Science, Technology and Mission Design for

The Laser Astrometric Test Of Relativity Mission

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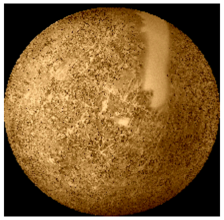
Проблемы Современной Астрометрии,
Всероссийская конференция-школа для молодых ученых
Звенигород, Россия - 22-26 октября 2007

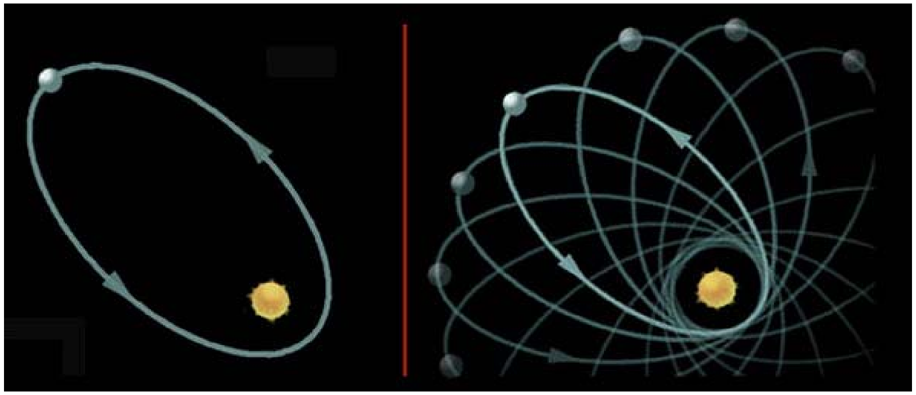
Triumph of Mathematical Astronomy in 19th Century

Discovery of Neptune: 1845

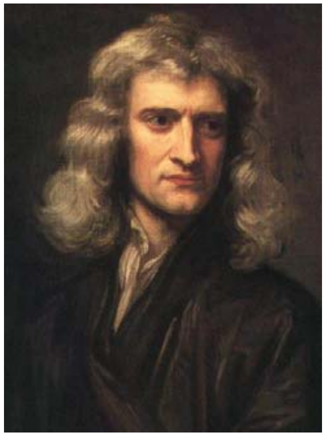
Urban LeVerrier
(1811-1877)



- 1845: the search for Planet-X:
  - Anomaly in the Uranus' orbit → Neptune
  - Anomalous motion of Mercury → Vulcan



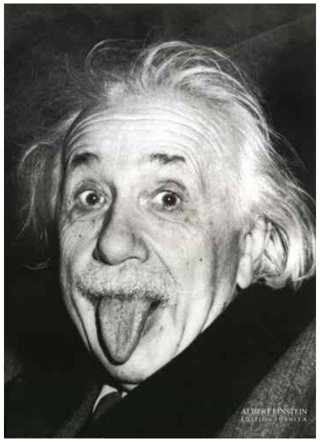
Newtonian Gravity General Relativity



Sir Isaac Newton
(1643-1727)

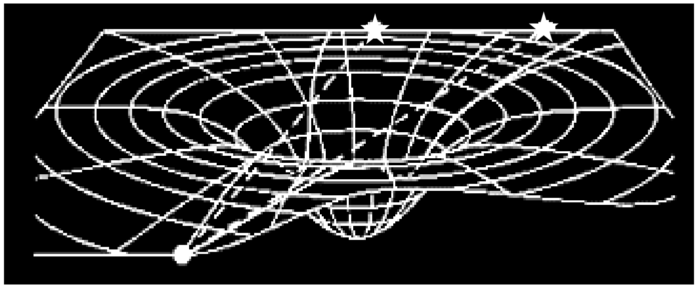
- Anomalous precession of Mercury's perihelion:
  - 43 arcsec/cy can not be explained by Newton's gravity
- Before publishing GR, in 1915, Einstein computed the expected perihelion precession of Mercury
  - When he got out 43 arcsec/cy – a new era just began!!

Nearly in one year LeVerrier both confirmed the Newton's theory (Neptune) & cast doubt on it (Mercury's' anomaly).



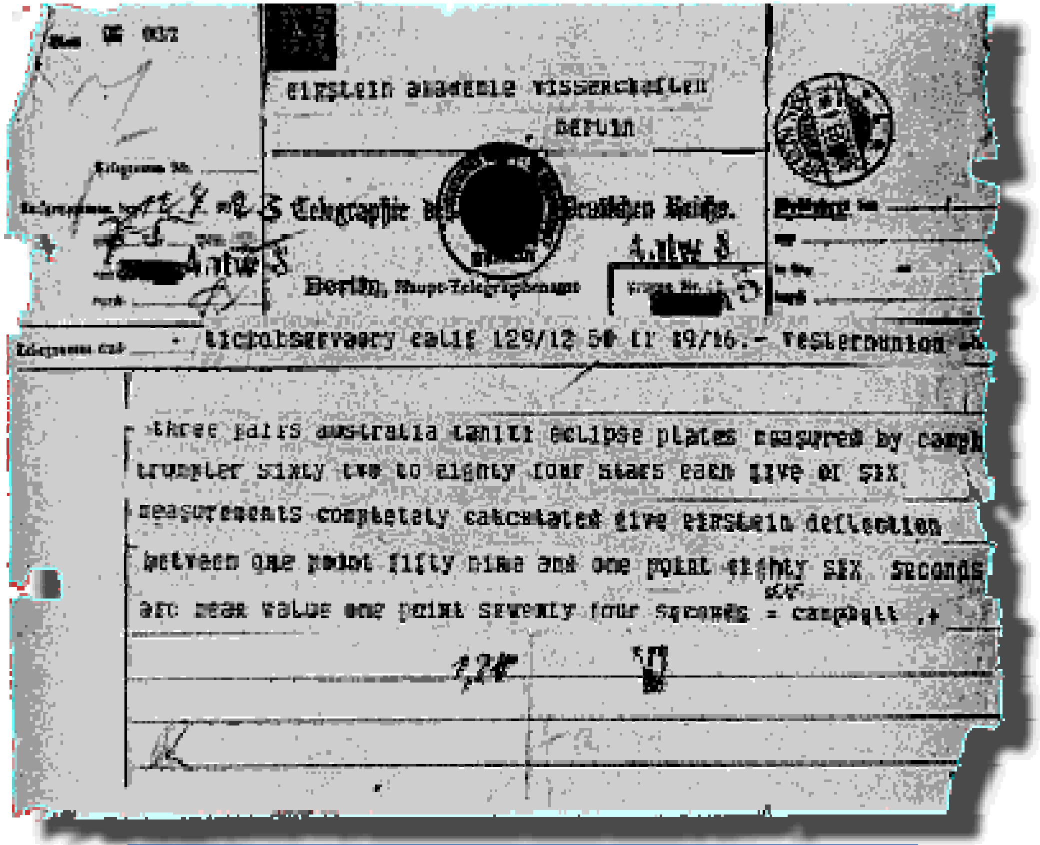
Albert Einstein
(1879-1955)

The First Test of General Theory of Relativity



Gravitational Deflection of Light:

Solar Eclipse 1919



einstein akademie wissenschaften
berlin

Telegraphie des Deutschen Reichs.

Berlin, Haupt-Telegraphenamt

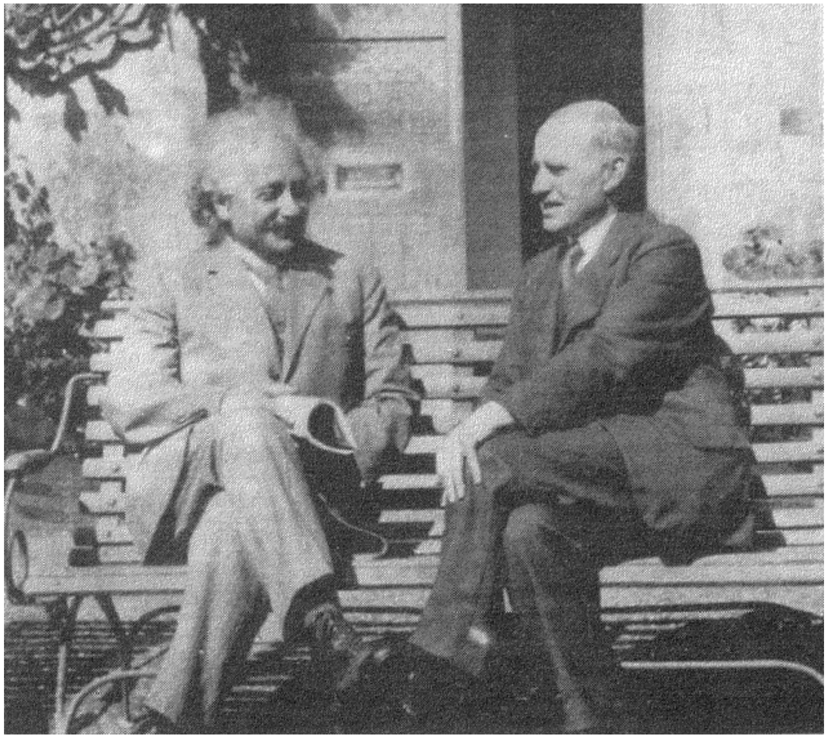
lickobservatory calif 129/12 50 ... 19/16.– westernunion

three pairs australia tahiti eclipse plates measured by campb
trumpler sixty two to eighty four stars each five or six
measurements completely calculated give einstein deflection
between one point fifty nine and one point eighty six seconds
arc mean value one point seventy four seconds = campbell .+

Eddington's telegram to Einstein, 1919

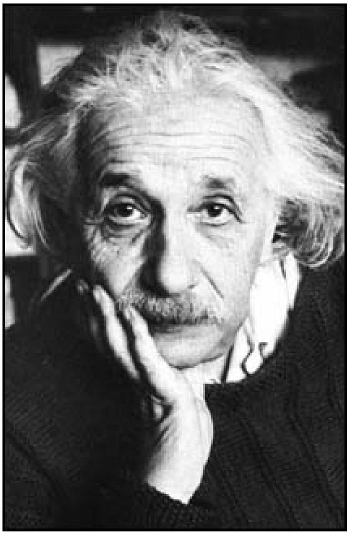
Possible outcomes in 1919:

Deflection = 0;
Newton = 0.87 arcsec;
Einstein = 2 x Newton = 1.75 arcsec



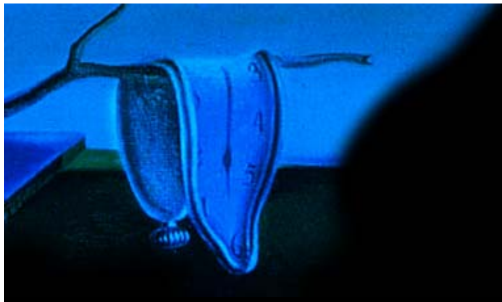
Einstein and Eddington, Cambridge, 1930

Gravitational Deflection of Light is a Well-Known Effect Today



Galaxy Cluster Abell 2218 **HST • WFPC2**

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08



Theoretical landscape of early 1970s:
Competing Theories of Gravity

- Newton 1686
- Poincaré 1890
- Einstein 1912
- Nordstrøm 1912
- Nordstrøm 1913
- Einstein and Fokker 1914
- Einstein 1916
- Whitehead 1922
- Cartan 1923
- Fierz and Pauli 1939
- Birkhoff 1943
- Milne 1948
- Thiry 1948
- Papapetrou 1954
- Papapetrou 1954
- Jordan 1955
- Littlewood and Bergmann 1956
- Brans and Dicke 1961
- Yilmaz 1962
- Whitrow and Morduch 1965
- Whitrow and Morduch 1965
- Kustaanheimo and Nuotio 1967
- Deser and Laurent 1968
- Page and Tupper 1968
- Bergmann 1968
- Nordtvedt 1970
- Bollini, Giambiagi and Tiomno 1970
- Wagoner 1970
- Rosen 1971
- Ni 1972
- Ni 1972
- Hellings and Nordtvedt 1972
- Will and Nordtvedt 1972
- Ni 1973
- Yilmaz 1973
- Lightman and Lee 1973
- Lee, Lightman and Ni 1974
- Rosen 1975
- Belinfante and Swihart 1975
- Lee et al. 1976
- Bekenstein 1977
- Barker 1978
- Rastall 1979
- Coleman 1983
- Kaluza-Klein 1932
- Overlooked (20thcentury)

35 Years of Relativistic Gravity Tests

Techniques for Gravity Tests:

Radar Ranging:
- Planets: Mercury, Venus, Mars
- s/c: Mariners, Vikings, Cassini, Mars Global Surv., Mars Orbiter
- VLBI, GPS, etc.

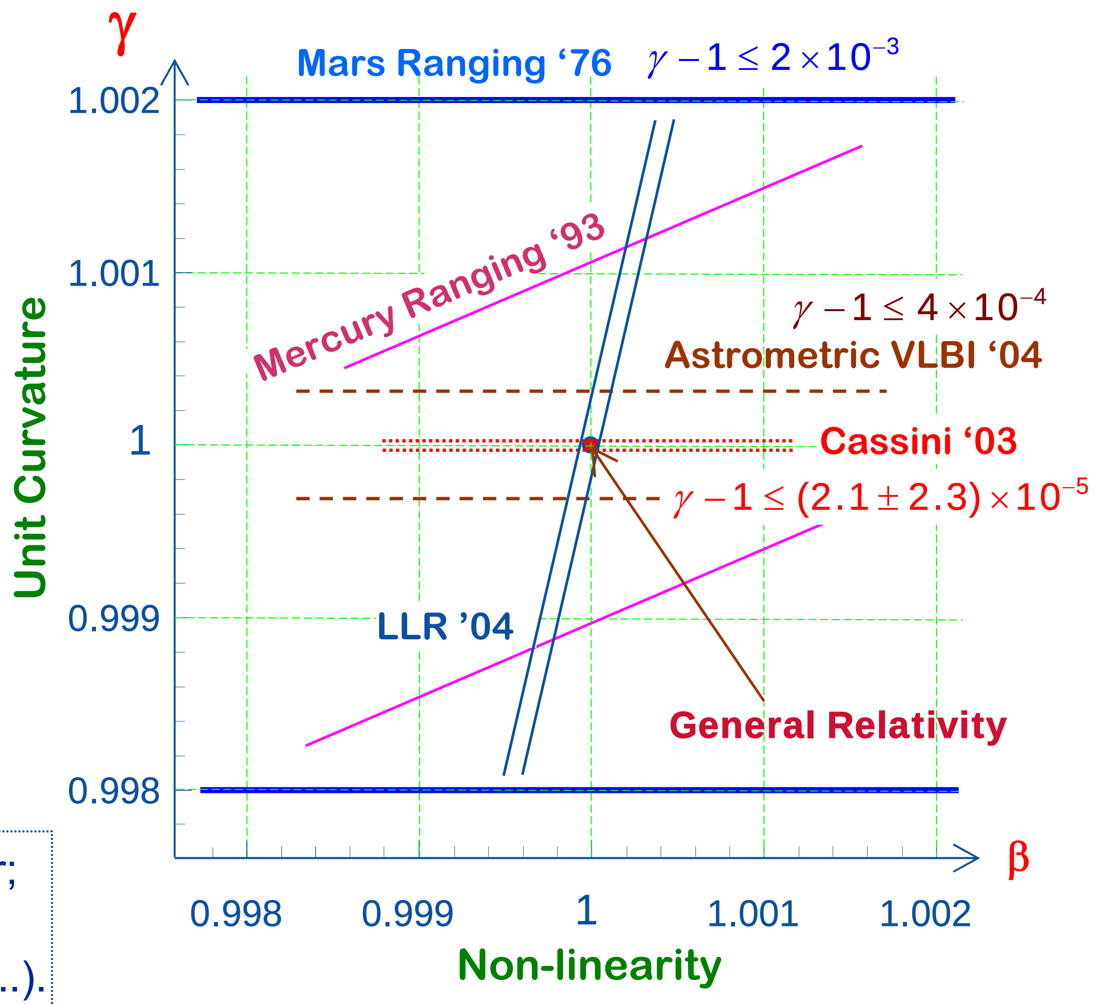
Laser:
- LLR, SLR, etc.

