BEACON

(Beyond Einstein Advanced Coherent Optical Network)

Testing General Relativity to 10^{-9}

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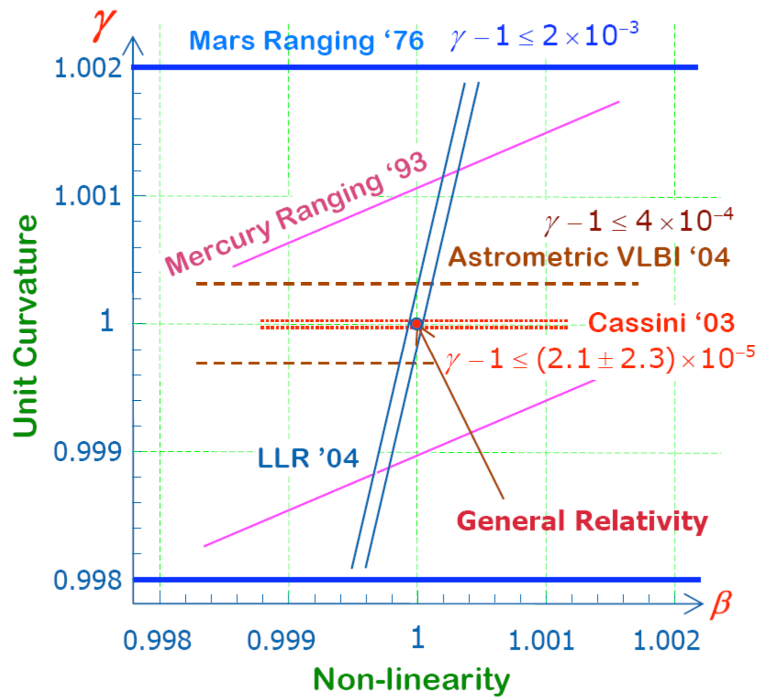
BEACON Science Objectives

- Qualitative Objectives, to test:
  - The metric nature of General Relativity (GR)
  - Alternative theories of gravity & cosmology (i.e. scalar-tensor) by searching for cosmological remnants of scalars in the solar system
- Quantitative Objectives, to measure:
  - The key Eddington PPN parameter γ with accuracy of 1 part in 10^9 – a factor of 30,000 improvement over Cassini results
  - Direct and independent measurement of the Eddington PPN parameter β via gravity effect on light to ~0.01% accuracy
  - The 2-nd order gravitational deflection of light with accuracy of ~1×10^{-4}, including first ever measurement of the PPN parameter δ
  - Frame dragging effect on light (first observation): ~1×10^{-3} accuracy



Relativistic Effect	Current	BEACON
Curvature of space-time, γ	2×10^{-5}	1×10^{-9}
Geodetic precession	4.7×10^{-3}	5×10^{-5}
Frame-dragging precession	1×10^{-1}	3×10^{-4}
Gravity inverse square law	2×10^{-11} @ 2.5 mAU	3×10^{-15} @ 0.5 mAU
2nd order gravity effects, μ G^2	n/a	3×10^{-4}

