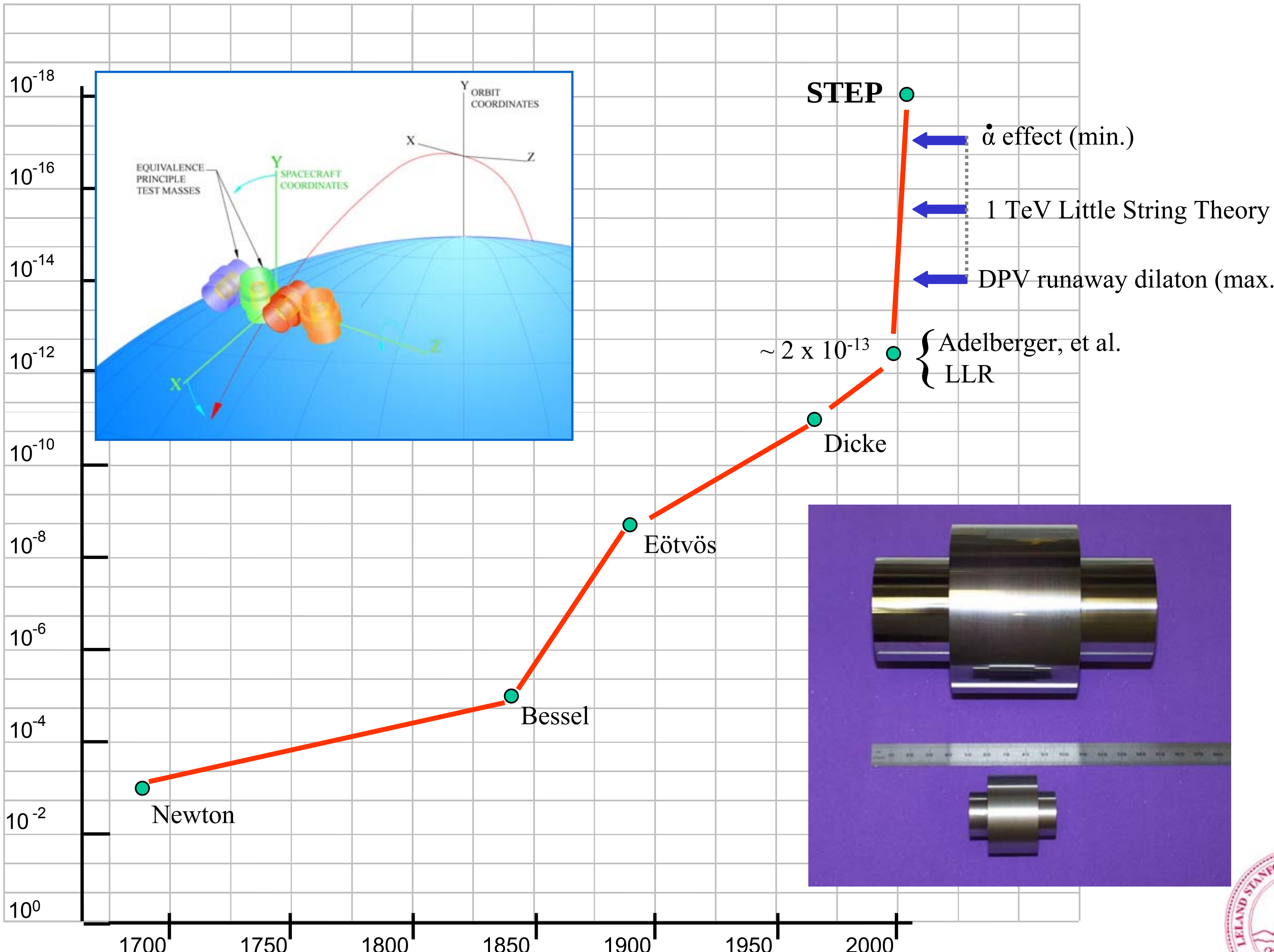
- **Partial steps toward Grand Unification**
  - Strings/supersymmetry in early Universe $\Rightarrow$ scalar-tensor theory, not Einstein's
  - Damour - Polyakov: small Λ $\Rightarrow$ long range equivalence-violating dilaton

- **EP violations inherent in all known GU theories**
  - Runaway dilaton theories { (Witten) / (Damour, Piazza, Veneziano) } η { $\gg 10^{-18}$ / up to 10^{-14} }
  - 1 TeV Little String Theory (Antoniadis, Dimopoulos, Giveon) η $\sim 10^{-15}$

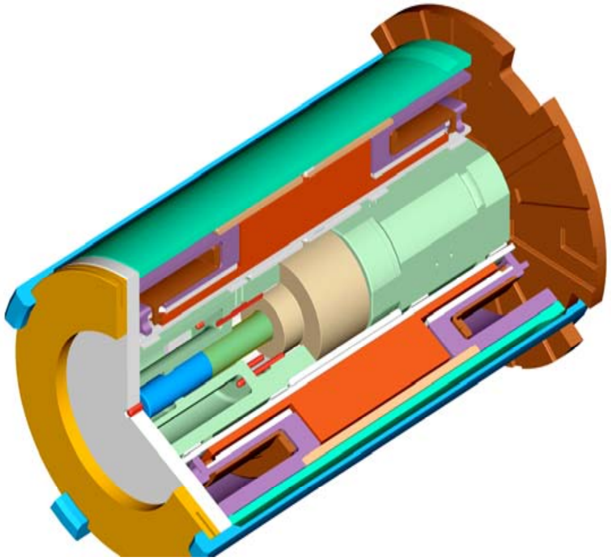
STEP's 5 orders of magnitude take physics into new theoretical territory

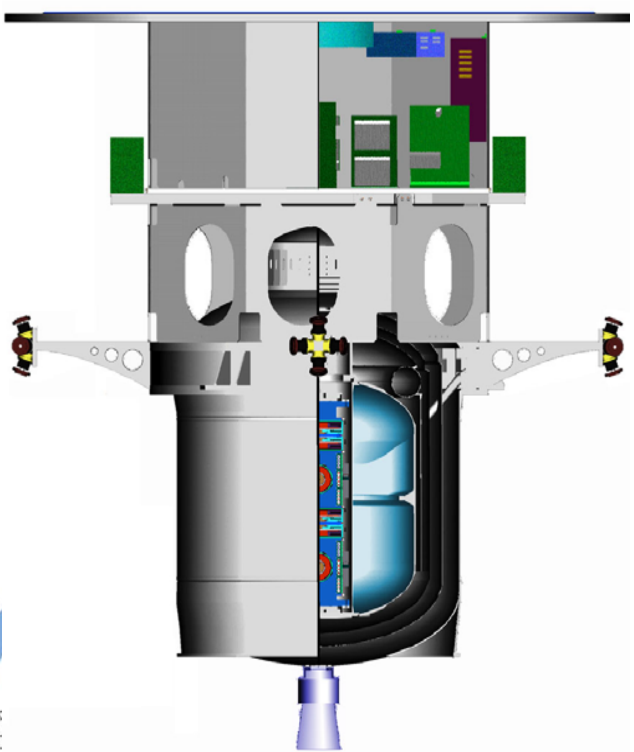
Space > 5 Orders of Magnitude Leap

STEP Goal: 1 Part in 10^{18}



STEP Mission





8 Month Lifetime

Sun synchronous orbit, I=97^{o}

550 Km altitude

Drag Free control w/ He Thrusters

Cryogenic Experiment

Superfluid Helium Flight Dewar

Aerogel He Confinement

Superconducting Magnetic Shielding

4 Differential Accelerometers

Test Mass pairs of different materials

Micron tolerances

Superconducting bearings

DC SQUID acceleration sensors

Electrostatic positioning system

UV fiber-optic Charge Control

Goal: EP Measurement to 1 part in 10^{18}

KACST-Stanford STEP Technology Development Program

Technology Program Goals:

Advance STEP Payload to NASA Technology Readiness Level 6

(System prototype demonstration in a relevant environment)

Enable a seamless transition to a flight Phase B

Technology Program Key Elements:

(w/ required additional Students, Post Docs or Visiting Researchers)

- Differential Accelerometer (2)
  - Accelerometer Fabrication and Piece Part Testing
  - Accelerometer Integrated Testing
- Cryogenic Systems and Cryoelectronics (1)
- Error Model Development (1)
- Precision Attitude and Translation Control (2)

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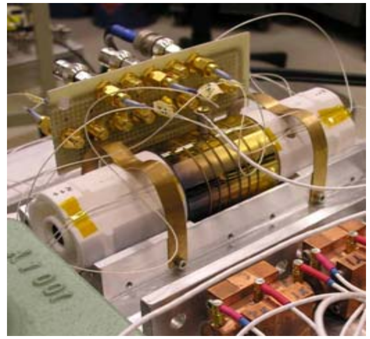
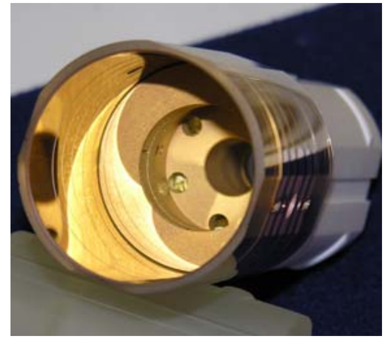
Accelerometer Development: Incremental Prototyping

Integrated Inner Accelerometers:

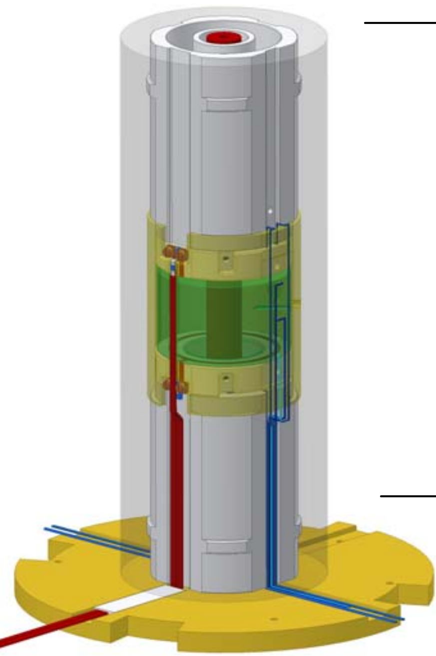
Brass-Board

BB 1



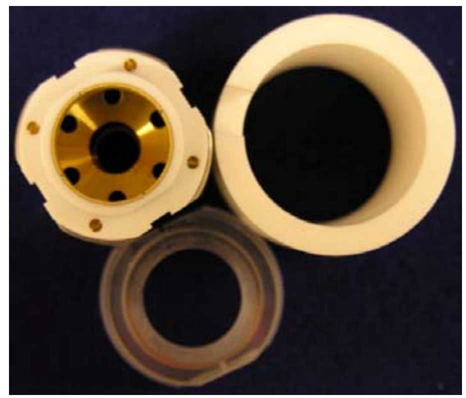


- Non-cryogenic operation
- Gold surface coatings
- Electrostatic subsystem fully-functional



Brass-Board

BB 2



- Cryogenic operation
- SQUID Readout
- MCG 25 micron tolerances

Engineering Model

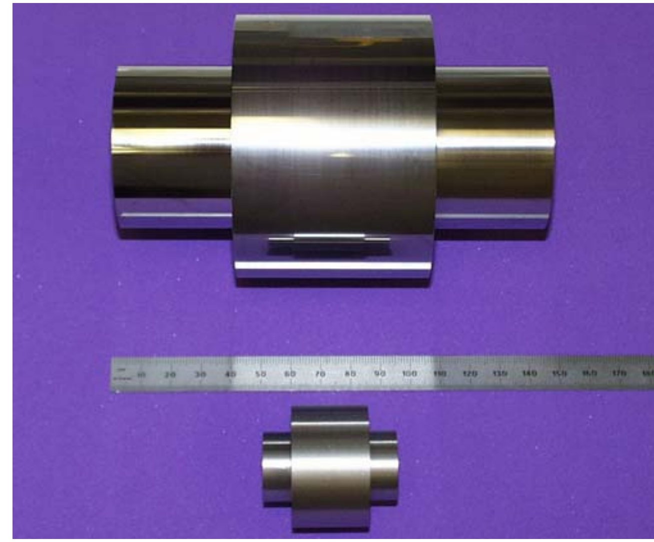
EM 1

- Precision quartz housing

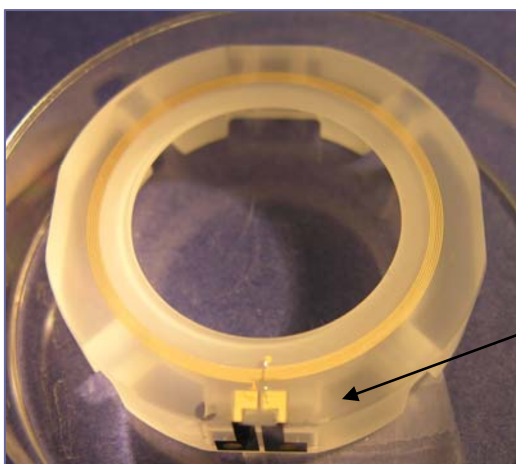
  1 micron tolerances
- BB2 functionality
- Axsys Technologies &

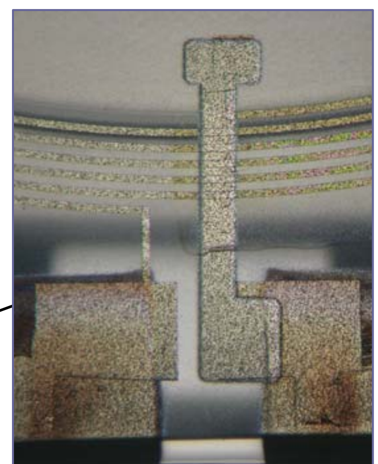
  In house processing

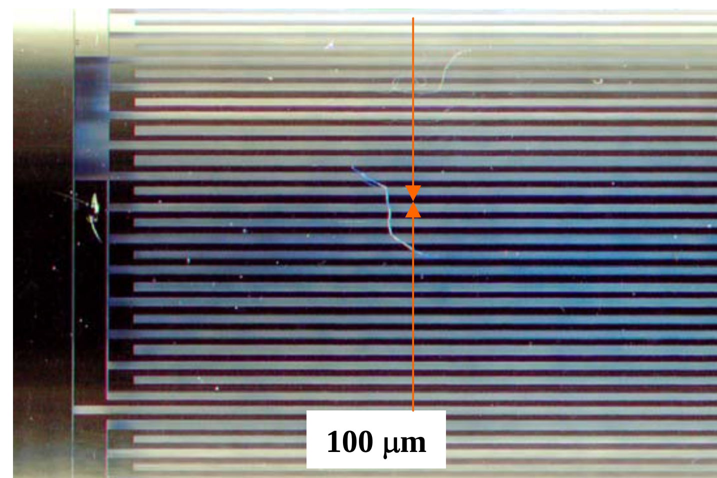
Flight Engineering Unit Inner Accelerometer