Designated Gravity Missions:

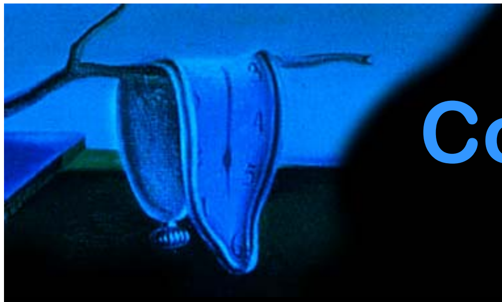
- **LLR (1969 - on-going!!)**
- GP-A, '76; LAGEOS, '76,'92; GP-B, '04; LISA, 2014

New Engineering Discipline – Applied General Relativity:

- Daily life: GPS, geodesy, time transfer;
- Precision measurements: deep-space navigation & astrometry (SIM, GAIA,....).



A factor of 100 in 35 years is impressive, but is not enough for the near future!



Conclusion for 20th Century Tests

Newton 1686 Poincaré 1890 Einstein 1912 Nordstrøm 1912 Nordstrøm 1913

Einstein and Fokker 1914 Einstein 1916 Whitehead 1922 Cartan 1923

Fierz and Pauli 1939 Birkhoff 1943 Milne 1948 Thiry 1948 Papapetrou 1954

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Yilmaz 1962 Whitrow and Morduch 1965 Whitrow and Morduch 1965

Kustaanheimo and Nuotio 1967 Deser and Laurent 1968 Page and Tupper 1968

Bergmann 1968 Nordtvedt 1970 Bollini, Giambiagi and Tiomno 1970 Wagoner 1970

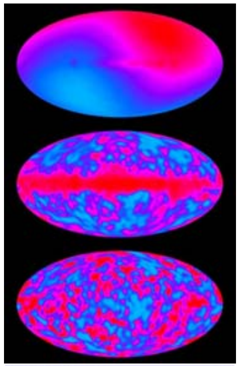
Rosen 1971 Ni 1972 Ni 1972 Hellings and Nordtvedt 1972 Will and Nordtvedt 1972

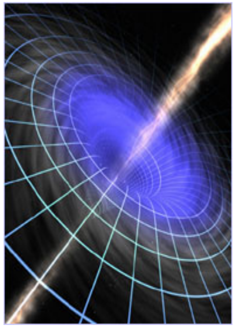
Ni 1973 Yilmaz 1973 Lightman and Lee 1973 Lee, Lightman and Ni 1974 Rosen 1975

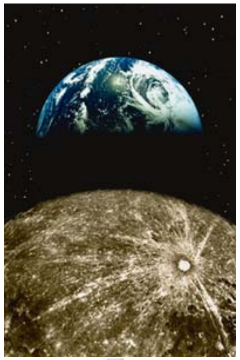
Belinfante and Swihart 1975 Lee et al. 1976 Bekenstein 1977 Barker 1978 Rastall 1979

Coleman 1983 Kaluza-Klein 1932 Overlooked (20thcentury)

Challenges to General Relativity







Fundamental Physics Challenges:

- Appearance of space-time singularities;
- Classical description breaks down in large curvature;
- Quest for Quantum Gravity → GR modification;
- Cosmology: accelerating Universe, *dark energy?!*

Alternative Theories of Gravity:

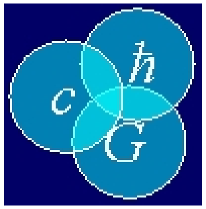
- Grand Unification Models, Standard Model Extensions;
- Inflationary cosmologies, strings, Kaluza-Klein theories;

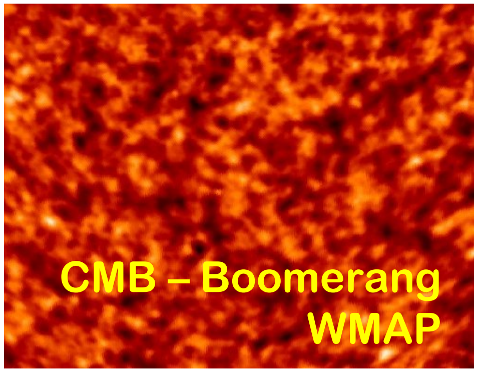
Common element:

scalar partners – dilaton, moduli fields…

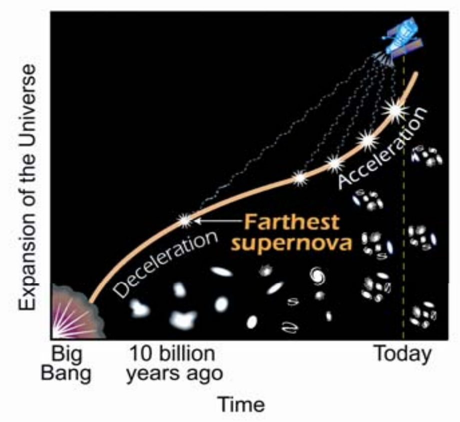
If scalar exists, how to observe it?

- Search for violations of the Equivalence Principle;
- Look for modification of large-scale gravity phenomena;
- Test for variability of fundamental constants (G, α, …);
- Gravity tests at short and solar system scales



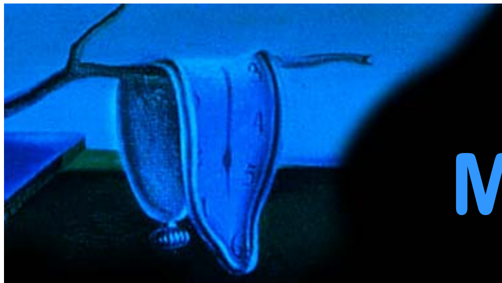


CMB – Boomerang WMAP



1998 SN Ia evidence for accelerating Universe

As a fundamental theory, GR must be tested to the highest level



Some Theories are Back!
More Accurate Tests Are Needed

Newton 1686 Poincaré 1890 Einstein 1912 Nordstrøm 1912 Nordstrøm 1913

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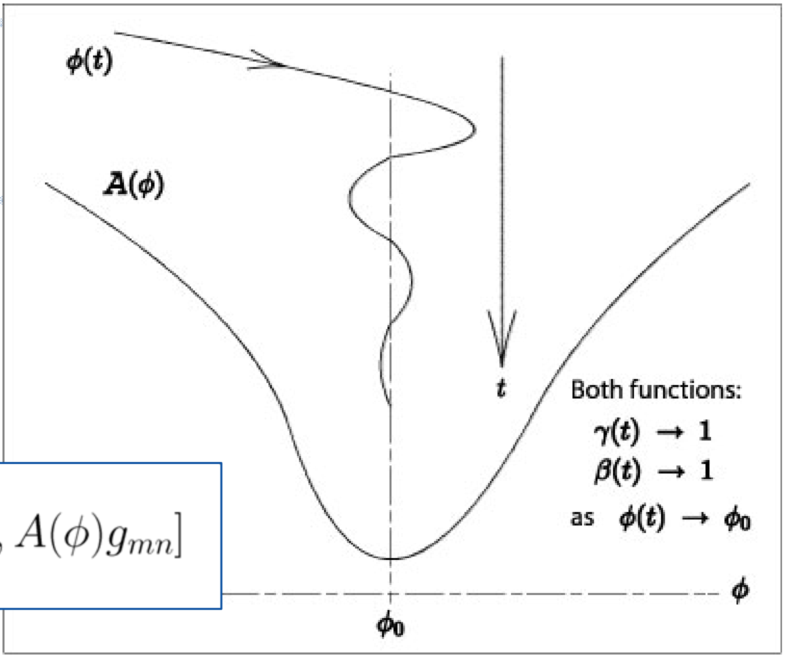
Coleman 1983 Kaluza-Klein 1932 Overlooked (20thcentury) Strings theory?

Bekenstein 2004 Moffat 2005 Dvali, Gabadadze, Porati 2003 Multiple anomalies

Generic Scalar-Tensor Theories Multiple GR modifications (21stcentury)

Theoretical Motivation for New Gravity Tests



Long-range massless [or low-mass] scalar:

The low-energy limit of the String Theory in 'Einstein Frame' (Damour-Nordtvedt-Polyakov 1993) suggests:

$$S = -\frac{1}{16\pi G}\int dx^4\sqrt{-g}\Big(R - 2g^{mn}\nabla_m\phi\nabla_n\phi\Big) + S_M[\psi_M, A(\phi)g_{mn}]$$

Expansion $A(\phi)$ around background value ϕ_0 of the scalar leads:

$$\ln A(\varphi) = \ln A(\varphi_0) + \alpha_0(\varphi - \varphi_0) + \frac{1}{2}k_0(\varphi - \varphi_0)^2 + \mathcal{O}(\Delta\varphi^3)$$

Slope α_0 measures the coupling strength of interaction between matter and the scalar.

$$\gamma - 1 \ = \ \frac{-2\alpha_0^2}{1+\alpha_0^2} \simeq -2\alpha_0^2$$

$$\beta - 1 = \frac{1}{2}\frac{\alpha_0^2 k_0}{(1+\alpha_0^2)^2} \simeq \frac{1}{2}\alpha_0^2 k_0 \simeq \frac{1}{4}(1-\gamma)k_0$$

Scenario for cosmological evolution of the scalar (Damour, Piazza & Veneziano 2002):

$$\gamma - 1 \sim 7.3\times 10^{-7}\left(\frac{H_0}{\Omega_0^3}\right)^{\frac{1}{2}} \quad \Rightarrow \quad \boxed{\gamma - 1 \sim 10^{-5} - 10^{-7}}$$

The unit curvature, PPN parameter γ – the most important quantity to test

Theoretical Motivation for New Gravity Tests

Composition dependent coupling of scalars:

Damour-Pioazza-Veneziano, 2002: the string-loop modifications of effective low-energy action:

$$S = \int d^4x \sqrt{\tilde{g}} \left(\frac{B_g(\phi)}{\alpha'} \tilde{R} + \frac{B_\phi(\phi)}{\alpha'} [2 \tilde{\Box} \phi - (\widetilde{\nabla} \phi)^2] - \frac{1}{4} B_F(\phi) \tilde{F}^2 - V + \cdots \right)$$

In general *B(ϕ)* is a complex function of the field coupling strength:

$$V(\chi) = \tfrac{1}{2} m_\chi^2(\phi) \chi^2$$

$$B_i(\phi) = e^{-\phi} + c_0^{(i)} + c_1^{(i)} e^{\phi} + c_2^{(i)} e^{2\phi} + \cdots$$

Slope α_0 measures the coupling strength of interaction between matter and the scalar.

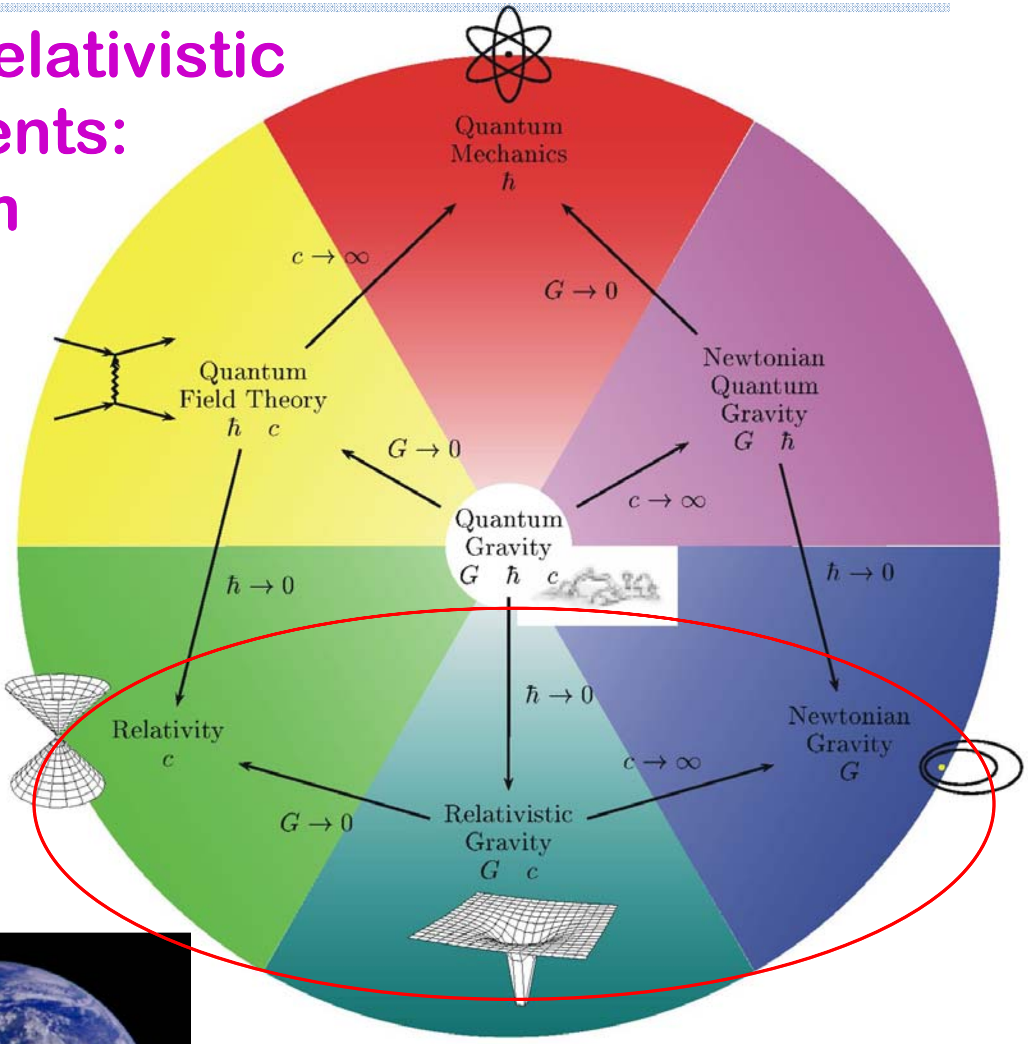
$$\left(\frac{\Delta a}{a} \right) \simeq -2.6 \times 10^{-5} (\gamma - 1) \qquad \frac{\Delta a}{a} \simeq 1.3 \left(\frac{b_F}{b_\lambda c} \right)^2 \times 10^{-12}$$

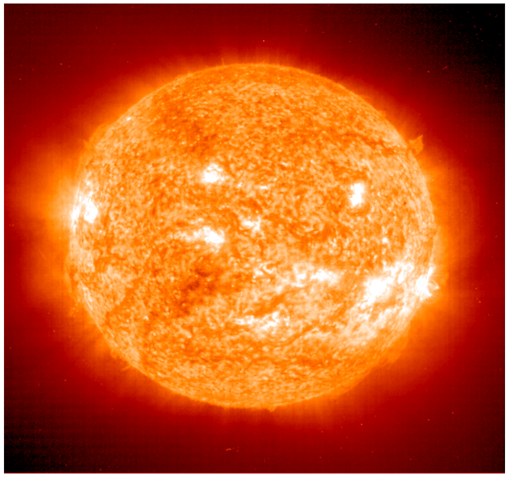
Scenario for cosmological evolution of the scalar (Damour, Piazza & Veneziano 2002):

$$d \ln e^2 / dt \sim \pm 2.0 \times 10^{-16} \sqrt{10^{12} \Delta a / a}\, \mathrm{yr}^{-1} \lesssim 5 \times 10^{-17}\, \mathrm{yr}^{-1} \quad \Longrightarrow \quad \Delta a / a \sim 10^{-13}$$

We almost reach these predictions… no signal …

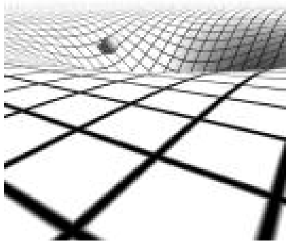
Laboratory for Relativistic Gravity Experiments: Our Solar System





Strongest gravity potential

$$\frac{GM_{Sun}}{c^2 R_{Sun}} \sim 10^{-6}$$



$$\frac{GM_{\oplus}}{c^2 R_{\oplus}} \sim 10^{-9}$$

Most accessible region for gravity tests in space:

- ISS, LLR, SLR, free-fliers

Technology is available to conduct tests in immediate solar proximity

Cassini 2003: Where Do We Go From Here?

Cassini Conjunction Experiment 2002:

- Spacecraft—Earth separation > 1 billion km
- Doppler/Range: X~7.14GHz & Ka~34.1GHz
- Result: $\gamma = 1 + (2.1 \pm 2.3) \times 10^{-5}$

Possible with Existing Technologies?!