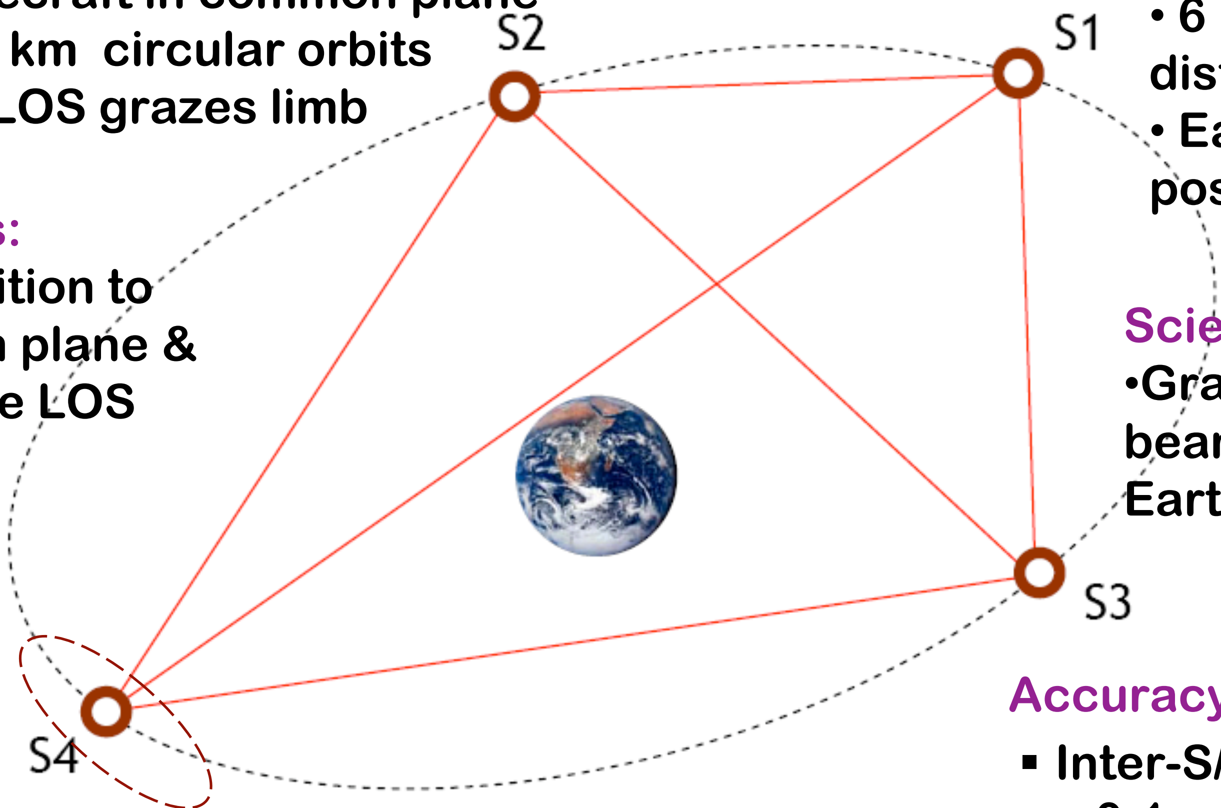
BEACON Mission Constraints

- The Mission Should be **Affordable** (Medium-class ~ $600M)
  - Single launch vehicle → Atlas V 501
  - Stay as close to Earth as possible → Super-GEO (80,000 km)
  - Simplify spacecraft as much as possible → Optical truss
  - Move mission segments to ground → Ground-based ranging
- The Mission Should be **Low Risk**
  - Leverage laser metrology developed by NASA for SIM
  - Beam acquisition & tracking from laser-com systems
  - GPS or GPS-like Navigation
  - Flight-heritage accelerometers (10^{-10} m/s^2)
  - Conventional thrusters (sub-mN range, ~200 m/s)

The BEACON Mission Concept

Configuration:
- 4 spacecraft in common plane
- 80,000 km circular orbits
- S1-S4 LOS grazes limb

Controls:
- S4 position to maintain plane & modulate LOS



Measurements:
- 6 inter-spacecraft distances
- Earth-relative position

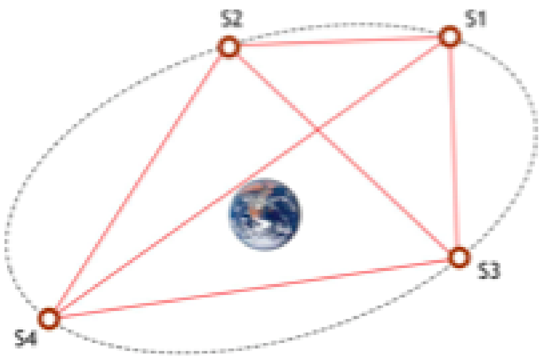
Science Signal:
- Gravitational delay of beam passing close to Earth limb ~ 10 cm

Accuracy needed:
- Inter-S/C Distance: ~ 0.1 nm
- Position relative to Earth: ~ 6 mm

Geometric redundancy enables a 10^{-9} measurement of curvature of the terrestrial gravity field without need for drag-free mass at 0.1 nm level