Quartz Housing Components and Test Masses μm Tolerances







Nb Superconducting thin film circuits: multilayer w/ dielectric crossovers and on cylinders

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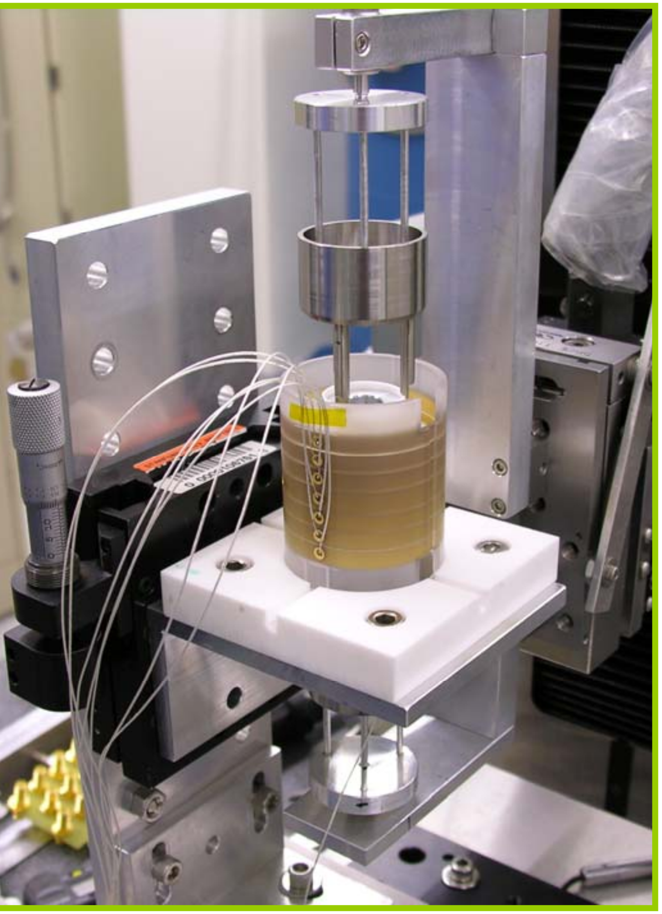
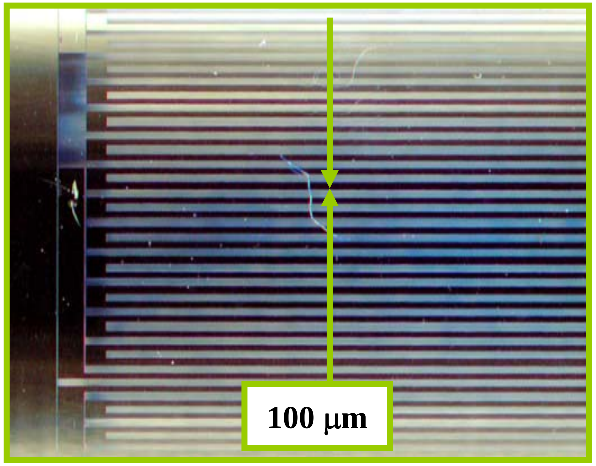
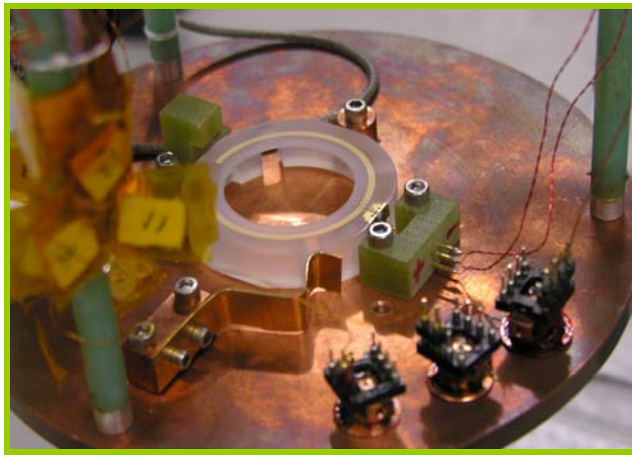
Piece Part Testing