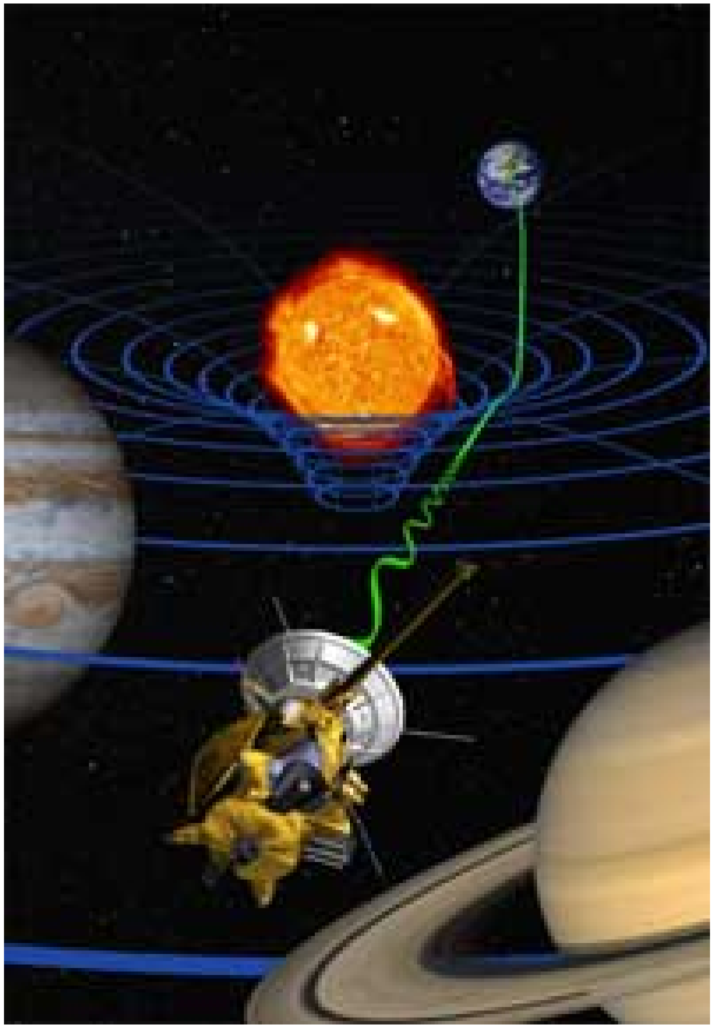
- VLBI [current $\gamma = 4 \times 10^{-4}$]: in 5 years $\sim 5 \times 10^{-5}$:
  - # of observations (1.6M to 16M → factor of 3)
- LLR [current $\eta = 4 \times 10^{-4}$]: in 5 years $\sim 3 \times 10^{-5}$:
  - mm accuracies [APOLLO] & modeling efforts
- μ-wave ranging to a lander on Mars $\sim 6 \times 10^{-6}$
- Optical astrometry [current $\gamma = 3 \times 10^{-3}$]:
  SIM & GAIA $\sim 1 \times 10^{-6}$ (2015/16?)

Accuracy $\sim G^2$ allows to probe new physics:

- Cosmologically evolved scalar field, etc.
- Gravity modifications [i.e. CMB-inspired, *f(R)*, etc.]

$$\gamma - 1 = -\frac{f''(R)^2}{f'(R) + 2f''(R)^2},$$

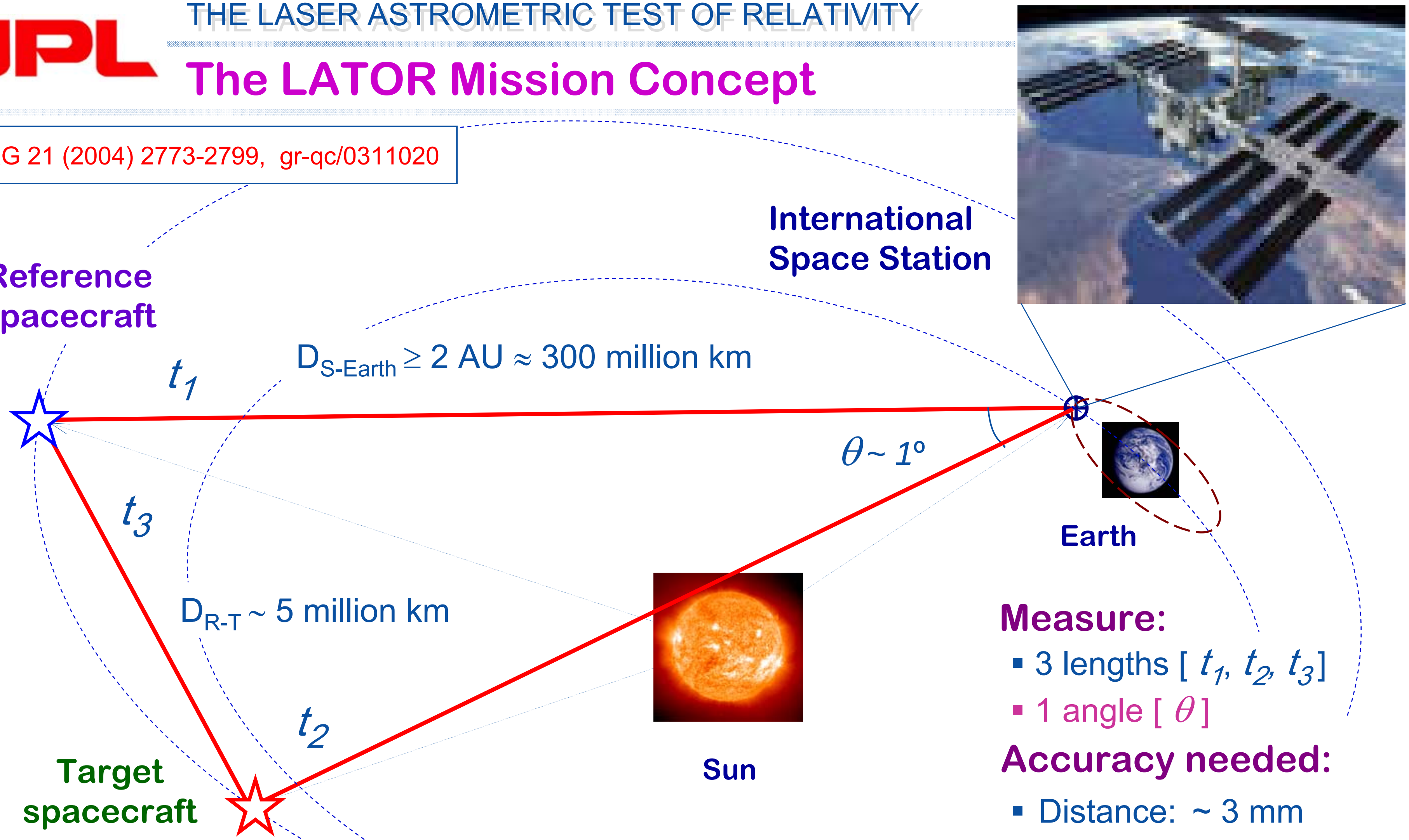
$$\beta - 1 = \frac{1}{4}\frac{f'(R)\cdot f''(R)}{2f'(R) + 3f''(R)^2}\frac{d\gamma}{dR}.$$



We need a dedicated mission to explore accuracies better than 10^{-6}

The LATOR Mission Concept

CQG 21 (2004) 2773-2799, gr-qc/0311020



International Space Station

Reference spacecraft

t_1

$D_{S\text{-Earth}} \geq 2$ AU ≈ 300 million km

$\theta \sim 1^{\circ}$

Earth

t_3

$D_{R\text{-T}} \sim 5$ million km

t_2

Target spacecraft

Sun

Measure:

- 3 lengths [t_1, t_2, t_3]
- 1 angle [θ]

Accuracy needed:

- Distance: ~ 3 mm
- Angle: 0.01 picorad

Euclid is violated in gravity:

$$\cos\theta \neq (t_1^{2}+t_2^{2}-t_3^{2})/2t_1t_2$$

Geometric redundancy enables a very accurate measurement of curvature of the solar gravity field

Accurate test of gravitational deflection of light to 1 part in 10^9

Sizes of the Effects & Needed Accuracy

		Deflection	B=100 m
Effect	Analytical Form	Value (μas)	Value (pm)
First Order	$2(1+\gamma)\frac{M}{R}$	1.75×10^6	8.487×10^8
Second Order	$([2(1+\gamma)-\beta+\frac{3}{4}\delta]\pi-2(1+\gamma)^2)\frac{M^2}{R^2}$	3.5	1702
Frame-Dragging	$\pm 2(1+\gamma)\frac{J}{R^2}$	± 0.7	± 339
Solar Quadrupole	$2(1+\gamma)J_2\frac{M}{R^3}$	0.2	97

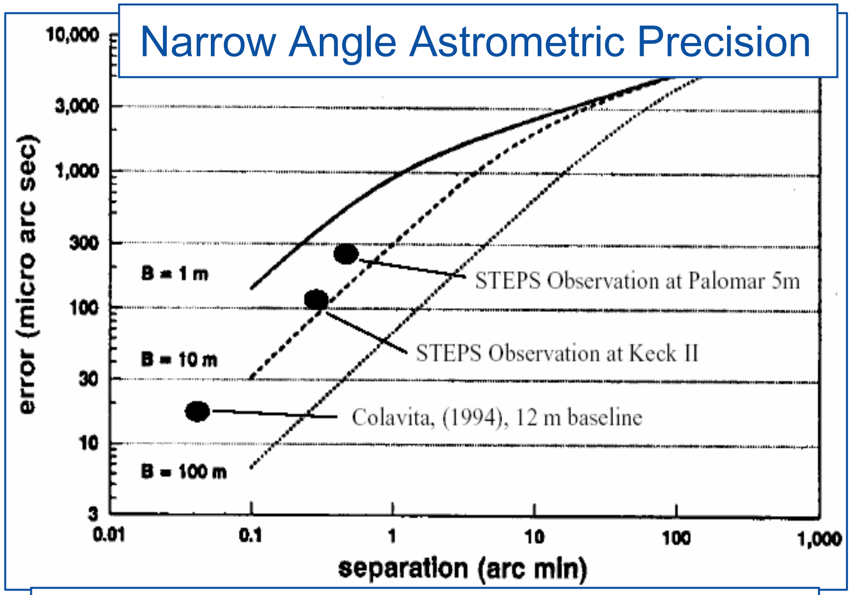
LATOR 1994 Proposal:

- Ground-based interferometer [B = 30km]
- Limited capabilities due to atmosphere

$(M/R)^2$ term ~0.2% accuracy [B =100 m]:
0.02 μas ⇒ 0.1 picorad ~10pm

LATOR 2007 (all in space):

- Interferometer on the ISS [B = 100m]
- Technology exists as a result of NASA investments in astrometric interferometry

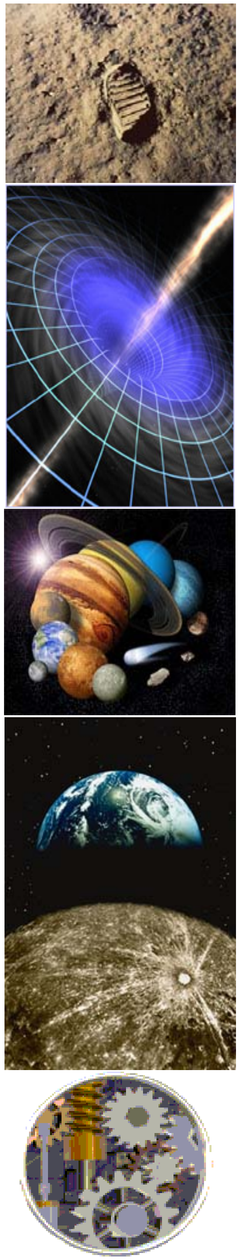


Narrow Angle Astrometric Precision

1 hour integration in 0.5 arcsec seeing

The key technologies are already available – SIM, TPF, Starlight, KI

Stellar Interferometry for Fundamental Physics



- The SIM mission
  - … is a very high accuracy astrometry instrument, designed to search terrestrial planets around nearby stars, as well as conduct a number of astrophysical investigations including the study of dark matter in the galactic disk, halo, and the local group.
- SIM completed its technology program in 2005, a lot of this technology is applicable to missions focused more directly on fundamental physics
  - Length metrology with single digit picometer accuracy
  - Very precise angle measurements,
- LATOR uses technology that is needed to measure angles with sufficient precision to measure γ to ~10^{-9}.

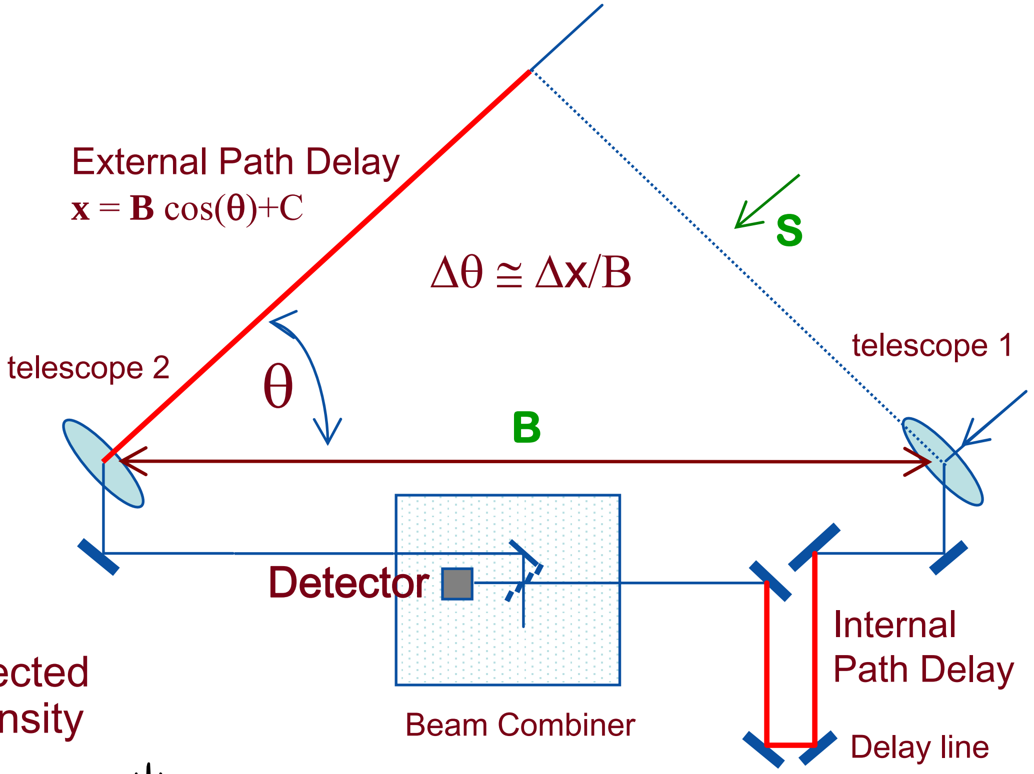
Comparison LATOR, SIM Planet Search

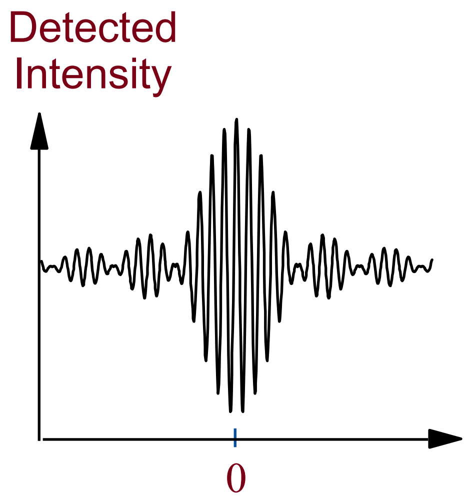
- **LATOR**
  - Narrow angle astrometry within 1~2 deg
  - 100m baseline interferometer
  - Angular measurement with a precision of 10 femto-radians (2 femtoarcsec) after a few weeks integration
  - Optical path precision ~1pm/100m is achieved after integration time of a few 100 hrs. (< ~1000hrs)

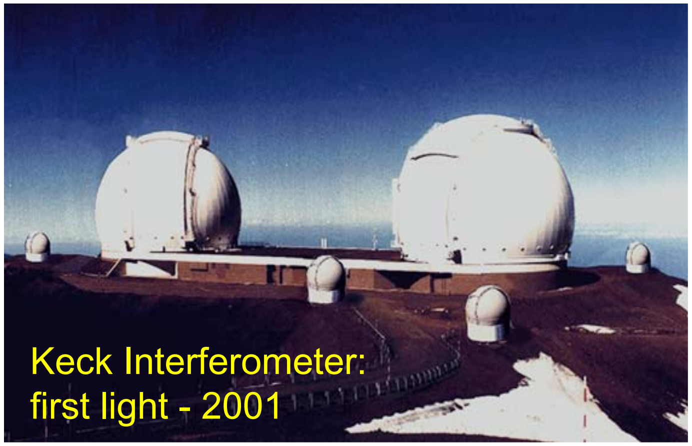
- **SIM Planet search**
  - Narrow angle astrometry within 1~2 deg
  - ~10m baseline
  - Single epoch (1/2 hr) accuracy 1 uas (~50 picometer OPD)
  - Planet search program ~50(2D) epochs over 5 yrs, implies that at the end of 5yrs OPD ~7pm (each axis) ~0.14 uas
  - Total integration time per target over 5yrs ~50 hrs

- LATOR borrows technology developed for other astrophysics missions
  - Precise length measurements
  - Precise angle measurement
  - More mundane, flight qualification of these components and subsystems. (high reliability flight lasers, 5~6σ)

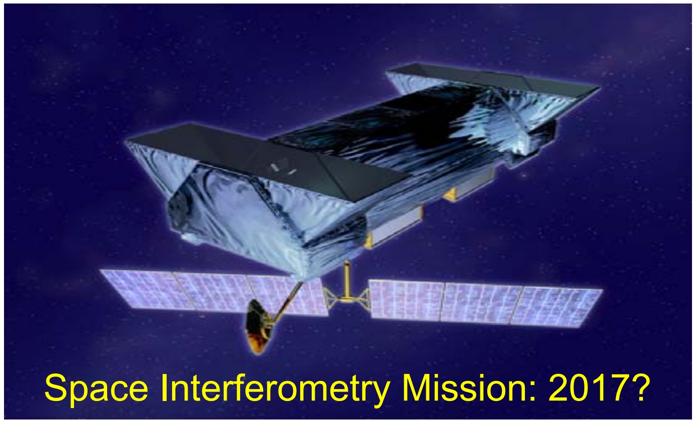
What Does a Stellar Interferometer Measure?