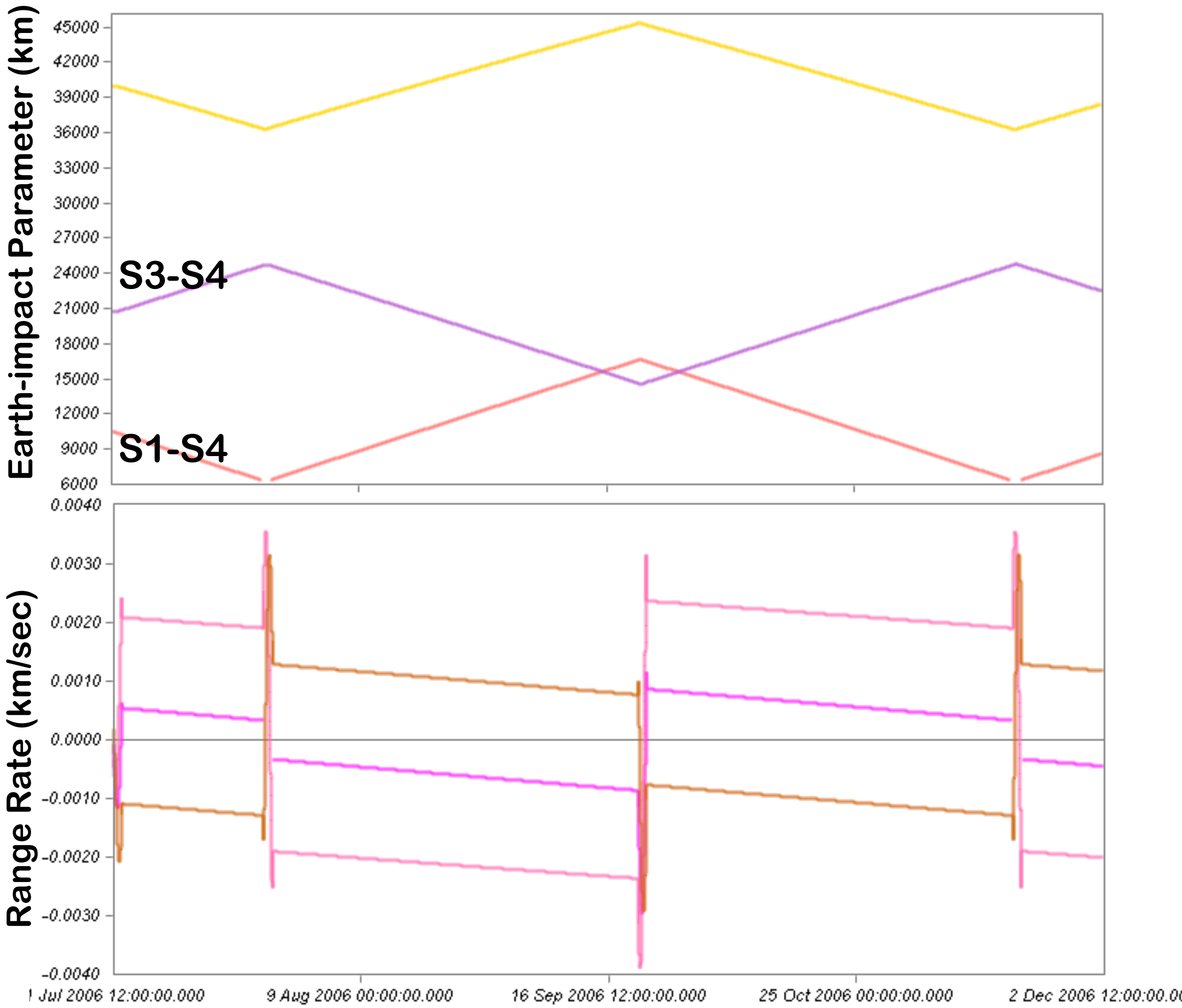
BEACON CONOPS

- S1, S2 & S3 maintain a circular, 80,000 km orbit.
  - Small burns to cancel Lunar, Solar, J2 & J4, radiation pressure.
- S4 is controlled actively to perform measurement cycles and stay in plane.
- A measurement cycle:
  1. Small pair of burns to lower S4 semi-major axis to 79,900 km and circularize.
  2. Let line of sight drift from 3 R_E to 1 $R_{E.}$ (few weeks), acquire data.
  3. Small pair of burns to raise S4 semi-major axis to 80,100 km and circularize.
  4. Let line of sight drift from 1 R_E to 3 R_E,acquire data.
- There is a trade between duration of cycles and ΔV.
  - For instance use 16 m/s per cycle and complete a cycle in about 1 month.



Active control of formation allows for repeated measurement cycles with small fuel expenditures.

Impact Parameters & Range Rates vs. Time



Impact parameter varies from 1 to 3 R_E while keeping range rates small enough to measure well.