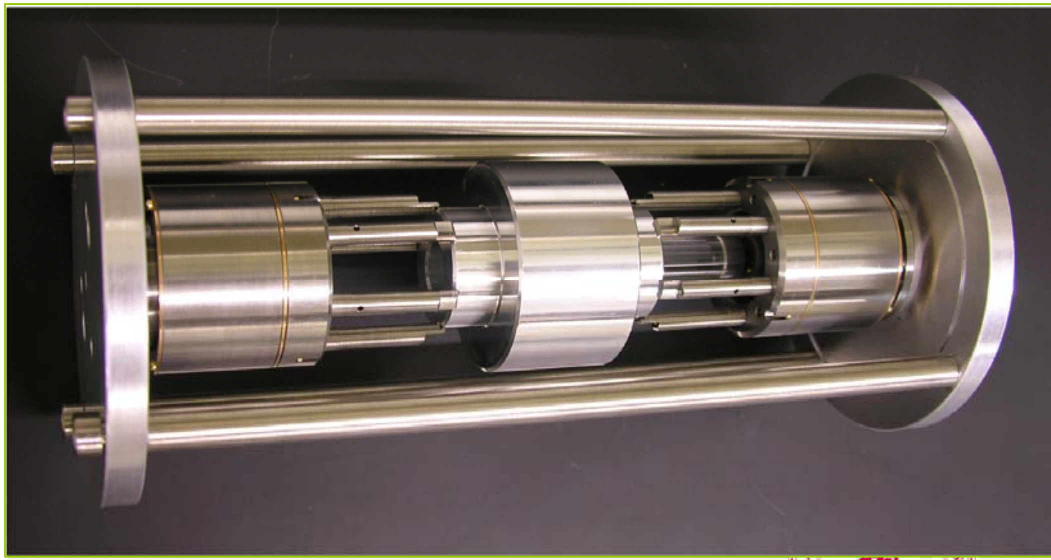
EPS Translation



Bearing Tc & Ic



SQUID Pickup loop Tc & Ic

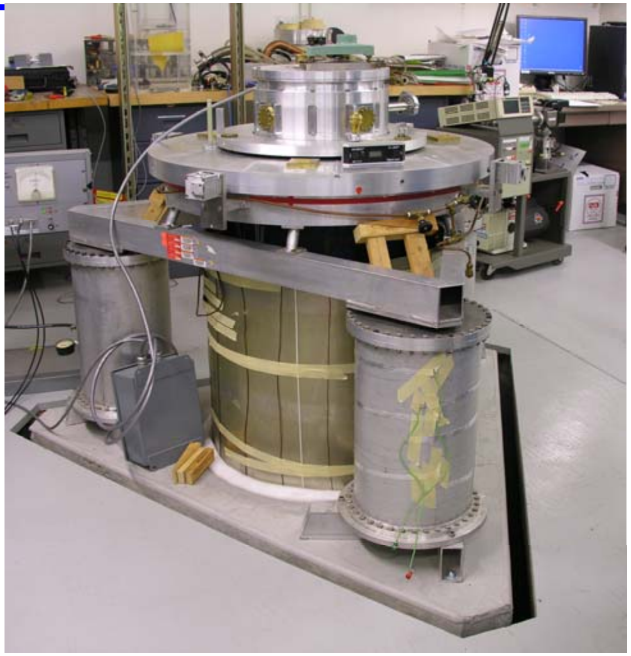


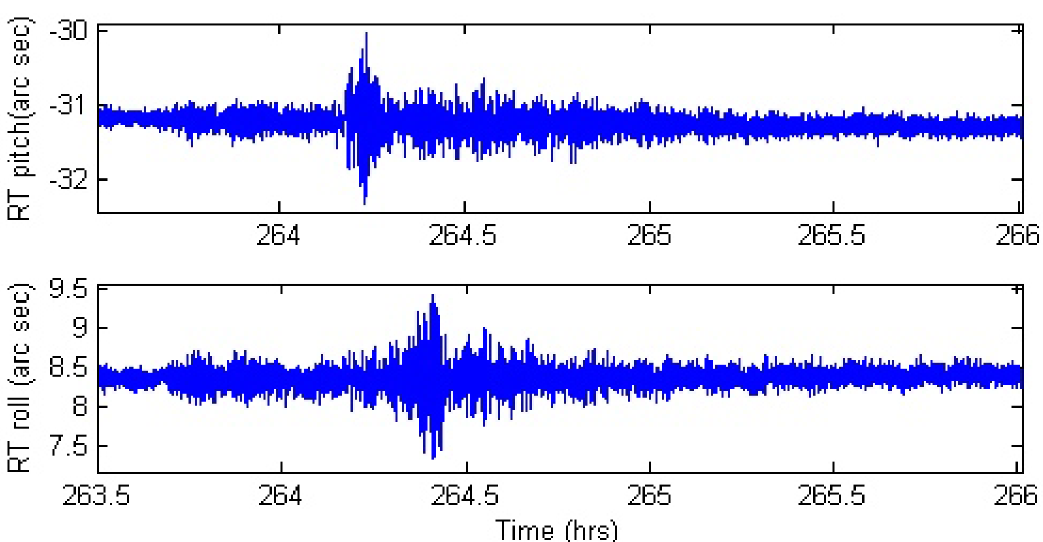
Caging System

Integrated Testing

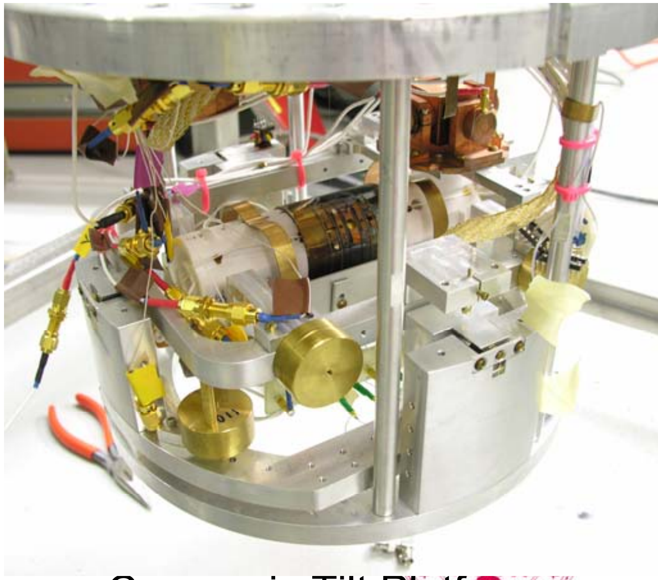
- Accelerometer Test Facility for Integrated testing
  - –Fiber supported testmass w/6 DOF control
- Demonstrated 5 nRad white noise with ss temp controlled actuators
- With Al cylinders as shown

tilt noise ~ 0.5 μRad but even this is sensitive enough to see external seismic systematics





Sichuan Earthquake 06:28:01 (UTC) May 12, 2008 06:28:01 (UTC)



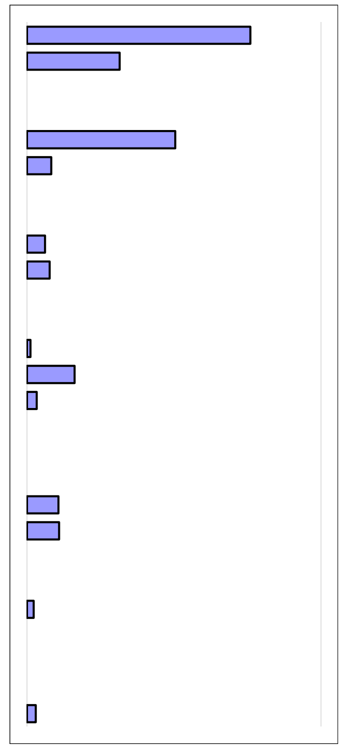
Cryogenic Tilt Platform

STEP Error Model

Comprehensive error model developed to give self consistent model of whole system

Class. Quantum Grav. 18 (2001), Space Science Reviews SSSI 35 (2009)

DFC Reference accelerometer Disturbance	Systematic component at signal frequency m/sec^2	Comment
SQUID noise	1.80E-18	acceleration equivalent to intrinsic noise
SQUID temp. drift	7.46E-19	regulation of SQUID carriers
Thermal expansion	8.69E-22	gradient along DAC structure
Differential Thermal expansion	3.35E-23	Radial gradient in DAC structure
Nyquist Noise	1.19E-18	RMS acceleration equivalent-no electronic cooling
Gas Streaming	1.94E-19	decaying Gas flow, outgassing
Radiometer Effect	2.51E-21	gradient along DAC structure
Thermal radiation on mass	4.58E-25	Radiation pressure, gradient
Var. Discharge uv light	1.45E-19	unstable source, opposite angles on masses
Earth field leakage to SQUID	1.84E-19	estimate for signal frequency component
Earth Field force	7.74E-22	estimate for signal frequency component
Penetration depth change	5.30E-23	longitudinal gradient
Electric Charge	3.06E-20	Assumptions about rate
Electric Potential	3.83E-19	variations in measurement voltage
Sense voltage offset	8.05E-20	bias offset
Drag free residual in diff. Mode	2.21E-22	estimated from squid noise
Viscous coupling	6.87E-26	gas drag + damping
Cosmic ray momentum	4.64E-21	mostly directed downward
Proton radiation momentum	2.54E-19	unidirectional, downward
dynamic CM offset	2.59E-19	vibration about setpoint, converted
static CM offset limit	1.38E-22	A/D saturation by 2nd harmonic gg
Trapped flux drift acceleration	1.03E-22	actual force from Internal field stability
Trapped flux changes in squid	5.54E-20	apparent motion from internal field stability
S/C gradient + CM offset	3.39E-37	gravity gradient coupling to DFC residual of S/C
rotation stability	1.02E-23	centrifugal force variation + offset from axis
Eccentricity subharmonic.	5.96E-21	real part at signal frequency
Helium Tide	7.00E-20	worst case



position sensor gap, mm	1.00	550000	Orbit height
differential mode period	1385	8.9E-13	CM distance, m
S/C rotation per orbit	-2.70E+00		
Summed error	**5.34E-18**	**RMS error** **2.37E-18**	m/sec^2

Verification and validation efforts with flight like hardware are ongoing

- lab system performance to be incorporated in Error Model

Precision Attitude and Translation Control Simulation to be incorporated in Error Model

Precision Attitude and Translation Control

STEP & Future Missions Require Attitude Control and Translation Control beyond the state of the art