Keck Interferometer:
first light - 2001



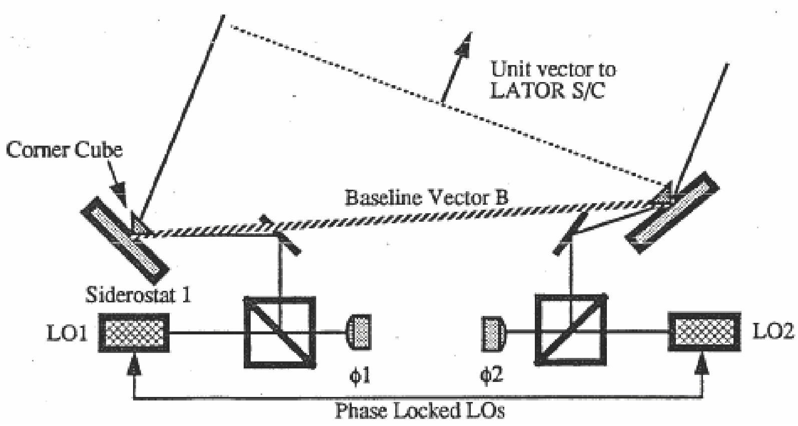
Space Interferometry Mission: 2017?

An interferometer measures (**B·s**) – the dot product of the baseline vector & a unit vector to the star,

or, the projection of the star vector in the direction of the baseline

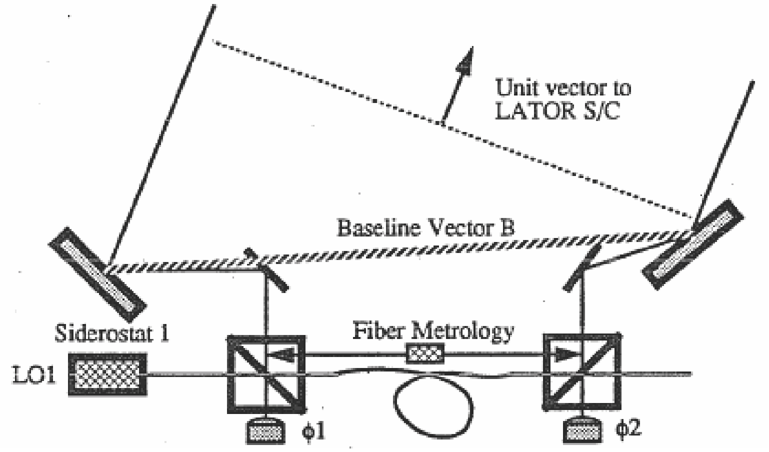
The peak of the interference pattern occurs when [Internal delay] = [External delay]

Heterodyne Optical Interferometry



Heterodyne interferometry (HI) on 1 s/c with phase-locked local oscillator – very difficult over long baselines

$$\theta = \arcsin[\frac{(2\pi n + \phi_1 - \phi_2)\lambda}{2\pi b}]$$

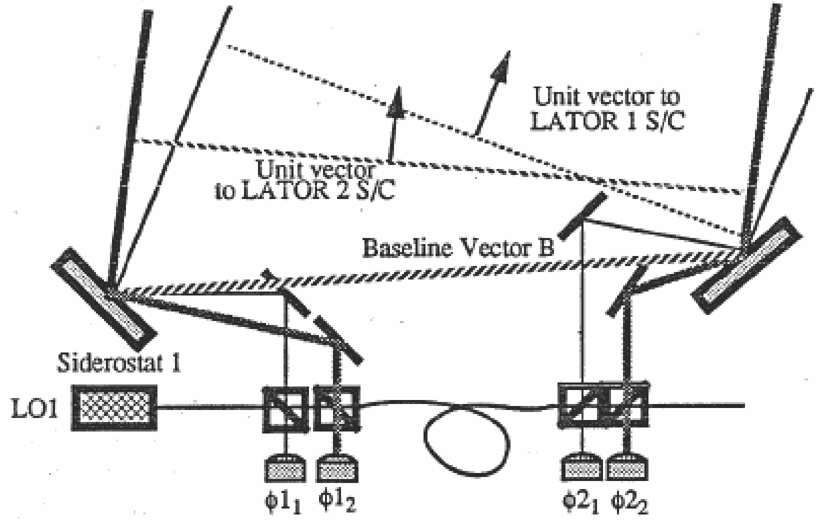


Fiber-linked HI & fiber metrology system.

$$\theta = \arcsin[\frac{(2\pi n + \phi_1 - \phi_2 + m_1)\lambda}{2\pi b}]$$

Heterodyne interferometry on 2 spacecraft

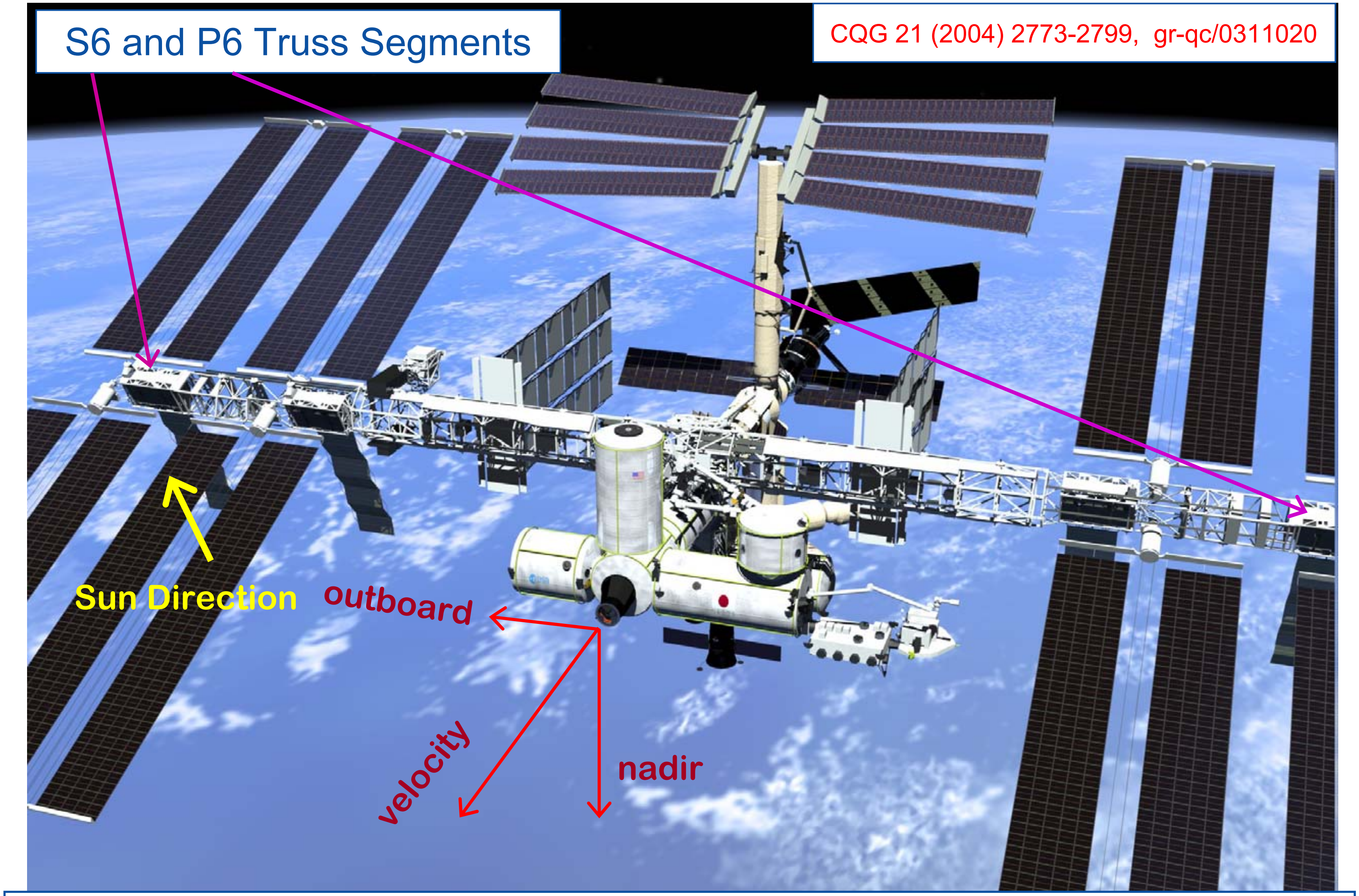
$$\Delta\theta = \arcsin\,[\frac{(2\pi(n_1 - n_2) + (m_1 - m_2))\lambda}{2\pi b} + \\ + \frac{((\phi 1_1 - \phi 1_2) - (\phi 2_1 - \phi 2_2))\lambda}{2\pi b}]$$



Heterodyne Interferometry is well understood

LATOR Interferometer on the ISS

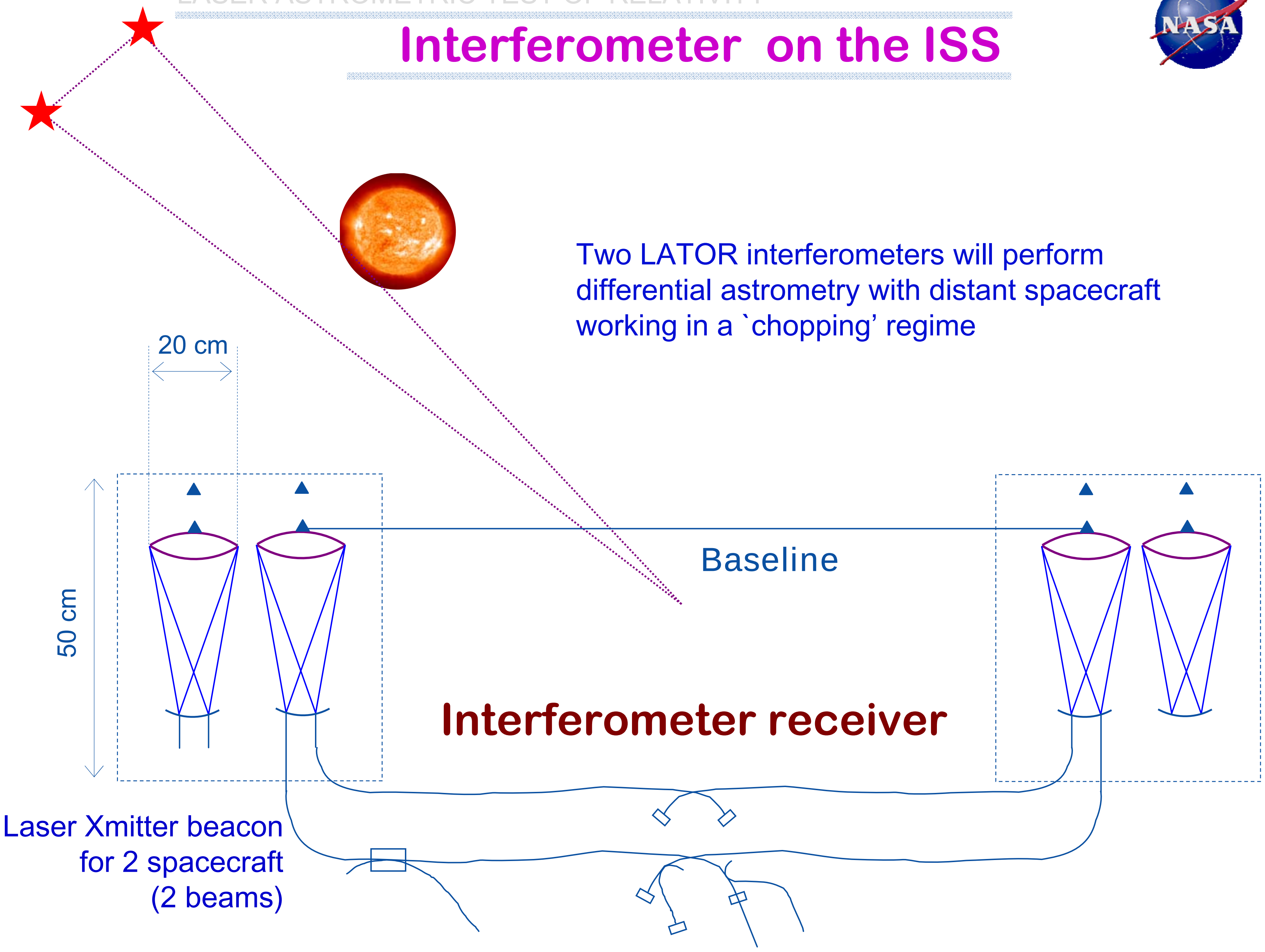
CQG 21 (2004) 2773-2799, gr-qc/0311020



To utilize the inherent ISS sun-tracking capability, the LATOR optical packages will be located on the outboard truss segments P6 & S6 outwards

Interferometer on the ISS

Two LATOR interferometers will perform differential astrometry with distant spacecraft working in a `chopping' regime