Focus #1: Laser Metrology Link

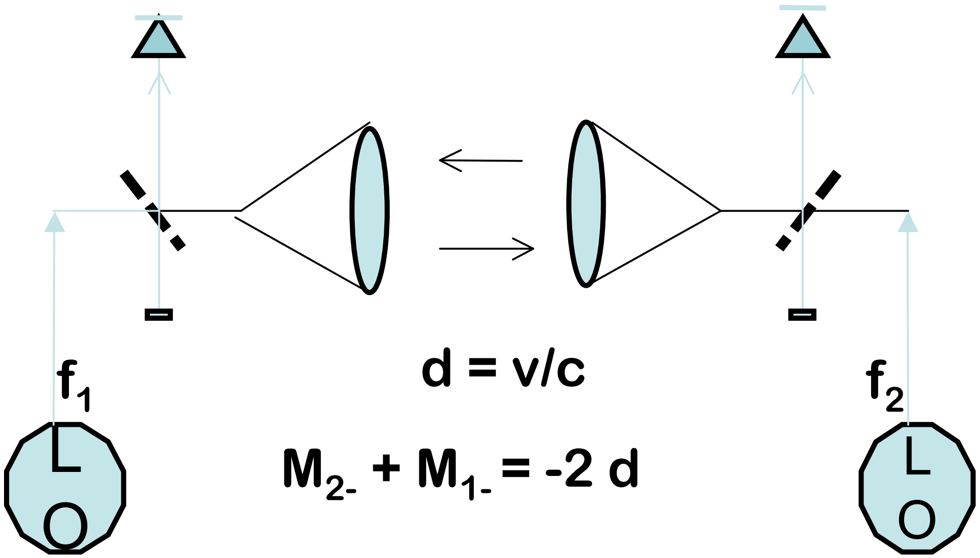
- Laser Ranging Between Spacecraft
  - Require: ~0.1 nm in 1000 sec
  - Max range rate < 10 m/s (d<10 MHz)

$M_{1-} = f_1-(f_2+d)$

$M_{1+} = f_1+(f_2+d)$

$M_{2-} = f_2-(f_1+d)$

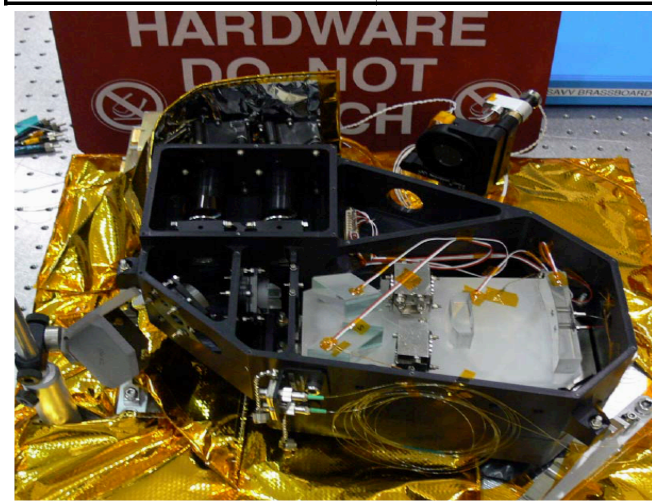
$M_{2+} = f_2+(f_1+d)$



$d = v/c$

$M_{2-} + M_{1-} = -2\,d$

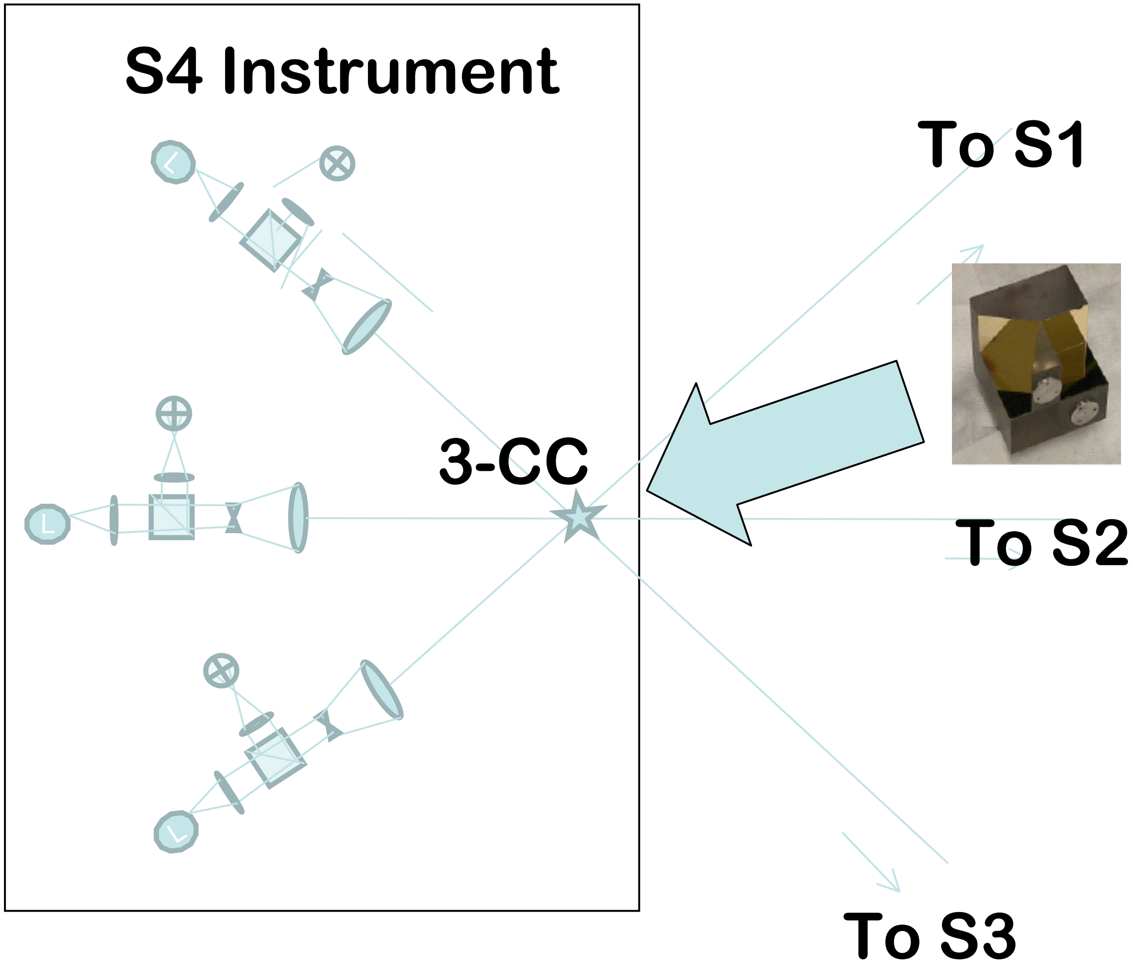
Parameter	Value
Telescope Diameter	0.1 m
Transmitted Power	0.1 W
Wavelength	1064 nm
Photons Transmitted	5.38e+16 ph/sec
Distance	160,000 km
Progagation Factor	2.39E-09
Transmission Eff.	9.2%
Received Power	2.19e-12 W
	1.18e+8 ph/sec
SNR in 1 sec	10870
Path Sigma in 1 sec	0.1 nm