Gravity Probe B engineering analysis=> these future missions are feasible

- GAIA global space astrometry mission– goal: most precise three-dimensional map of our Galaxy (attitude control)
- STEP – testing Equivalence Principle (attitude & translation control)
- LISA – gravitational wave mission (attitude & translation control, multiple spacecraft)

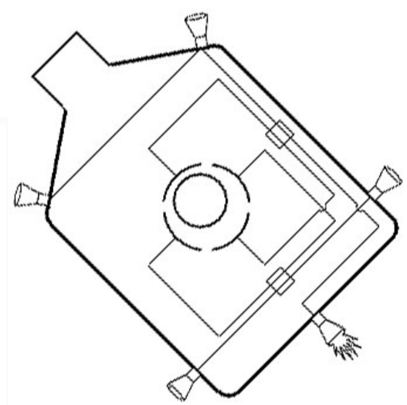
Translation Control for STEP

STEP Requirement: a seismically Quiet Environment -
$6 \times 10^{-12}\ m/s^2/\sqrt{Hz}$ at signal frequency

Free-flyer satellites above 500 km typically experience 10^{-7} to 10^{-8} g acceleration environments

+ internally induce vibrations from moving parts
gyros, momentum wheels, ISS acceleration noise ~ 10^{-4} g

⇒Control spacecraft to follow an inertial sensor ≡ Drag Free
Reduce drag, Radiation Pressure, Gravity Gradient & Magnetic torques



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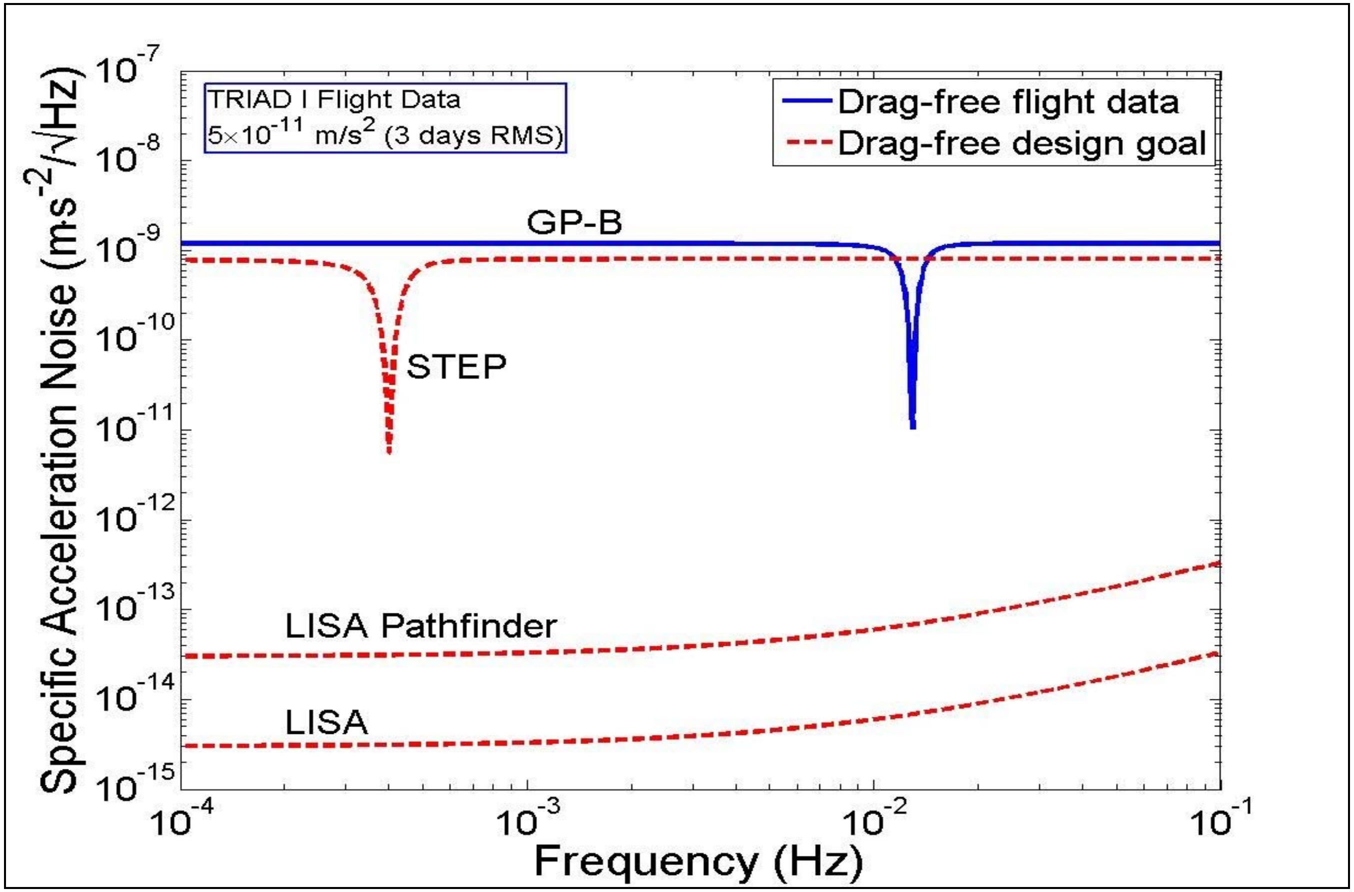
Drag Free Control



- STEP DFC Requirement slightly more stringent than GP-B
- More complex inertial sensor

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Drag Free History

Drag-Free Satellites have flown successfully

- TRIAD I : DISCOS - Disturbance Compensation System
  - 3 axis translation conttrol PI, Dan DeBra, Stanford,
  Navy Transit Navigation Program, JHU APL
  Launched September 2, 1972, Polar Orbit at 750 km

- TIPs (Transit System) One DOF translation control
  Paul Worden, Stanford Consultant

- And Now Also GP-B
  3 axis translation control
  3 axis active attitude control

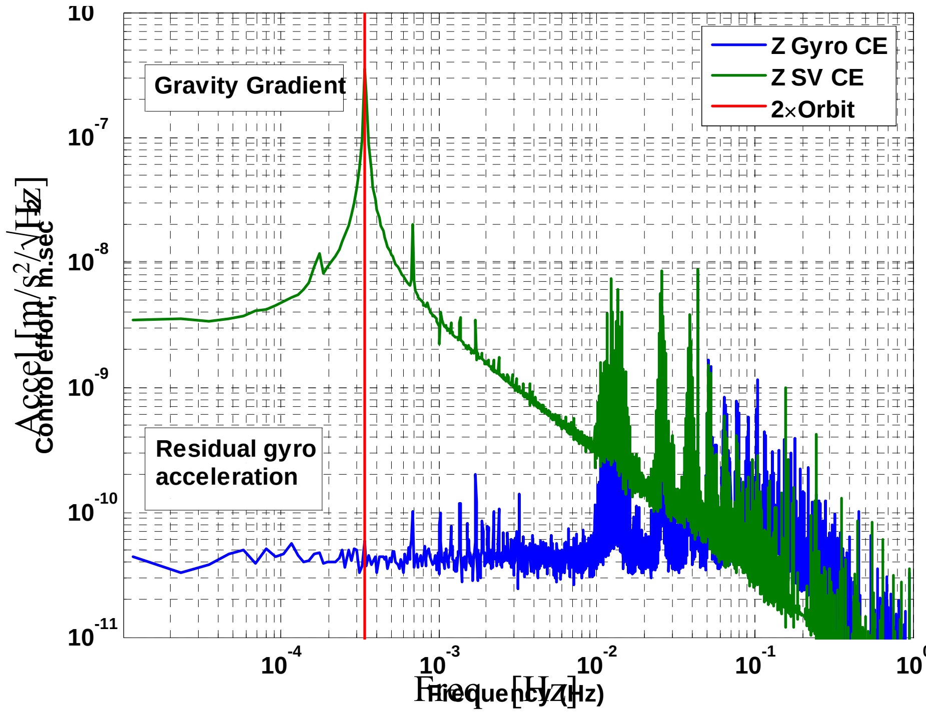
GP-B Lessons Learned

Initial Orbit Checkout (IOC), successful but challenging

4 month duration, 2 months planned

10,000 commands sent

Performance Requirements Ultimately Achieved



Among the many lessons learned:

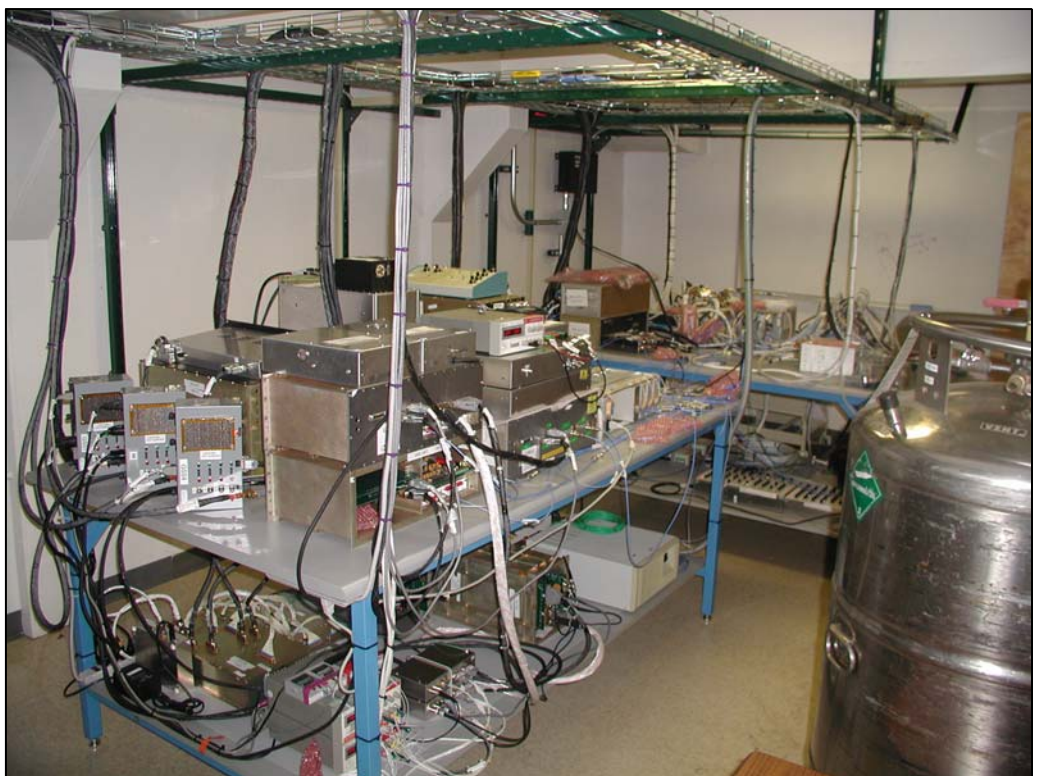
Necessity of accurate hardware-in-the-loop simulations.

High fidelity integrated payload/spacecraft simulator is valuable on orbit.

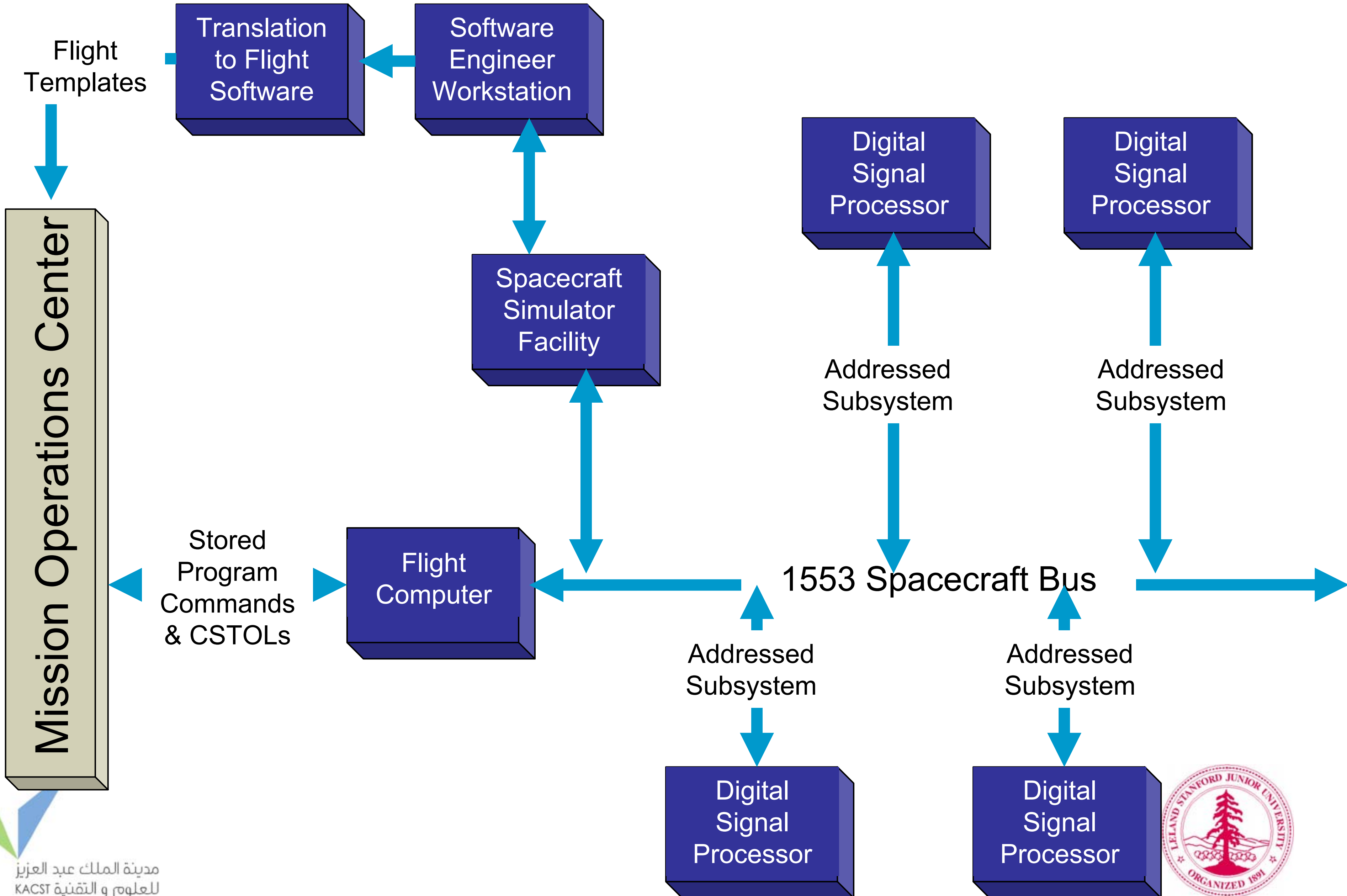
Advantage in use of simulators early in mission development life cycle.