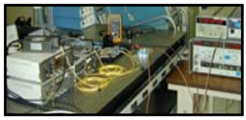
SIM Technology Components/Systems

Component Technology

Subsystem-Level Testbeds

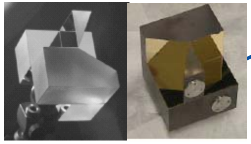
System-Level

Picometer **Knowledge** Technology

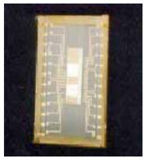
1999

Metrology Source

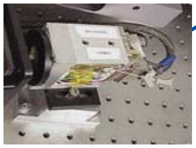
2001

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

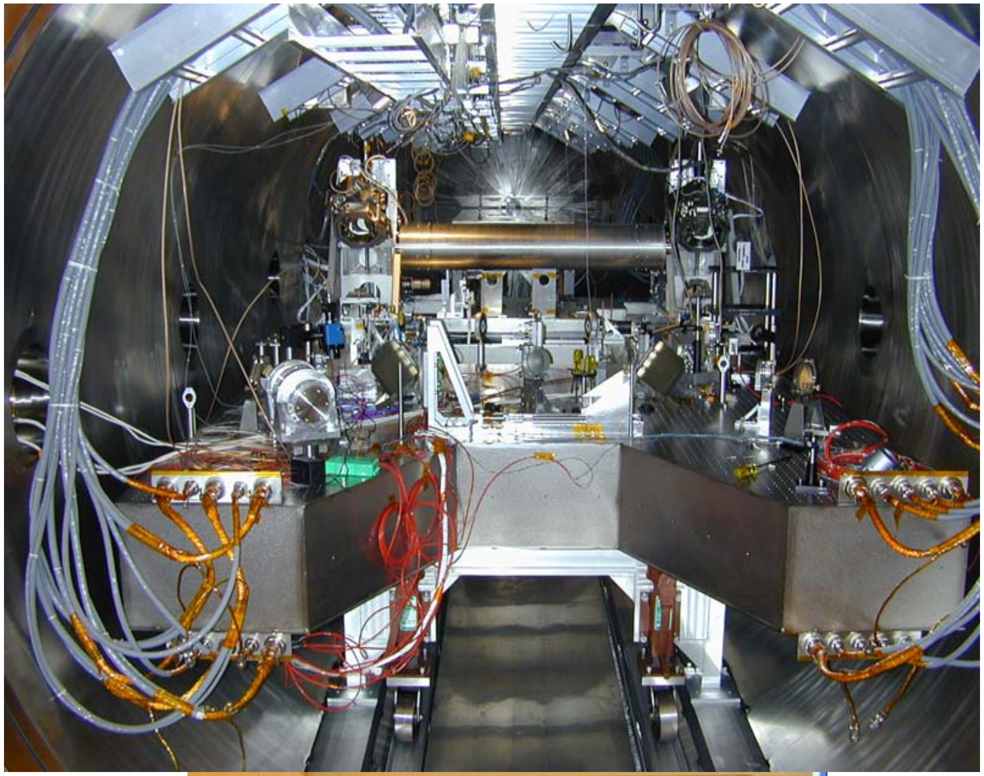

Hexapod Reaction Wheel Isolator
1998


1999
STB-1 (single baseline nanometer testbed)

2:Nov2001

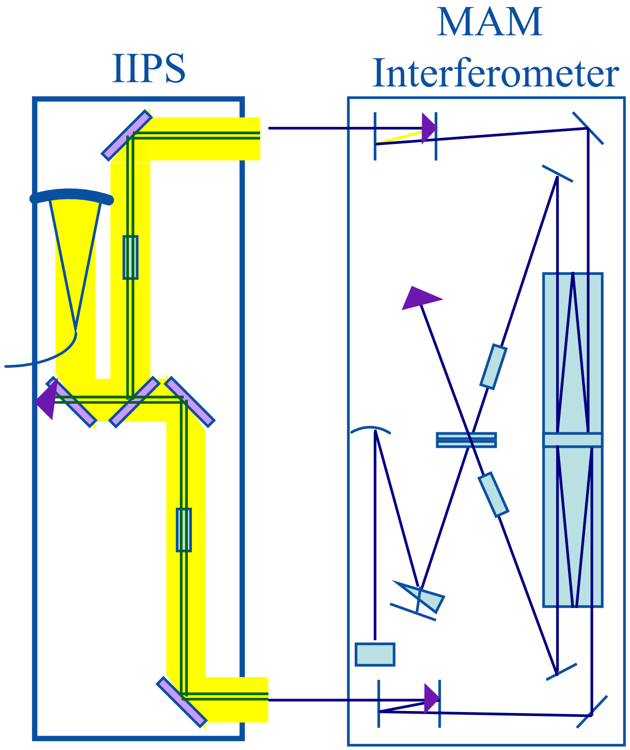
2: STB-3 (three baseline nanometer testbed)

The Micro Arcsec Metrology Testbed



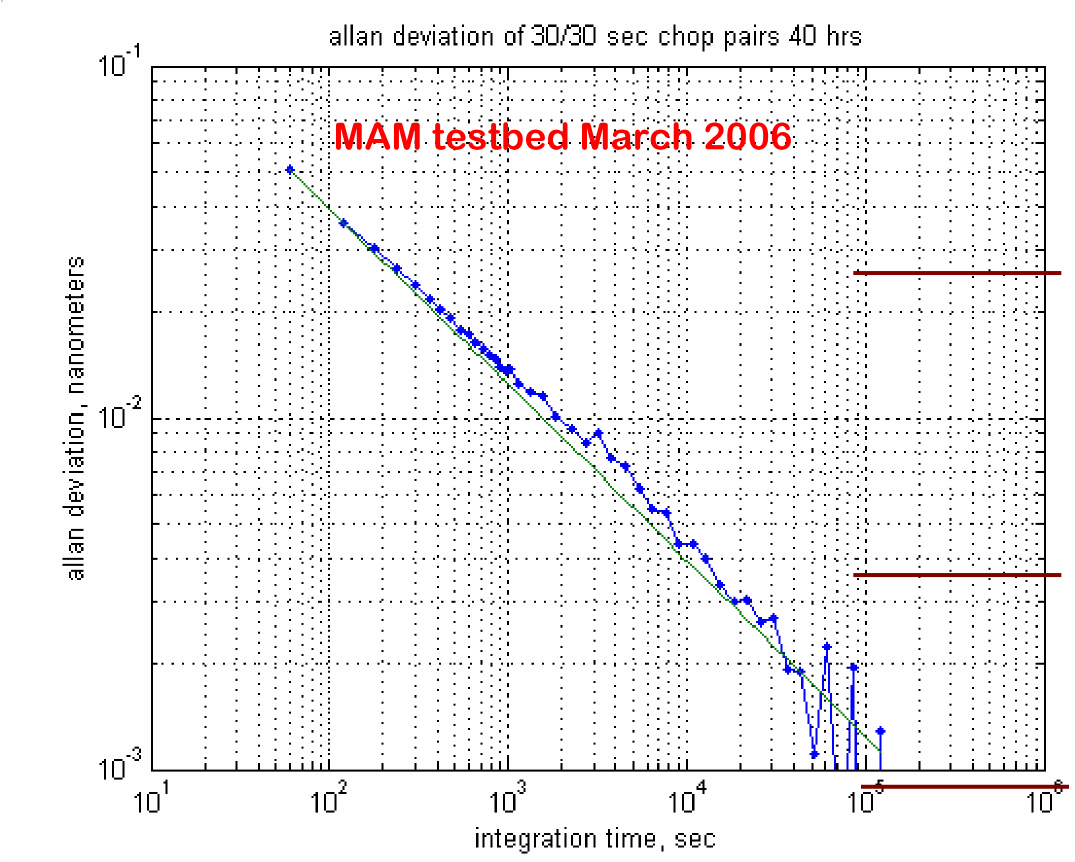
Laser metrology measures the position of the IIPS.

Test is to compare metrology to whitelight (starlight) fringe position.



Long Integrations, instrumental errors

- Instrumental errors in the SIM testbed (chopped) does integrate down as sqrt(T)
  - At least down to 1~2 picometer after 10^5 sec

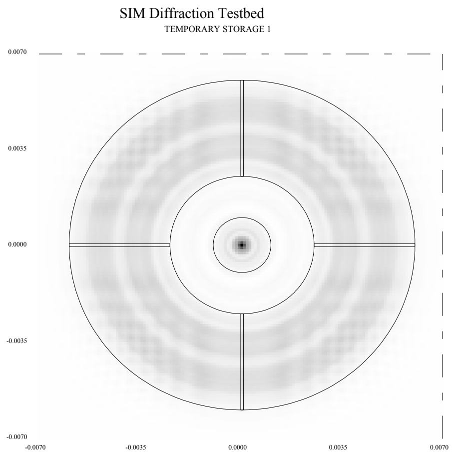


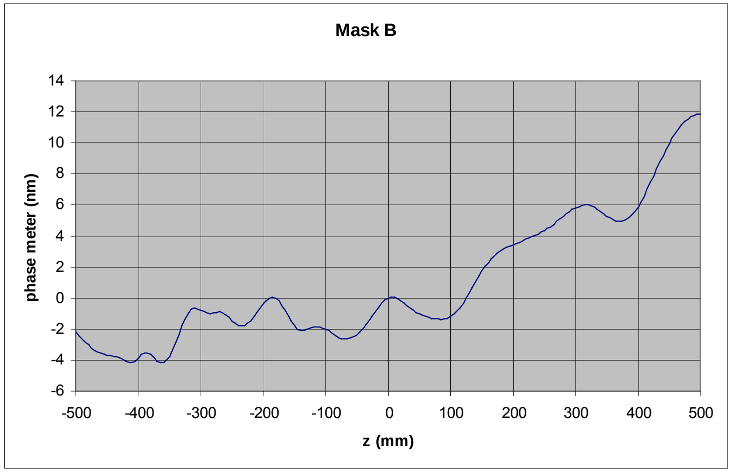
Terrestrial Planet search
Single epoch precision 1 μas

Terrestrial Planet search
5 yr mission precision 0.14 μas

LATOR goal 10^{-9} measurement of γ,
0.002 μas (100m baseline)

Examples of Systematic Errors

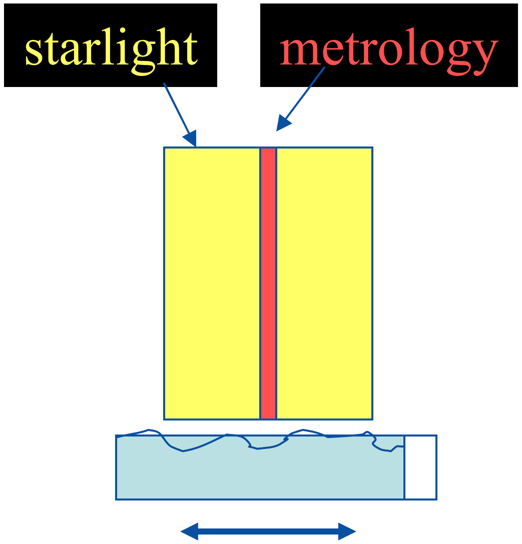




Diffraction:

The metrology beam and starlight beam are different diameters, see different obscurations.

After propagating ~10 meters the optical phase of the wavefront of metrology and starlight are different



Beamwalk:

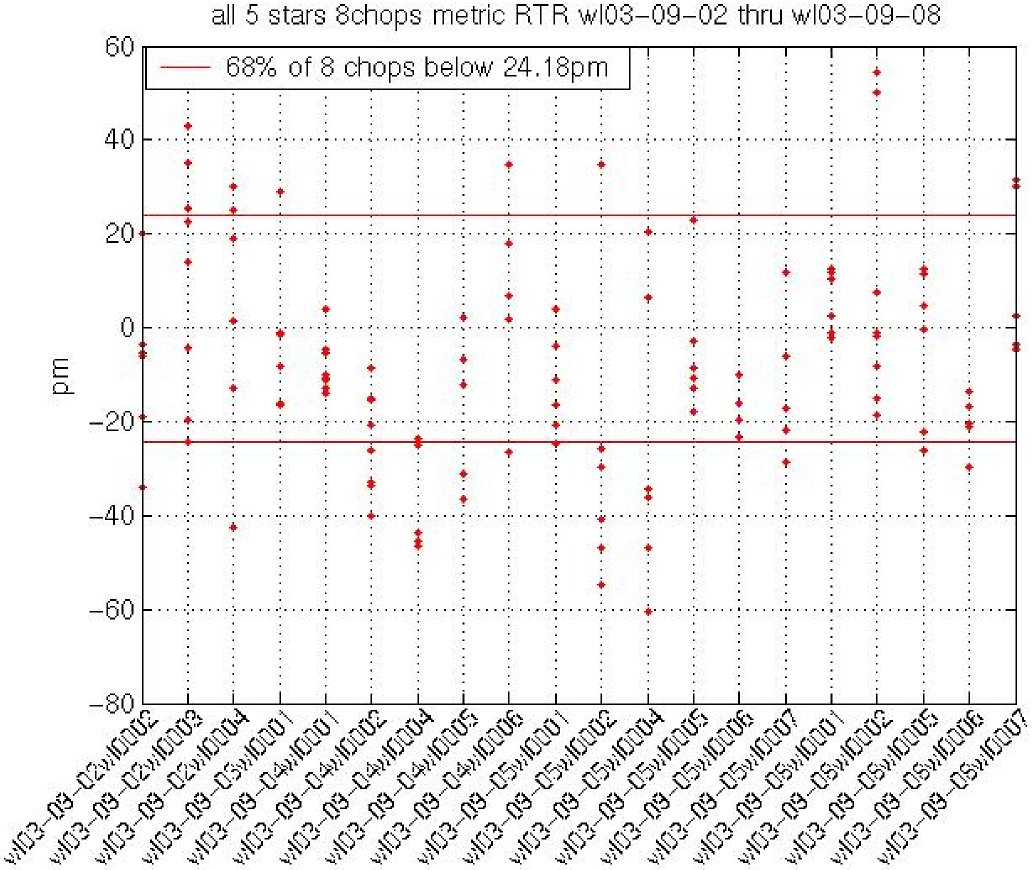
The metrology beam samples a different part of the optic than the starlight beam. If the optical surface is perfect at λ/100 rms, the surface has 6nm hills and valleys.

If we want to measure optical path to 50 picometers we have to make sure we sample the same hills and valleys everytime.

Single Epoch Accuracy

MAM test: 4 ref stars, 1 target star, (T, R1, T, R2, T, R3, T, R4 …. Repeat)

~20 runs conducted over ~1 week in 2003



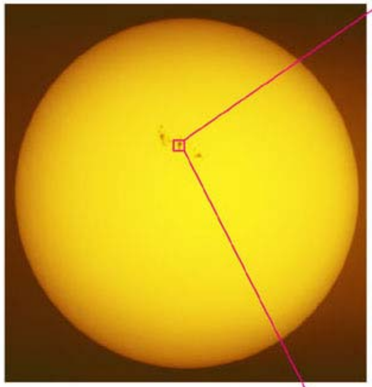
1 uas total error
0.7 to photon noise
0.7 to instrument
0.5 to science interf