Laser-link margins are good!

Simplified Instrument Layout

- Each spacecraft requires 3 laser tranceivers
- The three links require a common metrology fiducial to define truss vertex.
  - Laser links & multi-facet corner cubes have been developed for SIM
- The beam-launchers will require actuation in one axis as LOS changes.



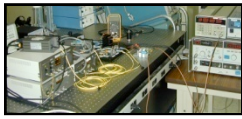
- The Space Interferometry Mission (SIM) is a very high accuracy astrometry (1 micro-arcsecond) instrument, designed to study
  - Terrestrial planets around nearby stars,
  - Dark matter in the galactic disk, halo, and the local group.
- Although SIM is a stellar interferometer, it required the development of high precision laser metrology flight hardware.
- SIM completed its technology program in 2005
- Developed laser path-length metrology with single digit picometer accuracy

SIM Technology Components/Systems

Component Technology	Subsystem-Level Testbeds	System-Level

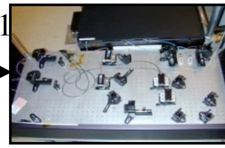
Picometer ***Knowledge*** Technology

1999



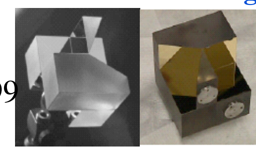
Metrology Source

2001



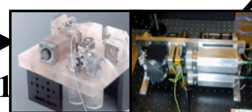
Absolute Metrology

1999



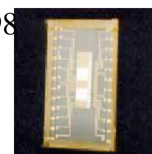
Multi-Facet Fiducials

1:Aug2001



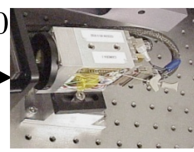
1: Beam Launchers

1998



High Speed CCD

2000

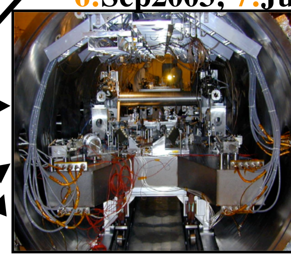


Fringe Tracking Camera

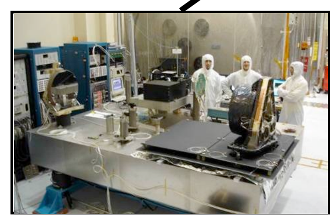
4:Oct2002

4: Kite Testbed (Metrology Truss)

3:Sep2002; 5:Mar2003
6:Sep2003; 7:Jun2004

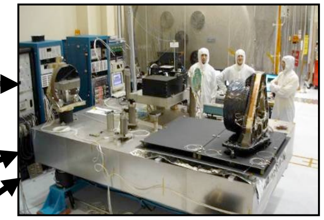


3, 5, 6, 7: MAM Testbed (single baseline picometer testbed) Narrow & Wide Angle Tests



TOM Testbed (distortion of front end optics)