Vehicle: Integrated Test Facility (ITF)

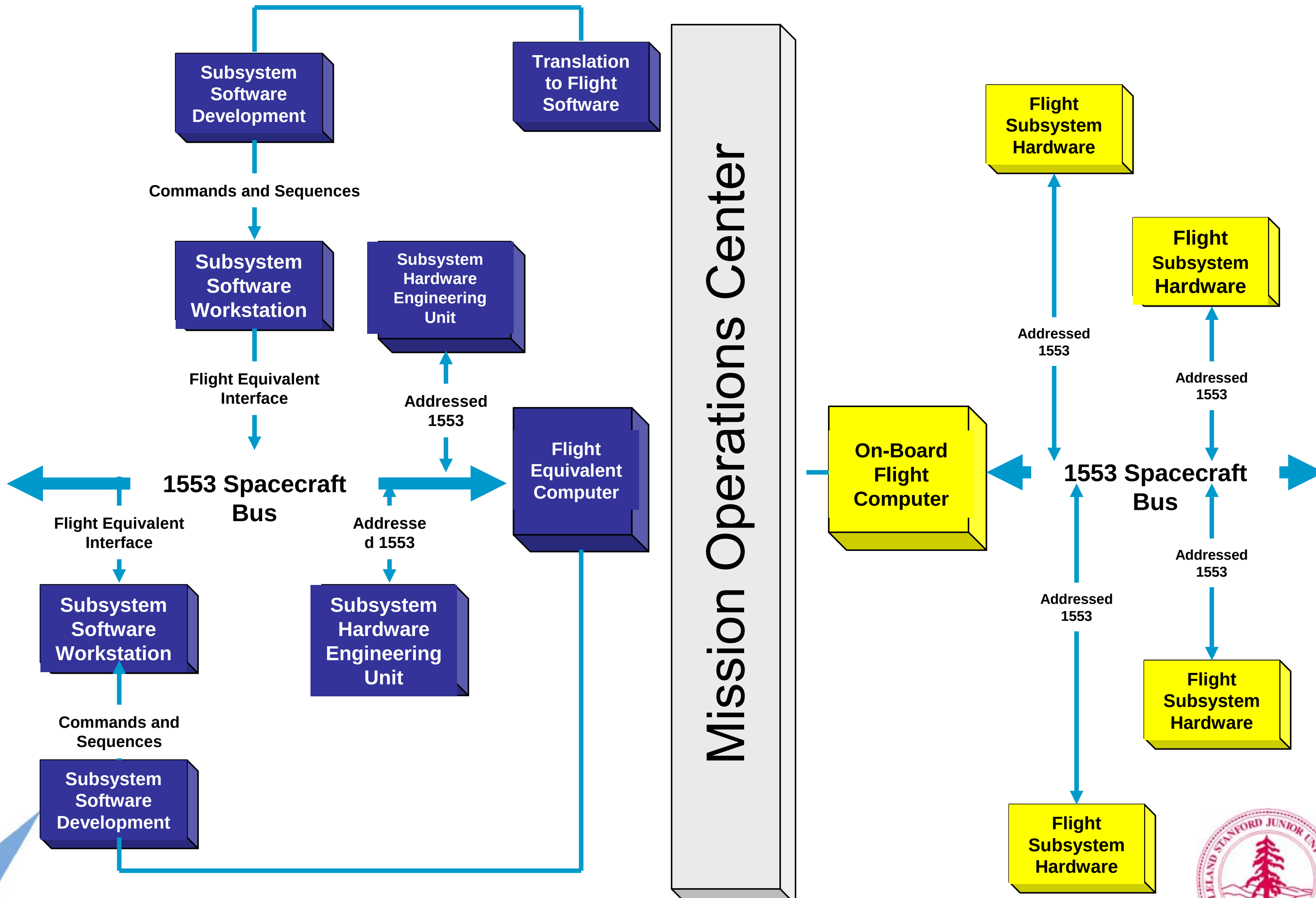
- ITF is the GP-B on-ground vehicle simulator
  - FEU or flight-spare hardware
  - 100% Flight software (SV + GSS)
  - Payload signal simulators (SQUID, gyro simulator, etc)
  - Used to test and verify command sequences on the ground
  - Orbital dynamics provided by dedicated simulator and SW interface (VES)



Simulation During Mission Development



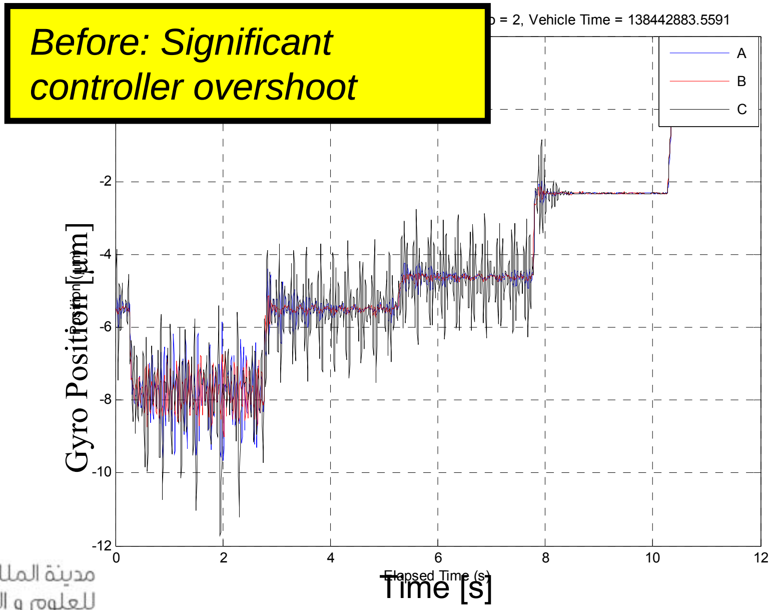
Simulation During Flight

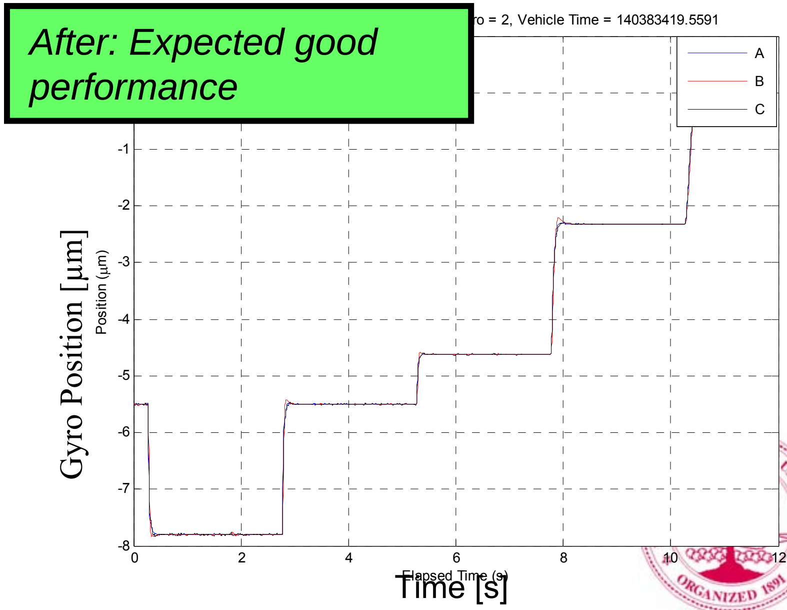


On-orbit issues resolved using ITF

- Initial digital gyro levitation failure (A-018)
- Drag-free performance tune-up (A-110)
- Dewar slosh mode investigation (A-117)
- Single axis charge measurement investigation.
- Drag-free/center of mass performance assessment
- Gyro/gyro polhode modulation coupling
- Vehicle (ARP)/gyro coupling