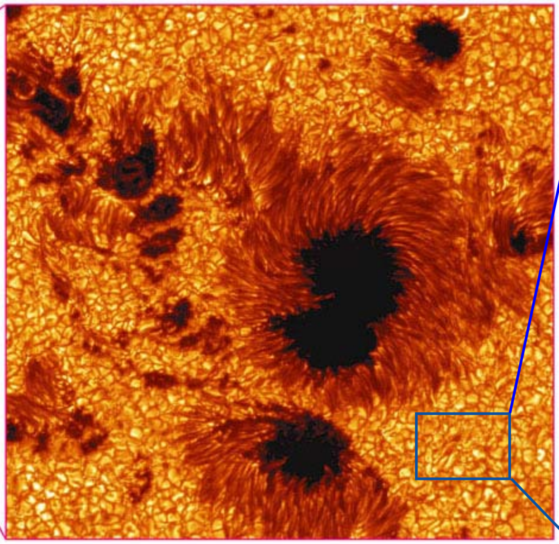
0.5uas ~25 pm

Meet 25pm in 8 chops

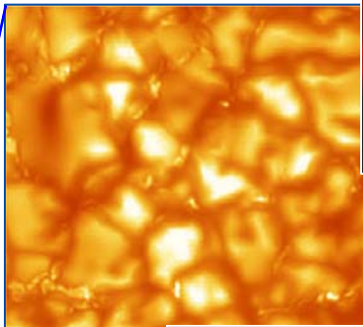
Each dot is an 8 chop average

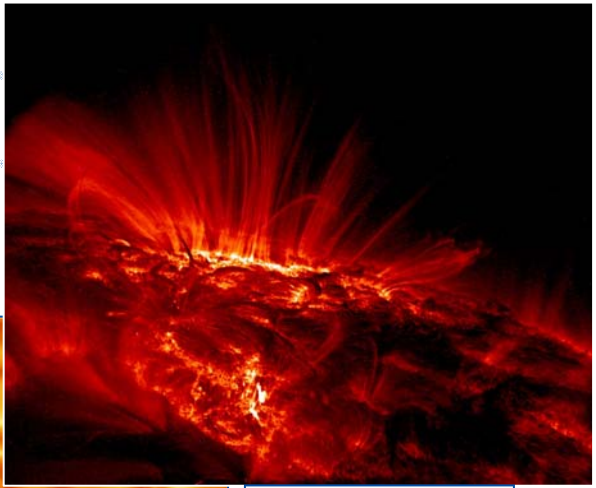
The Solar Boundary





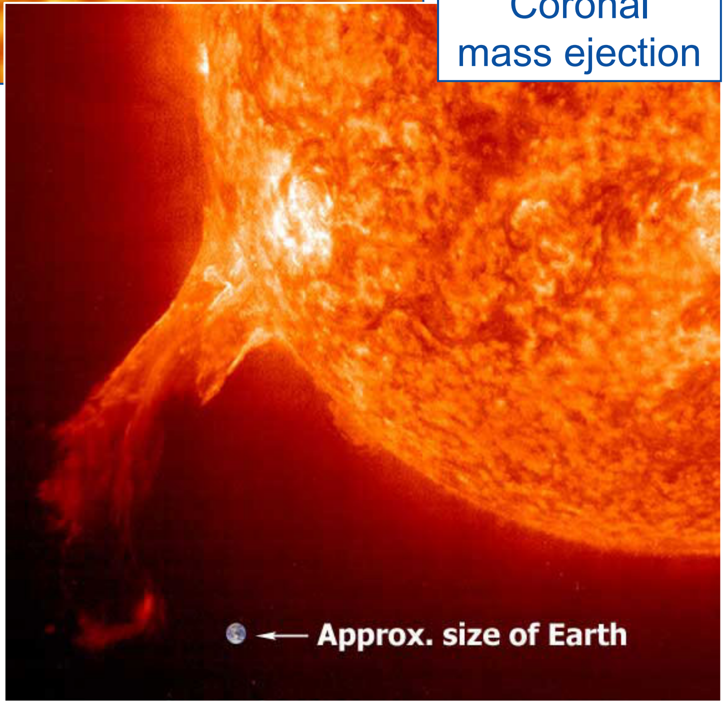
Granulation of solar surface

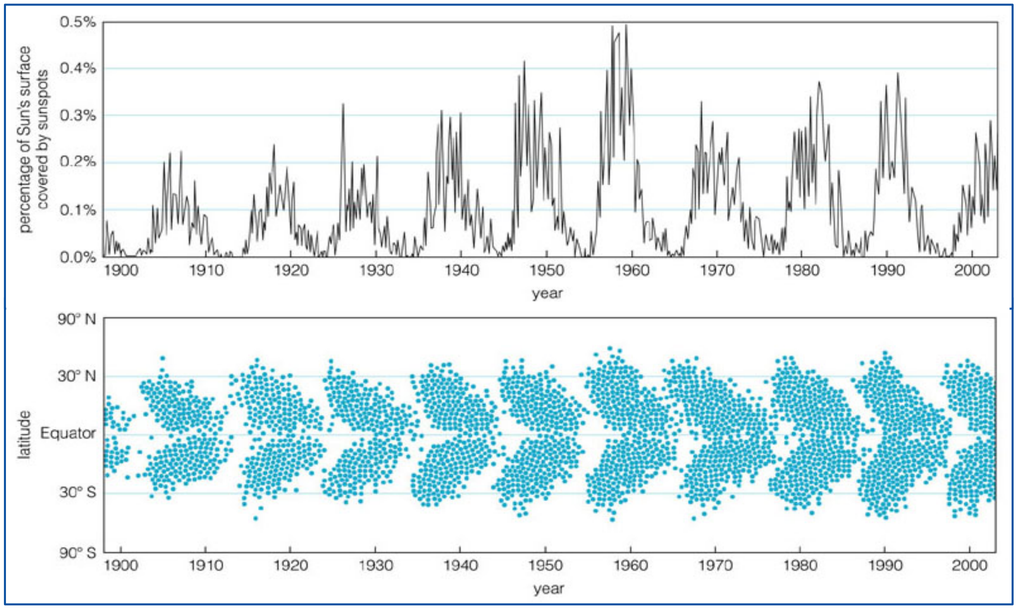




A solar flare

Coronal mass ejection





Solar boundary is complex – how to define the limb of the Sun at 0.1 picorad (or ~1.5 cm)?

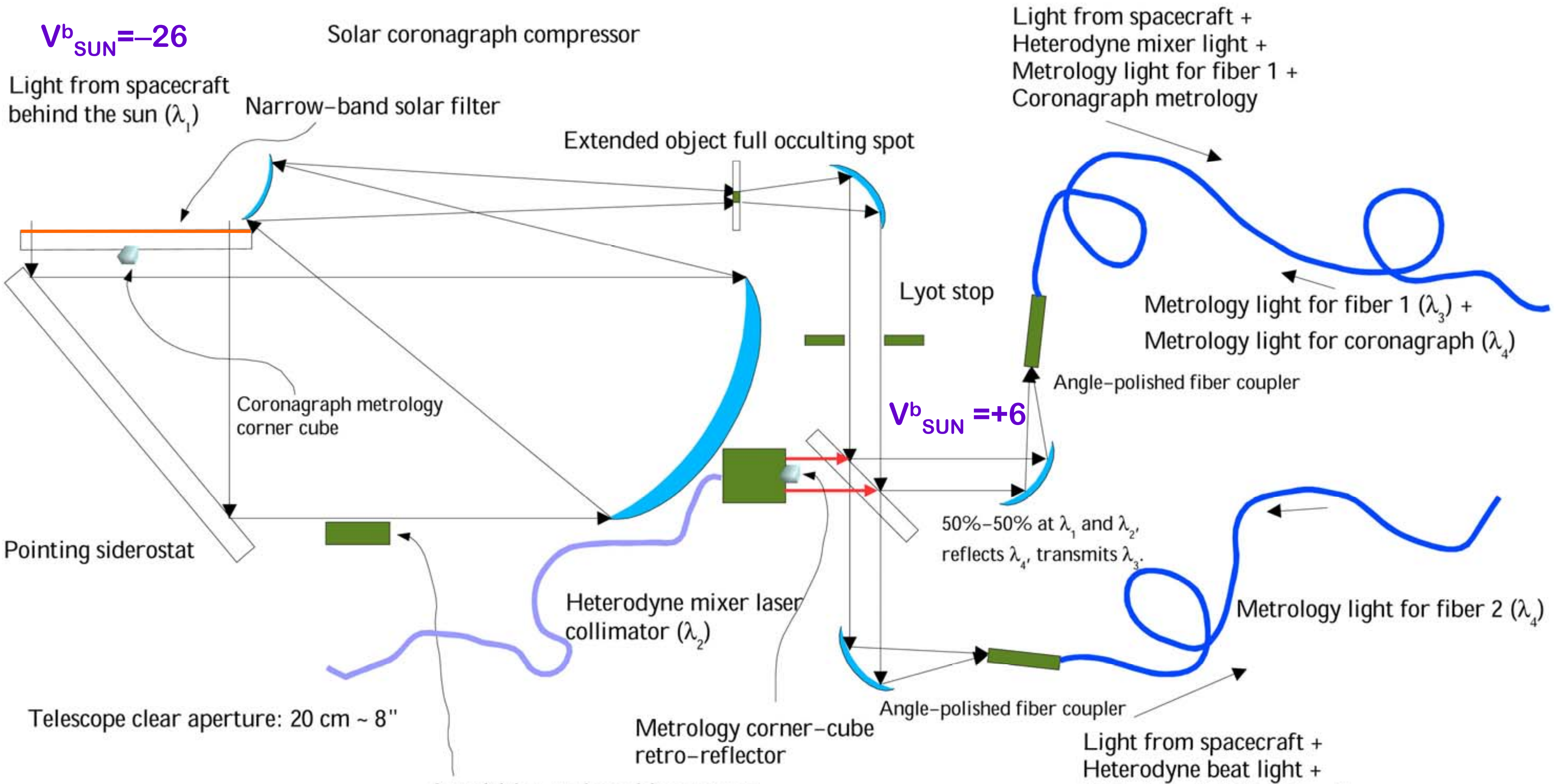
Optical Receivers Looking Next to the Limb of the Sun

Spatial filtering (coronagraph) to avoid the solar surface, as well as light diffracted by the optical aperture. Leaving just the solar corona as background (-26mag $\Rightarrow$ 4 mag/arcsec^2, ~10^{-6})

Spectral filtering, first stage an interference filter, but most of the rejection comes from heterodyne detection, bandwidth set by laser line width ~ 3 khz bandwidth/300Thz (~ 10^{-11} rejection)

Possible rejection 10^{-17}, only need 10^{-10} ~ 10^{-11} rejection to be photon limited

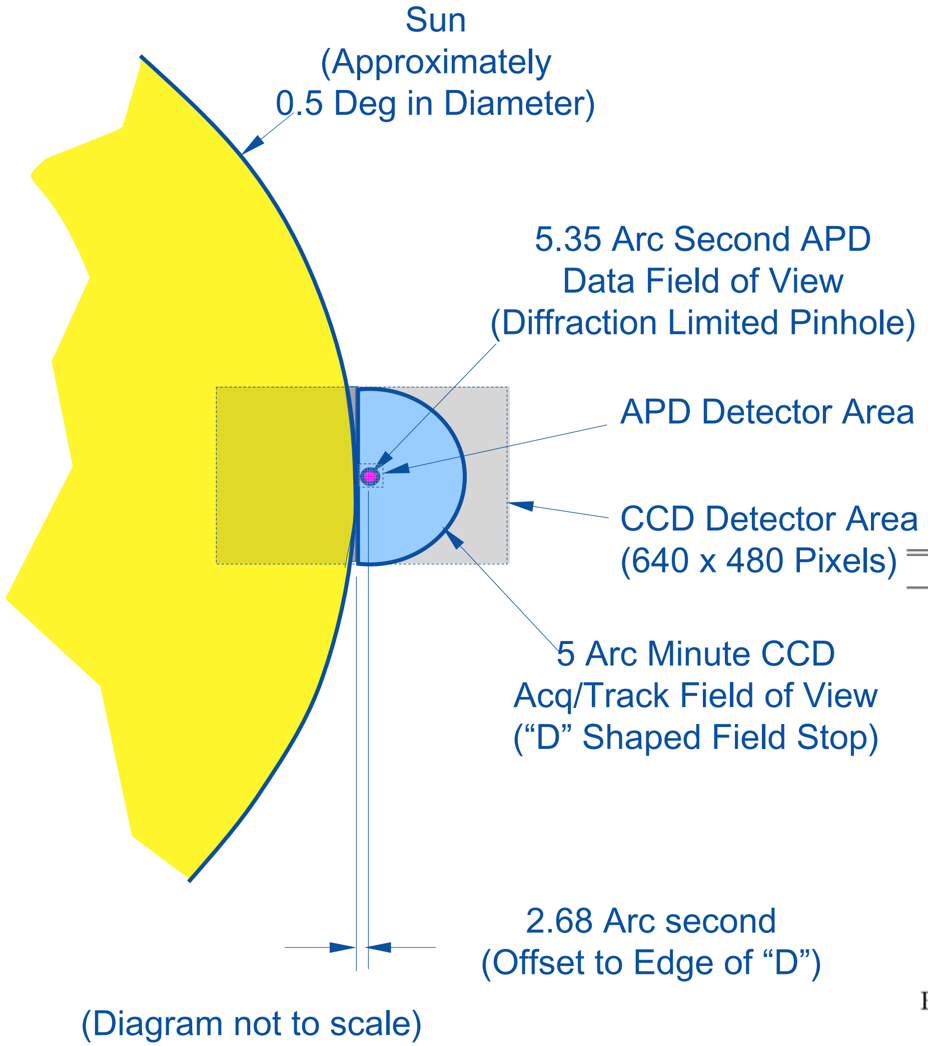
Fiber-Coupled Tracking Interferometer



Basic elements:

- Full aperture ~20cm narrow band-pass filter; corner cube [baseline metrology];
- Steering flat; off-axis telescope w/ no central obscuration [for metrology];
- Coronagraph; ½ plane focal plane occulter; Lyot stop;
- Fibers for each target (1 on S/C and 2 on the ISS).

Focal Plane Mapping



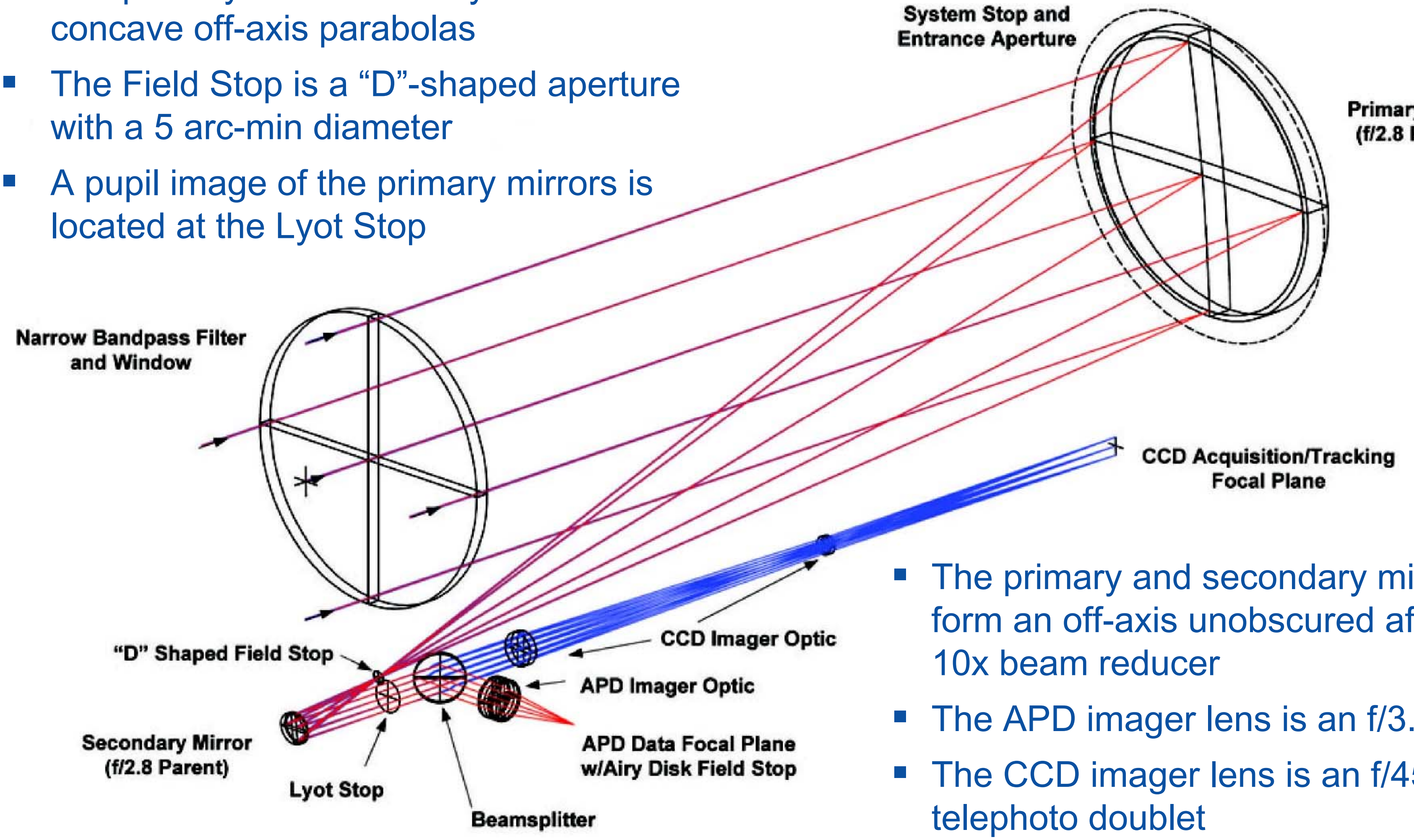
- The straight edge of the "D"-shaped CCD Field Stop is tangent to both the limb of the Sun and the edge of APD field stop (pinhole)
- There is a 2.68 arcsecond offset between the straight edge and the concentric point for the circular edge of the CCD Field Stop ("D"-shaped aperture)
- The APD field of view and the CCD field of view circular edges are concentric with each other

Parameters/Requirements	Value/Description
Aperture	100 mm, unobstructed
Wavelength	1064 nm
Narrow bandpass Filter	2 nm FWHM over full aperture
Focal Planes	APD Data & CCD Acquisition/Tracking
APD Field of View	Airy disk field stop (pinhole) in front of APD
APD Field Stop (pinhole)	Approximately 0.009 mm in diameter
APD Detector Size	TBD (a little larger than 0.009 mm)
CCD Field of View	5 arc minutes
CCD Detector Size	640 × 480 pixels (9.6 mm × 7.2 mm)
CCD Detector Pixel Size	15 μm
Beamsplitter Ratio (APD/CCD)	90/10
Field Stop	'D'-shaped at primary mirror focus
Lyot Stop	Circular aperture located at telescope exit pupil