8:Jul2005



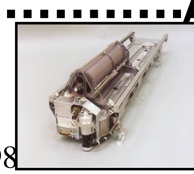
8: Overall system Performance via Modeling/Testbed Integration

Numbers before box labels indicate HQ Tech Gate #'s (**1** through **8**)

All 8 Completed

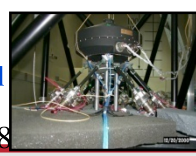
Nanometer ***Control*** Technology

Optical Delay Line

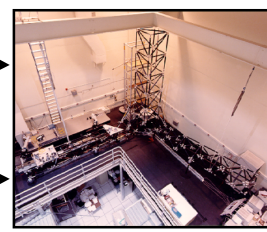


1998

Hexapod Reaction Wheel Isolator



1998



1999

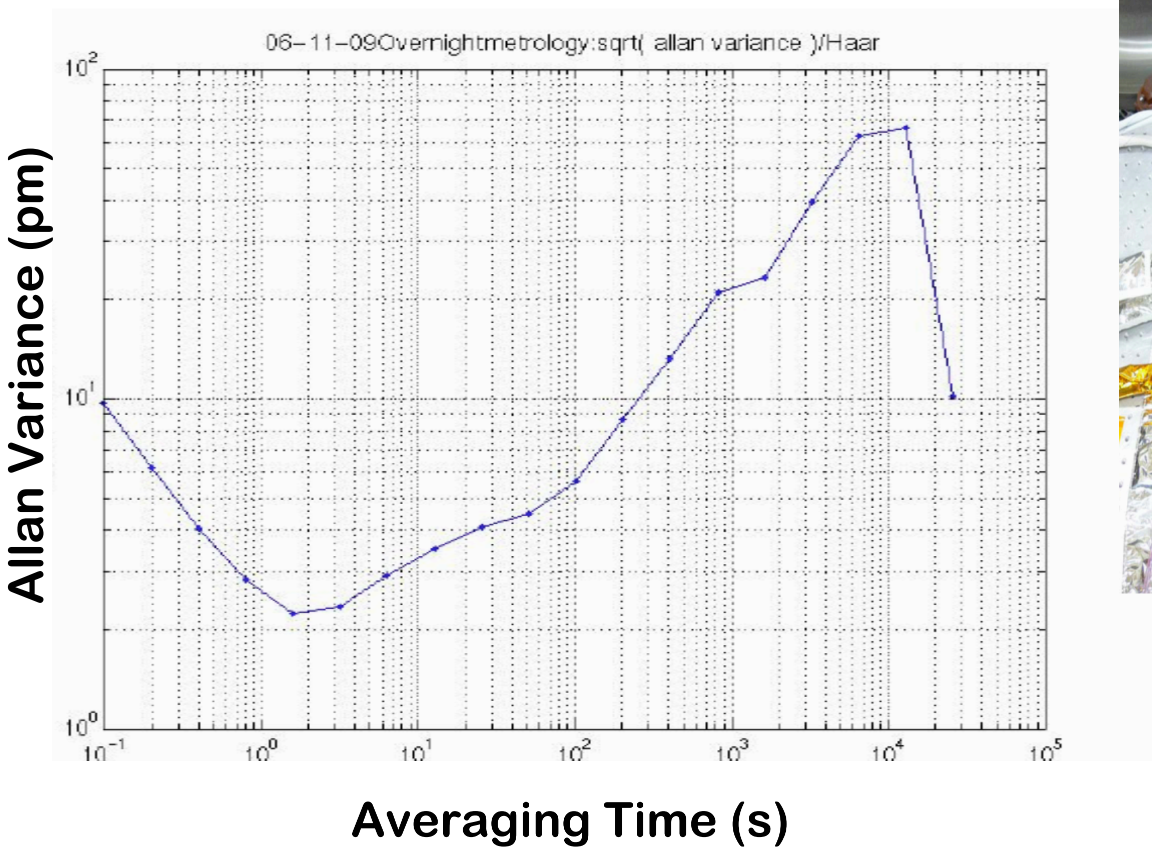
STB-1 (single baseline nanometer testbed)

2:Nov2001

2: STB-3 (three baseline nanometer testbed)

Metrology Stability

- Instrumental errors in the SIM metrology laboratory testbed
  - At least down to 0.1 nm after 10^4 sec
  - This was *without* a T-stabilized reference cavity