- **Gyro controller instability (O-085)**

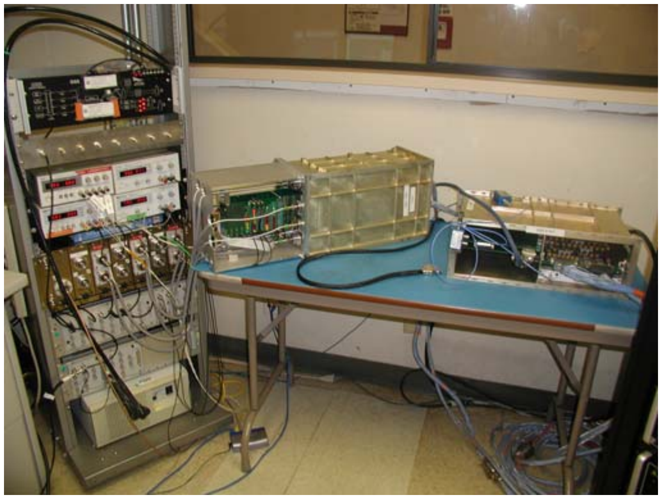


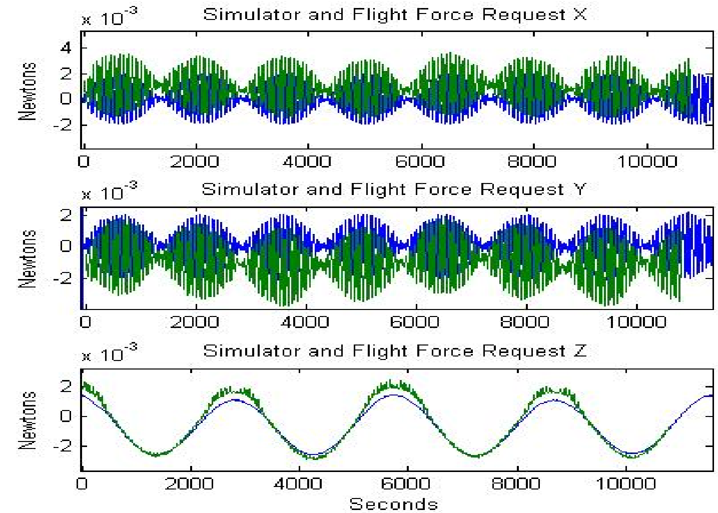


Ongoing ATC Work at Stanford

- ZARM ‘First Look’ Program Collaborating Institutions
  - ZARM, University of Bremen, Matthias Matt, Ivanka Pelivan, Stefan Theil Institute of Astronomy, Cambridge University,GAIA group
  - ATC Simulator Development
  - Use GP-B data to validate simulator
- University of Rome”Sapienza”
  - Modeling of STEP accelerometer inertial sensor, Valerio Ferroni

Simulator Dynamics Match Flight Data

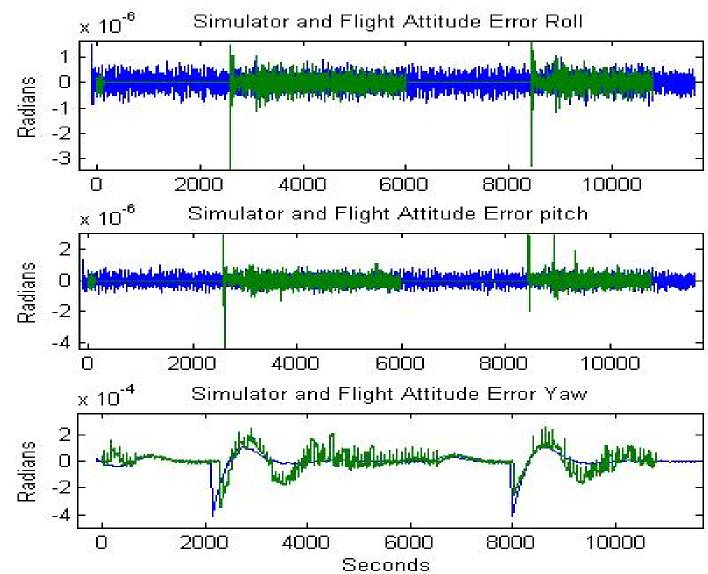




Attitude

Simulation vs Flight

- GP-B attitude and translation simulation validated
- GP-B 4 gyroscope configuration complete
- Stanford and ZARM simulations in agreement
- Ready for more complicated flight data comparisons



Translation

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KACST - Stanford Proposed Work

1) Develop fully integrated sensor-controller-actuator simulations of STEP, operating across the payload/spacecraft interface

2) Exploit modular architecture to enable exchange of software models for hardware units for hardware-in-the-loop verification

3) USE high fidelity spacecraft bus and flight CPU to enable flight software validation and verification with the science payload

4) Integrate Mission Operations consoles for command generation and verification - anticipate on orbit tuning

Required: 2-3 Students, Post Docs or Visiting Researchers

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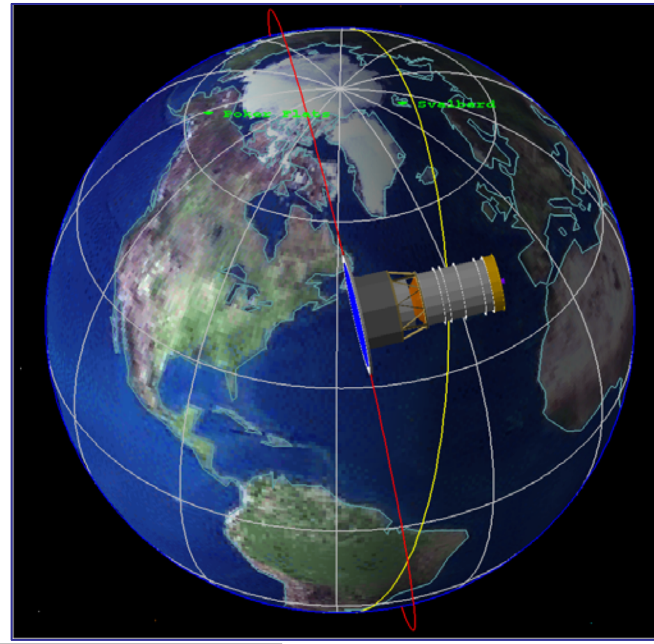
LELAND STANFORD JUNIOR UNIVERSITY
ORGANIZED 1891

STEP: Credibility & Impact

- Robust Equivalence Principle data
  - 4 accelerometers, each ⇨ η to 10^{-18} in 20 orbits
- Positive result (violation of EP)
  - Discovery of new interaction in Nature
  - Strong marker for unified theories
  - Implications for dark energy
- Negative result (no violation)
  - Severely limits approaches to problems of unification & dark energy
  - Strongly constrains supersymmetric & quintessence theories



SMEX 2008 Science Implementation Peer Review:

- The proposed instrument can be built with technologies described.
- The data returned will directly address the science goals and, … the instrument is likely to provide the necessary data quality.
- The probability of success seems high

"Improvement by a factor of around 10^5 could come from an equivalence principle test in space . … at these levels, null experimental results provide important constraints on existing theories, and a positive signal would make for a scientific revolution." (p. 162)

Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century (2003)

-- National Academies Press, the National Academy of Sciences