Summary of design parameters for the LATOR optical receiver system

The LATOR Receiver Optical System Layout

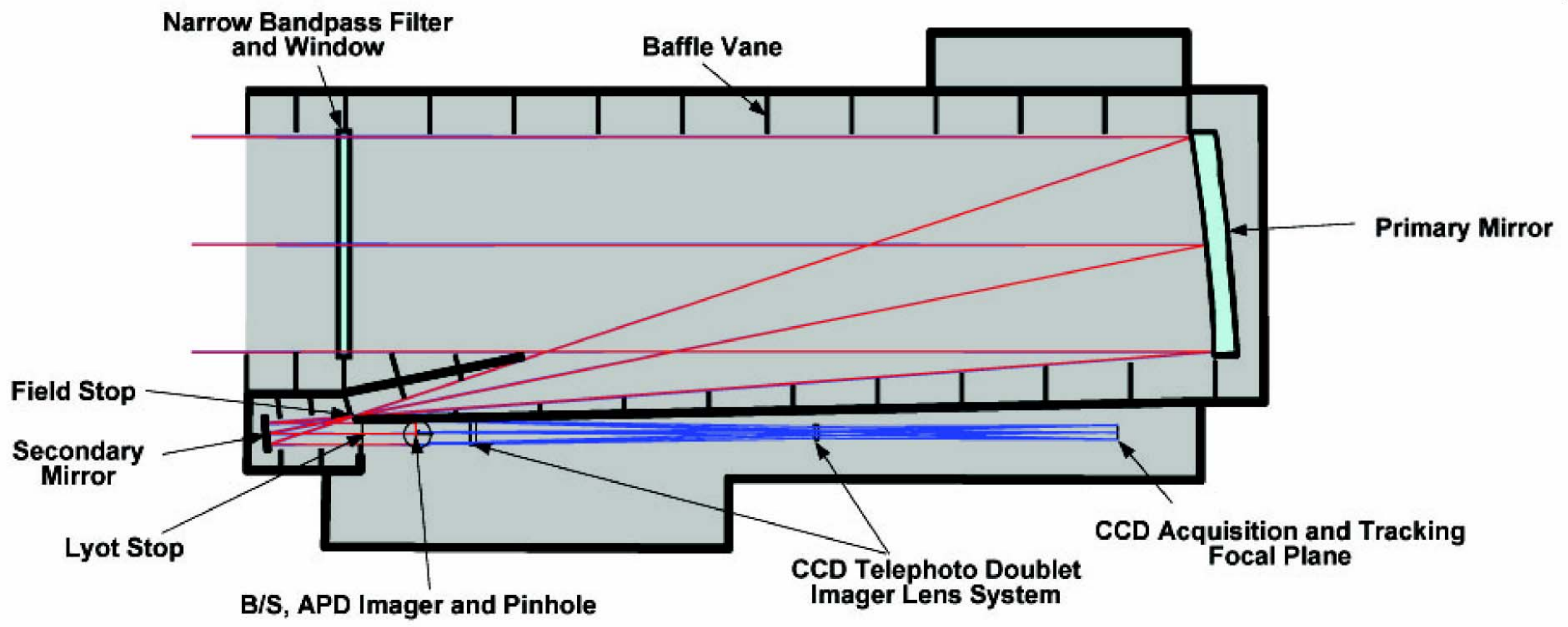
- The primary and secondary mirrors are concave off-axis parabolas
- The Field Stop is a “D”-shaped aperture with a 5 arc-min diameter
- A pupil image of the primary mirrors is located at the Lyot Stop



- The primary and secondary mirrors form an off-axis unobscured afocal 10x beam reducer
- The APD imager lens is an f/3.6 triplet
- The CCD imager lens is an f/45.5 telephoto doublet

The LATOR 200mm receiver optical system is located one each of two separate spacecraft to receive optical communication signals form a transmitter on the ISS.

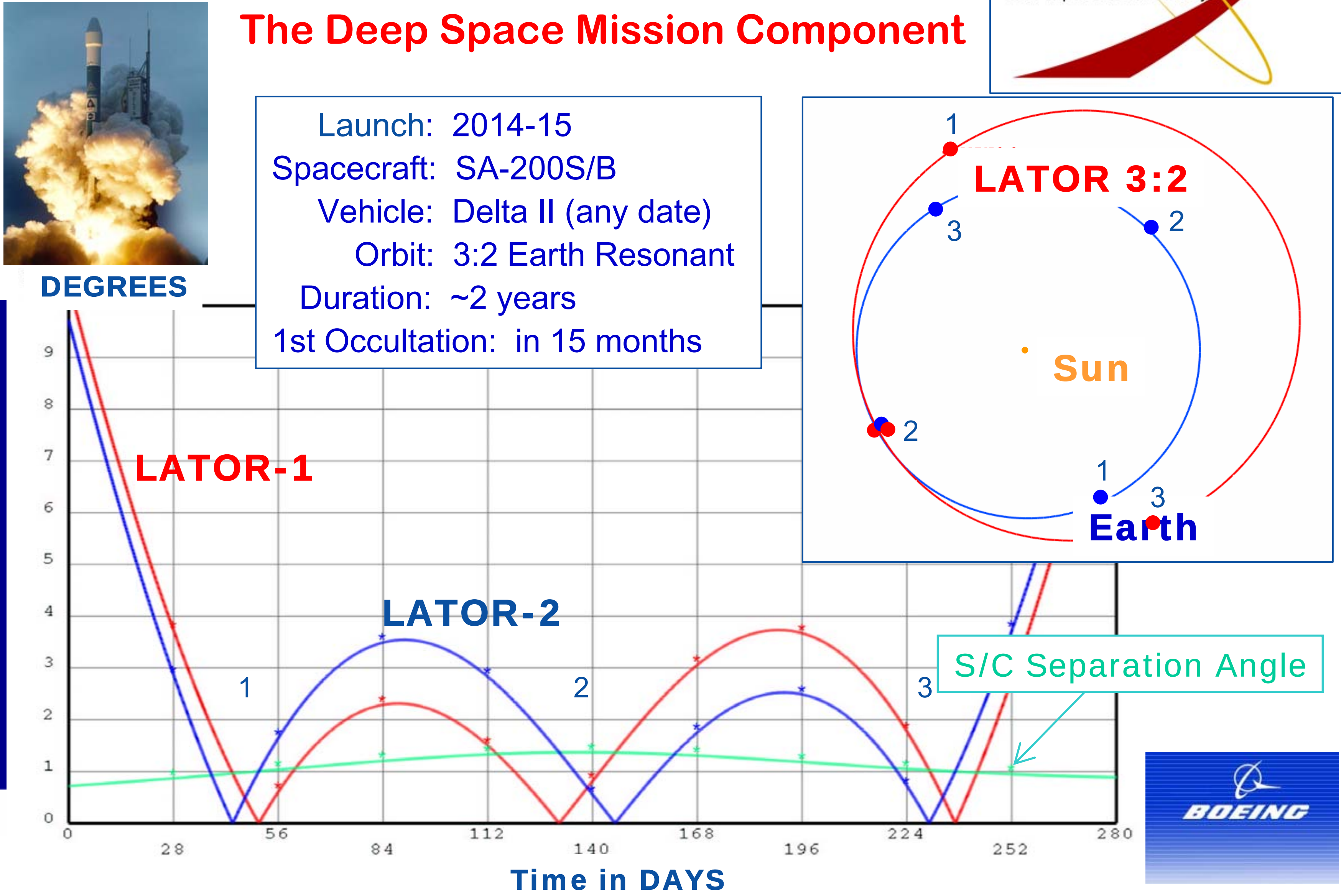
Preliminary Baffle Design



- Out-of-field solar radiation (SR) will fall on the narrow band pass filter and primary mirror. Scattering from these optical surfaces will put some SR into the FOV of the two focal planes.
- The Field Stop will eliminate direct out-of-field SR at the two focal planes, but it will not eliminate narrow angle scattering from the filter and primary mirror.
- The Layot stop will eliminate out-of-field diffracted SR at the two focal planes.
- Baffle vanes may be needed in several places in the optical system

Recent JPL Team X Mission Study:

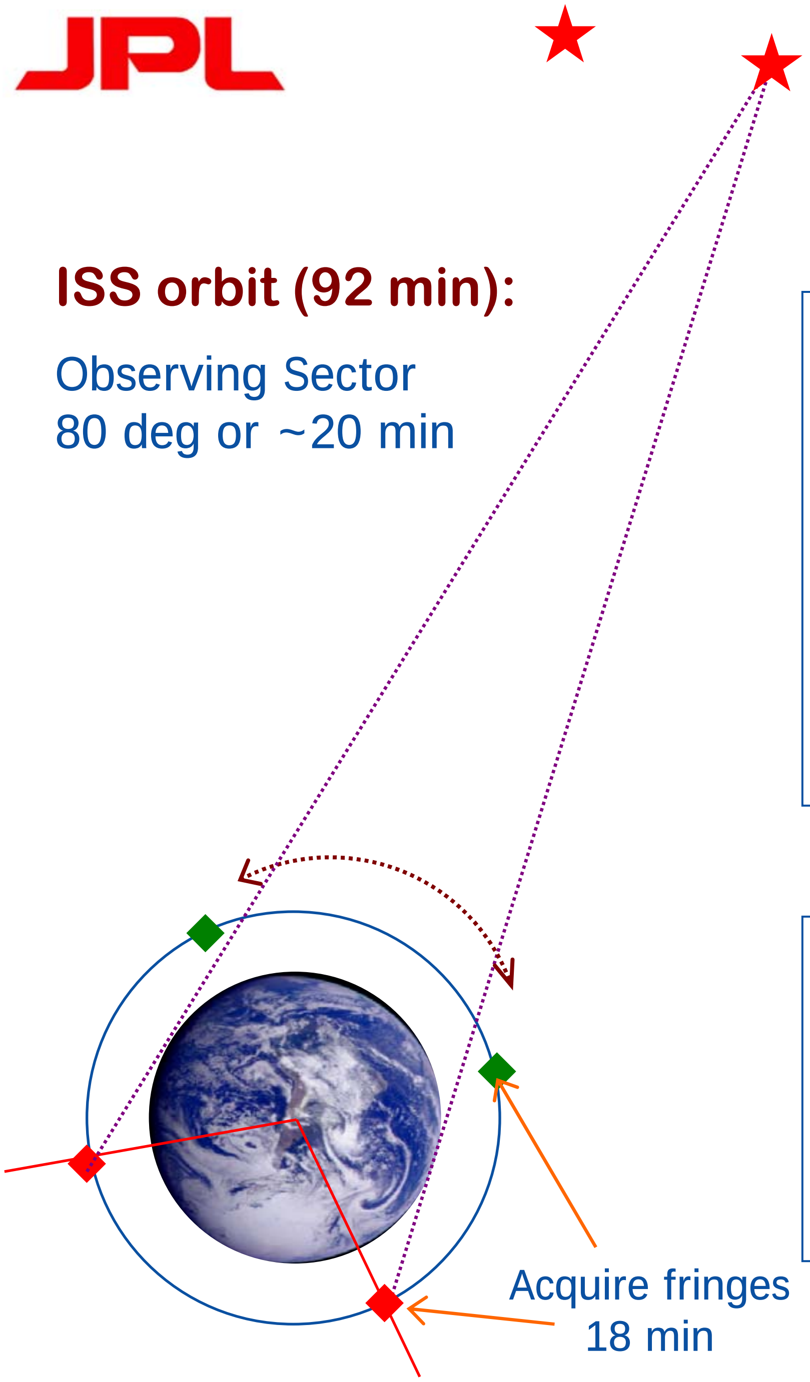
The Deep Space Mission Component



Launch: 2014-15
Spacecraft: SA-200S/B
Vehicle: Delta II (any date)
Orbit: 3:2 Earth Resonant
Duration: ~2 years
1st Occultation: in 15 months

JPL Team X study demonstrates feasibility of LATOR as a MIDEX

Operations on the ISS



ISS orbit (92 min):

Observing Sector
80 deg or ~20 min

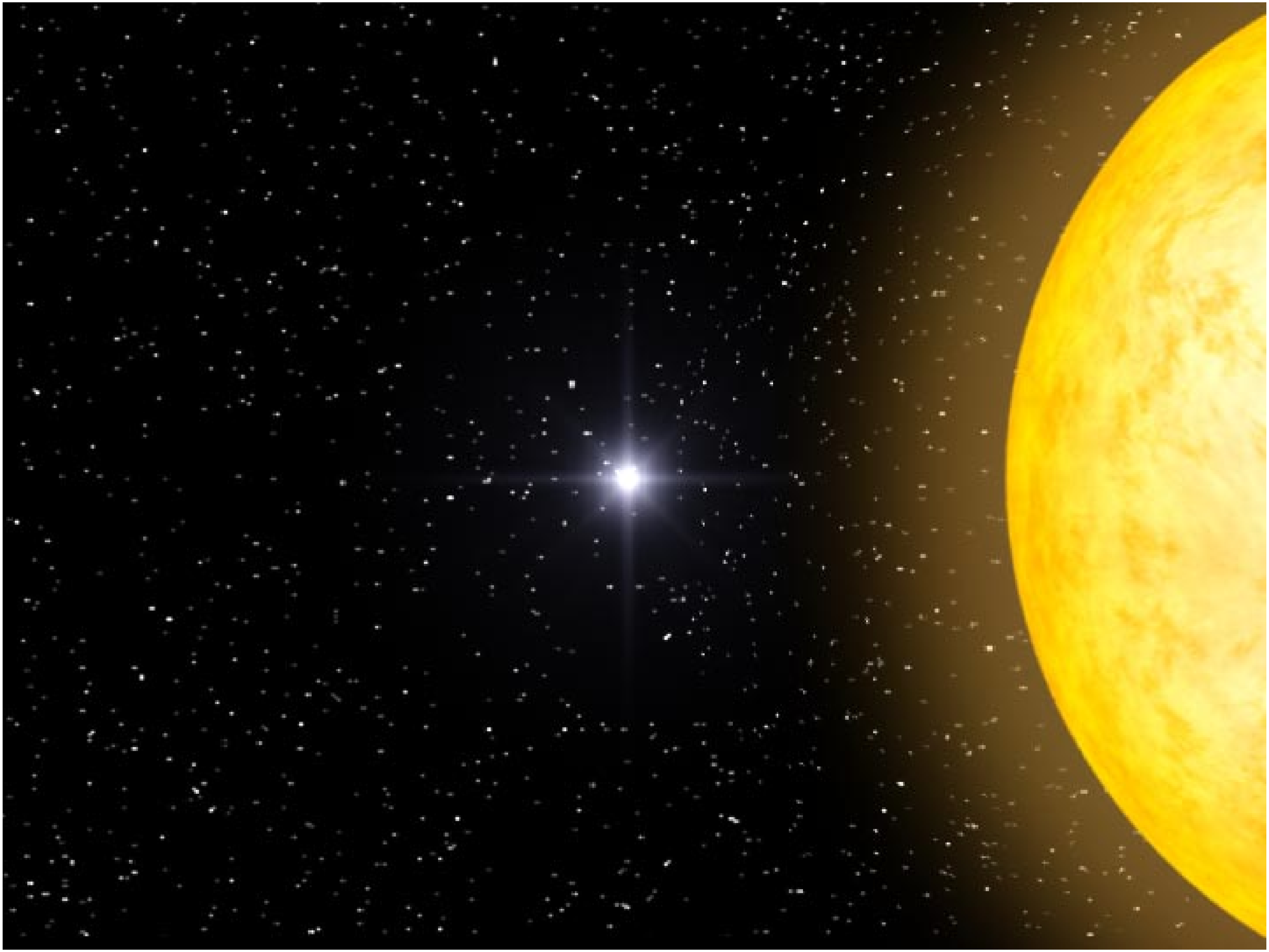
Acquire fringes
18 min

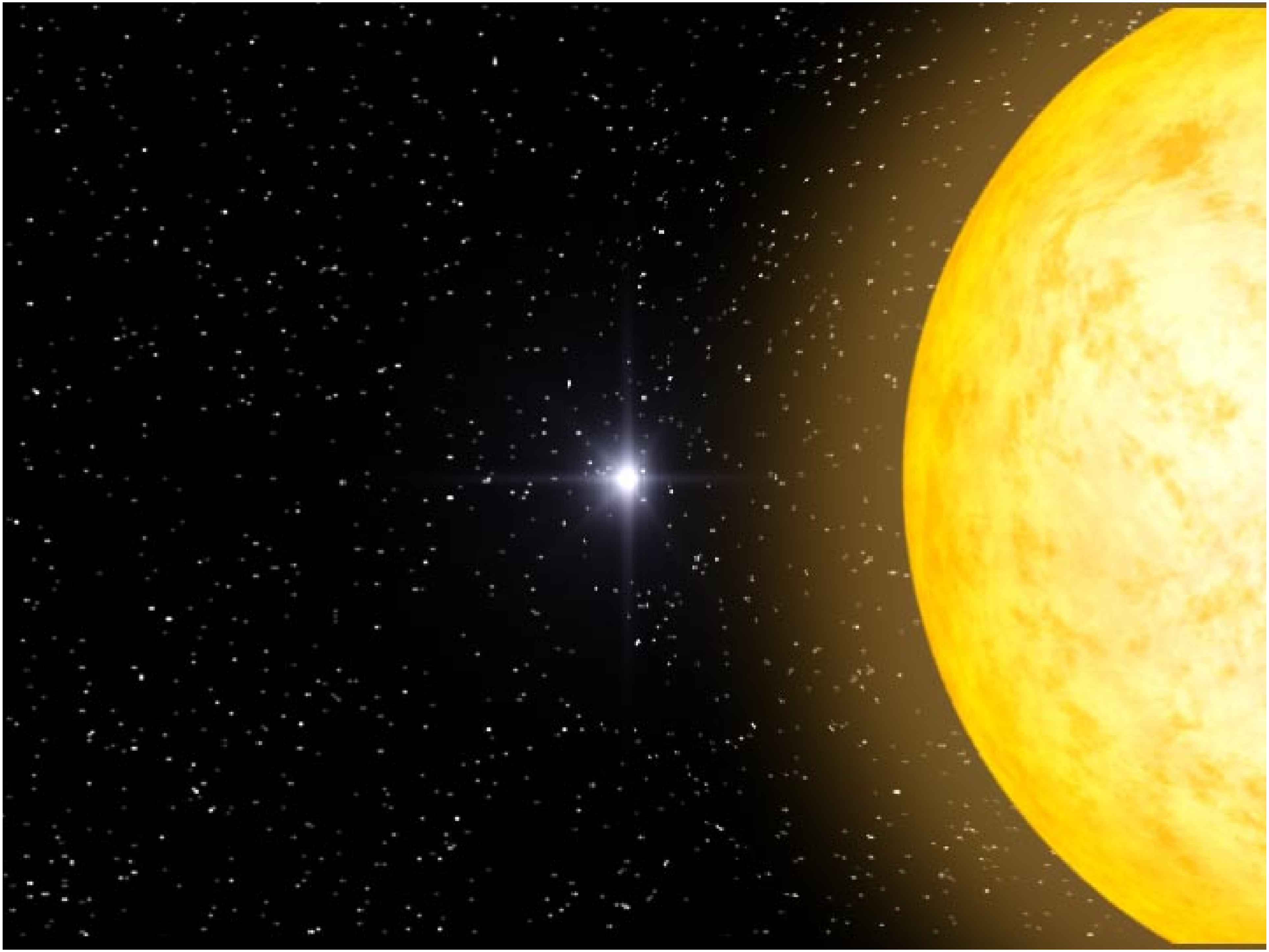
Acquisition (each orbit of ISS):