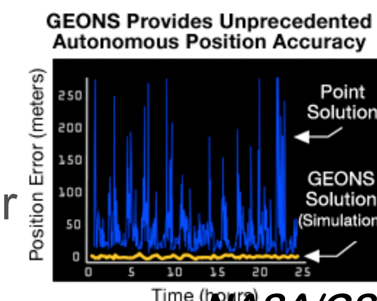


Laboratory testbeds have demonstrated required pathlength measurement stability

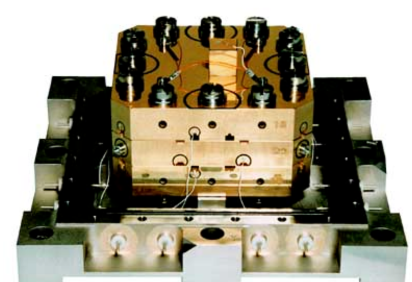
Focus #2: Formation Knowledge

- Beam impact parameter must be known to 10^{-9}, i.e. 6 mm
- Laser ranging or microwave tracking for absolute position/orbit determination
  - Achieves ~ mm performance using lasers
  - GPS-like system offers possibility of *autonomous* measurement onboard spacecraft (simpler ops = lower cost), but requires multi-frequency tracking
- Sensitive accelerometers to measure non-gravitational forces
  - ONERA SuperSTAR accelerometer on GRACE achieves a sensitivity of ~ 10^{-10} m/s^2 sufficient to cover ~3 (impact parameters) to 12 (formation plane) hours
  - The SuperSTAR is a drag-free mass of sorts, but requirements are much relaxed: 10 cm vs 0.1 nm. This is by virtue of the reliance on the optical truss.

Combination of flight-heritage hardware and existing facilities will provide required positional knowledge.



NASA/GSFC



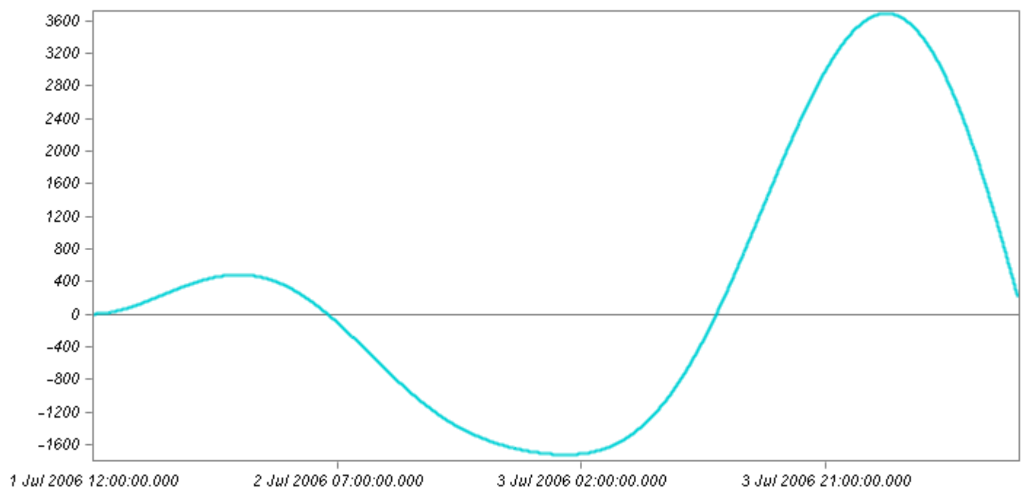
ONERA

Focus #3: Formation Control

- Spacecraft must be maintained in plane to ~10 cm
  - Largest single source of perturbation in this orbit is the Moon, which produces ~ 2 x 10^{-7} m/s^2 accelerations.
    - Cannot be left uncontrolled more than ~ few minutes
    - Minimize out-of-plane effect by putting formation in Lunar orbit plane as well as possible (precession limits).
  - Continuous low-thrust corrections needed
    - ~200 m/s/year very conservatively
    - ~0.5 mN max thrust levels (conventional monopropellant)
  - Trade-off between 3 passive & 1 active spacecraft, or 4 active spacecraft
    - Redundancy, identical spacecraft, inter-spacecraft communications

Formation Control Simulations

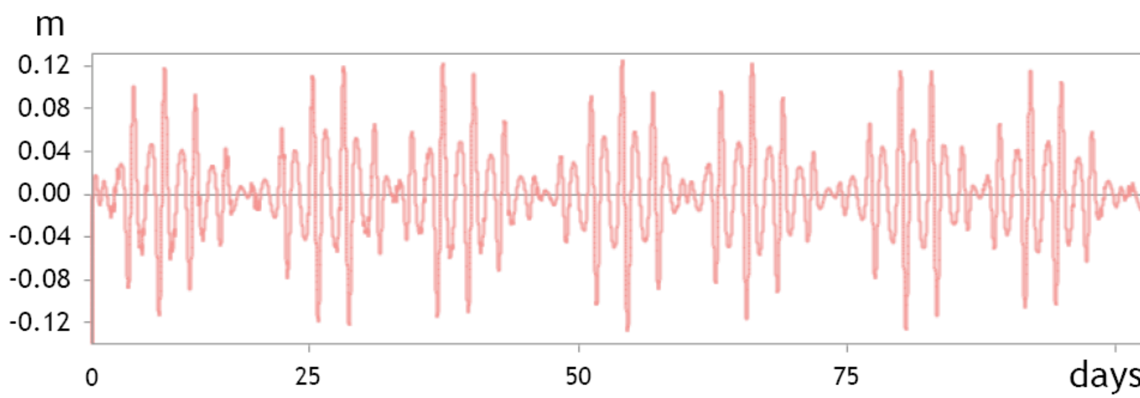
Un-controlled



Simulation includes:
- 32-term gravity model
- Lunar, Solar & Planetary perturbations
- Solar radiation pressure

Controlled

Total ΔV = 57 m/s



High-fidelity simulations indicate S4 can be kept within 0.1 m of formation plane for months using small amounts of thrust out of plane.

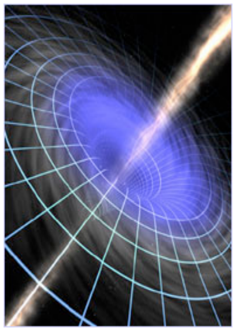
BEACON Budgets

Item	Mass (kg)	Cont. Factor	Allocated Mass (kg)	
Mechanical/Structure	30	30.0%	39	kg
Thermal	5	30.0%	6.5	kg
Attitude Control	7	30.0%	9.1	kg
RF Communications	5	30.0%	6.5	kg
Command & Data Handling	4	30.0%	5.2	kg
Electric Power	15	30.0%	19.5	kg
Propulsion	10	30.0%	13	kg
Harness	8	30.0%	10.4	kg
Spacecraft Bus Mass	84		109.2	kg
Laser Local Oscillator	3	30.0%	3.9	kg
Beam Launchers	30	30.0%	39	kg
GPS Receiver/Transponder	5	30.0%	6.5	kg
Instrument Thermal Control	10	30.0%	13	kg
Instrument Harness	5	30.0%	6.5	kg
Instrument Mass	53		68.9	kg
Observatory Dry Mass	137		178.1	kg
Desired ΔV	400	m/s	Assumed Isp	
Required Propellant Mass	35.7	kg	224	sec
Propellant Mass Provided	39.278	kg		
Observatory Wet Mass	176	kg	217	kg

Item	Mass (CBE)	Cont. Factor	Allocated Mass	
Observatory Dry Mass	137	30.0%	178.1	kg
Observatory Wet Mass	176.3	23.3%	217.4	kg
Number of Observatories	4			
Carrier Structure	173.9	30.0%	226.1	kg
Constellation Mass	879.0		1095.6	kg
Apogee Burn ΔV	1367.5	m/s	Assumed Isp (s)	315
Required Propellant	612.4	30.0%	796.2	kg
Propulsion System Mass	200	30.0%	260.0	kg
Flight System Dry Mass	921.9	30.0%	1198.5	kg
Flight System Wet Mass	1691.5	27.2%	2151.8	kg
Launch Vehicle Capability	3604	kg		
Dry Mass Margin	1452	kg		
	121.2%			

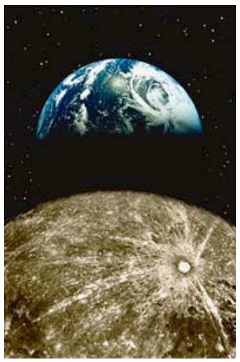
Cost by Phase	Cost (FY08$M)	Dev Cost, %
Phase A	$ 12.5	1.9%
Phase B	$ 123.6	19.1%
Phase C/D	$ 512.4	79.0%
Phase E	$ 27.6	
Total:	$ 676.1	100.0%

A 21st Century Test of Gravity



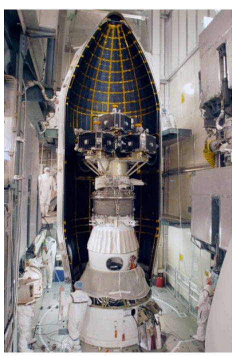
Optical vs. Microwave:

- Leverage advances in optical metrology from SIM & telecom boom to yield 10^5 increase in path-length precision.
- Factor of ~30,000 improvement in state-of-art tests of GR



Simplified Experimental Approach:

- Redundant optical truss implies no need for ultra-precise drag-free environment for BEACON spacecraft



A Low Cost Experiment:

- Geocentric orbit
- Optical apertures 10-15 cm
- Conventional thrusters (monopropellant)
- Flight-heritage accelerometers
- Leverage GPS & laser tracking stations