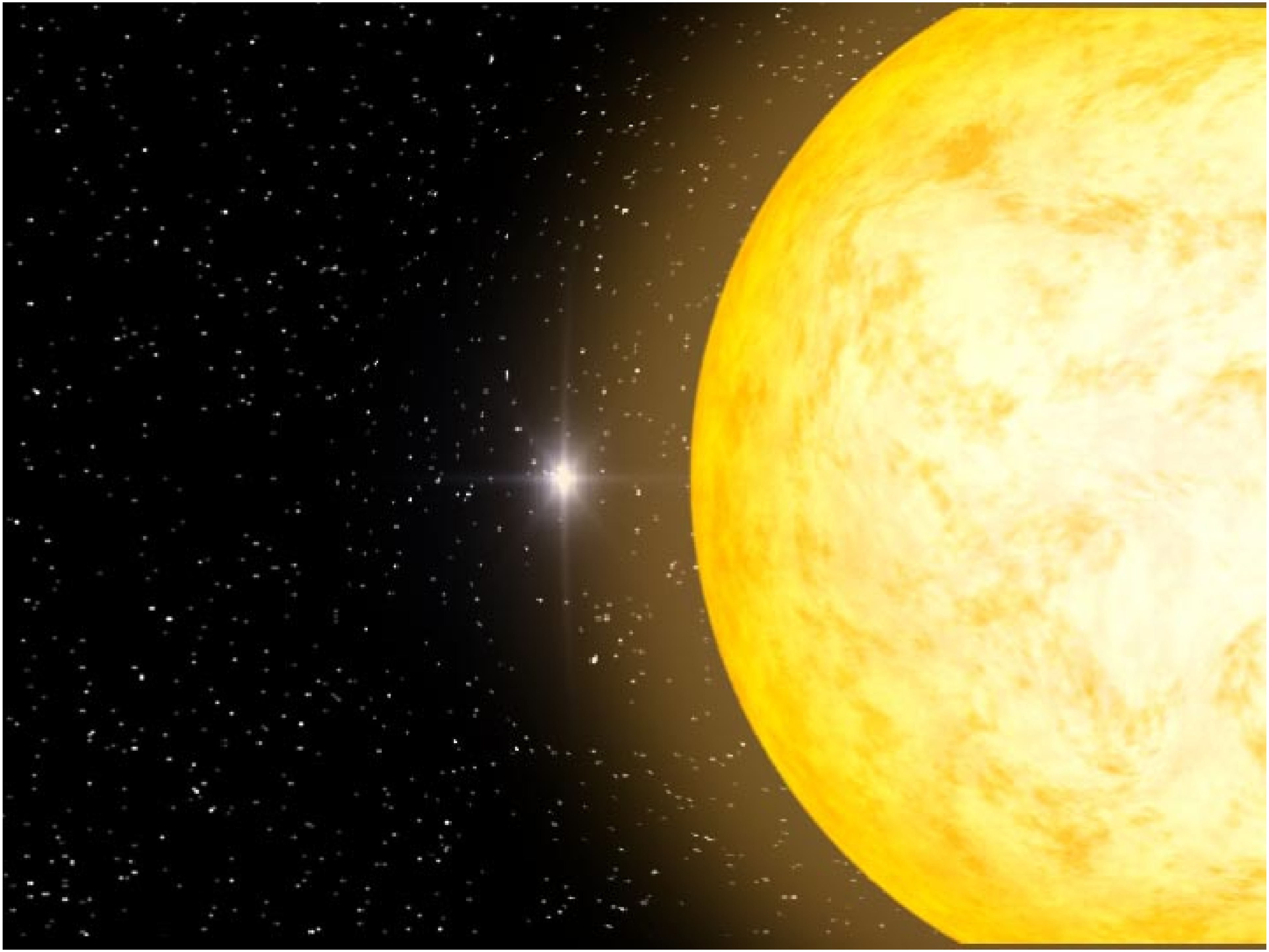
- Transmitters on S/C and ISS broadcast in wide beam mode [50 urad, depending on attitude knowledge of the ISS, and S/C]
- Receivers use long (<100sec) integration time to find beacons 2AU away; after finding beacons, narrow xmitted beam to ~5 urad (diff limit)
- It takes ~18 minutes for the narrow beam to travel 2 AU; as soon as “bright” narrow beam is received, observations start.

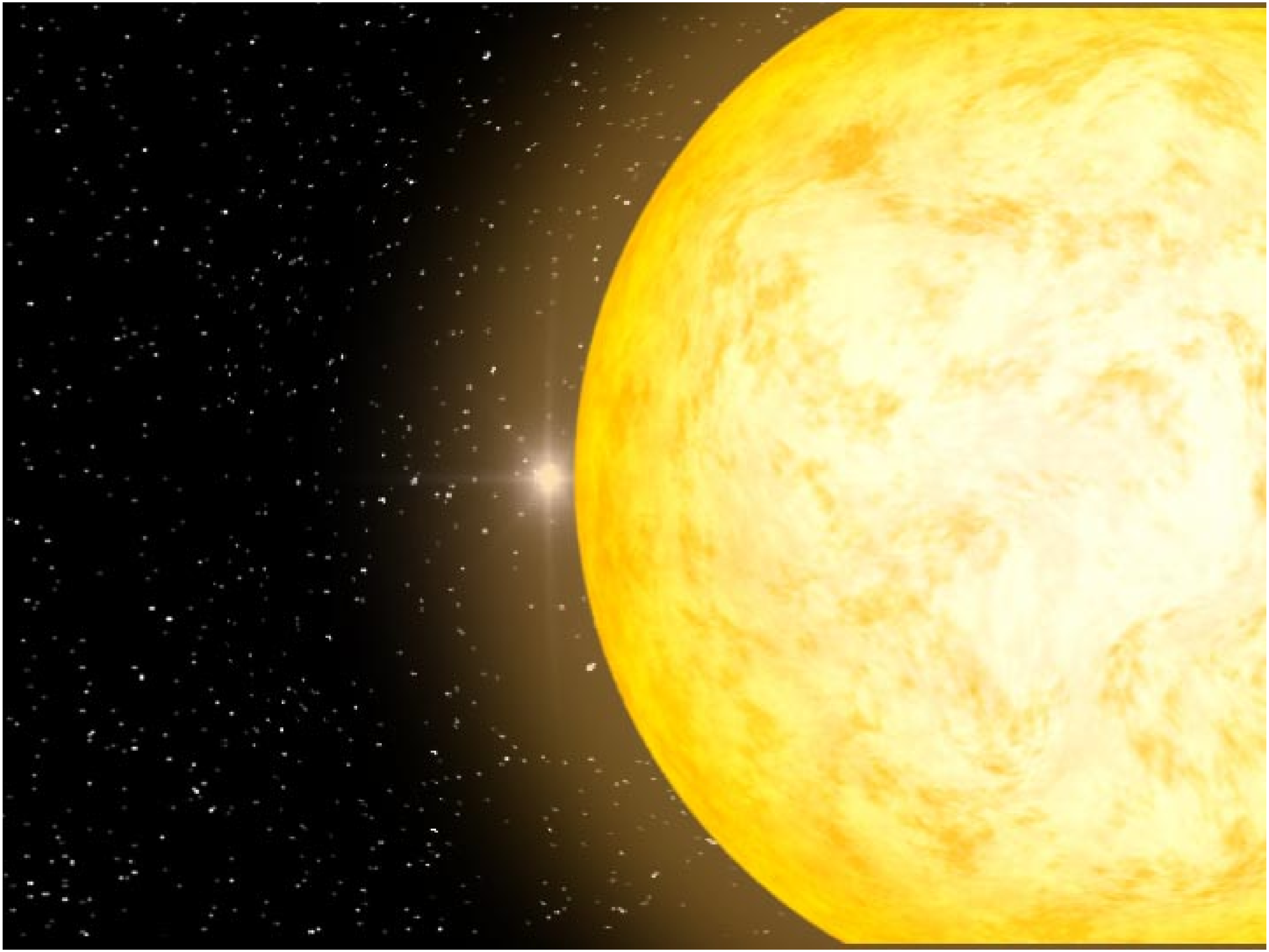
Fringe ambiguity:

- Laser Astrometric Interferometer has N*l ambiguity, which is resolved by varying the baseline length over ~30%.
- Change of effective baseline length achieved by ISS flying with constant attitude w.r.t. the Earth rather than w.r.t. inertial space.

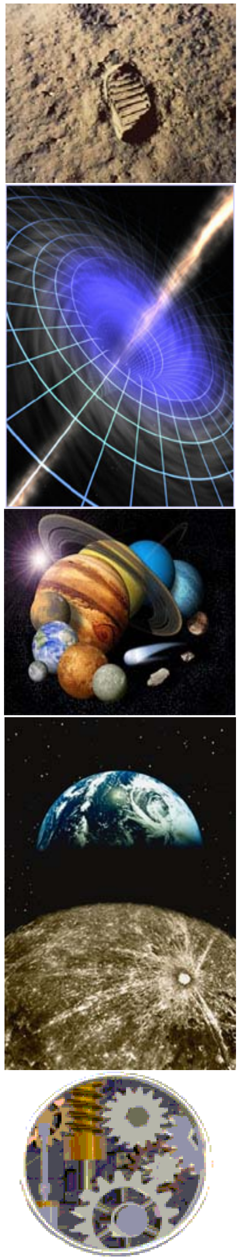








Science Objectives



CQG 21 (2004) 2773-2799, gr-qc/0311020

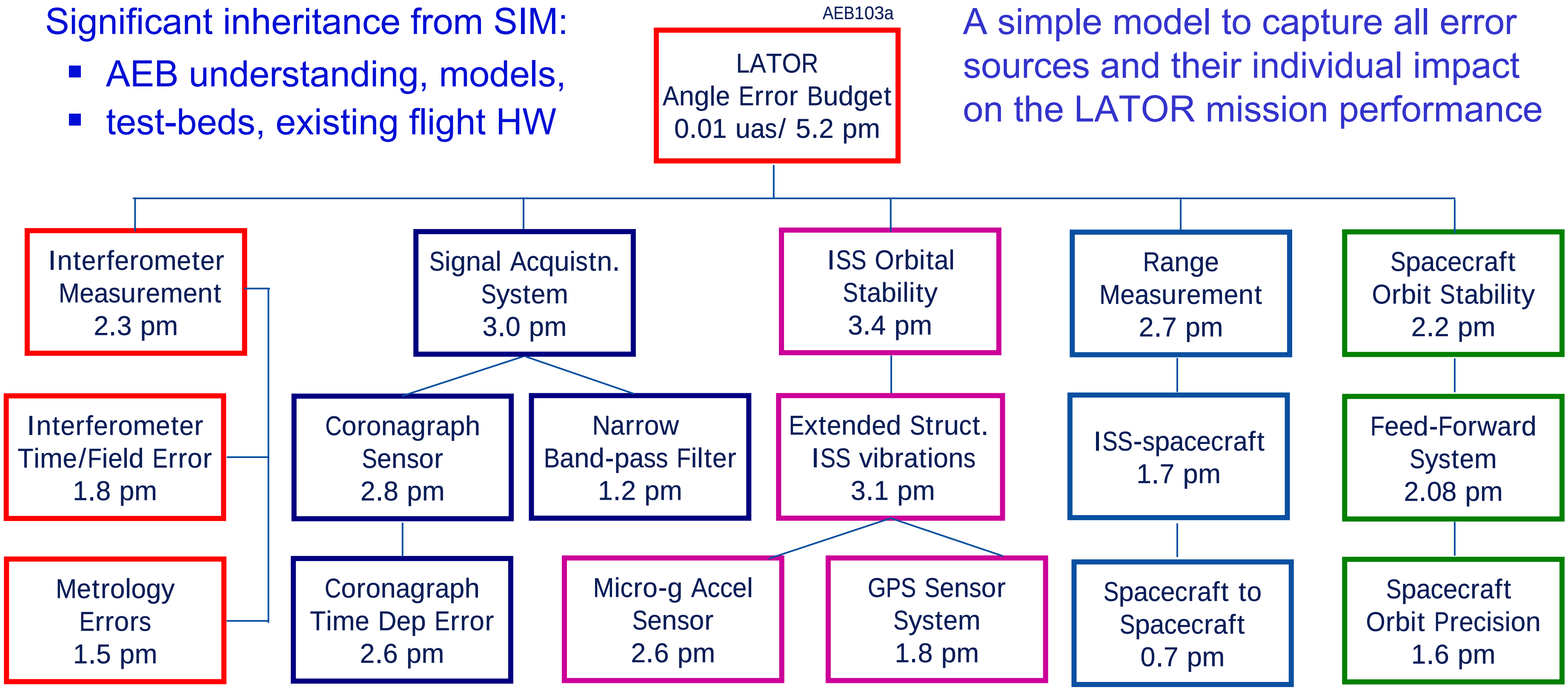
- Qualitative Objectives, to test:
  - The metric nature of GR in the most intense gravitational environment in the solar system – the extreme proximity to the Sun
  - Alternative theories of gravity & cosmology (i.e. scalar-tensor) by searching for cosmological remnants of scalars in the solar system
  - Models of light propagation to the accuracy of ~G^2 v/s
- 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
  - The solar quadrupole moment J_2 to 1×10^{-2} (currently unavailable)
  - Frame dragging effect on light (first observation): ~1×10^{-3} accuracy
  - Additional Possibilities: solar physics and related technology

LATOR Astrometric Error Budget

Significant inheritance from SIM:

- AEB understanding, models,
- test-beds, existing flight HW

A simple model to capture all error sources and their individual impact on the LATOR mission performance



AEB103a

LATOR Angle Error Budget 0.01 uas/ 5.2 pm

Interferometer Measurement 2.3 pm

Interferometer Time/Field Error 1.8 pm

Metrology Errors 1.5 pm

Signal Acquistn. System 3.0 pm

Coronagraph Sensor 2.8 pm

Narrow Band-pass Filter 1.2 pm

Coronagraph Time Dep Error 2.6 pm

ISS Orbital Stability 3.4 pm

Extended Struct. ISS vibrations 3.1 pm

Micro-g Accel Sensor 2.6 pm

GPS Sensor System 1.8 pm

Range Measurement 2.7 pm

ISS-spacecraft 1.7 pm

Spacecraft to Spacecraft 0.7 pm

Spacecraft Orbit Stability 2.2 pm

Feed-Forward System 2.08 pm

Spacecraft Orbit Precision 1.6 pm

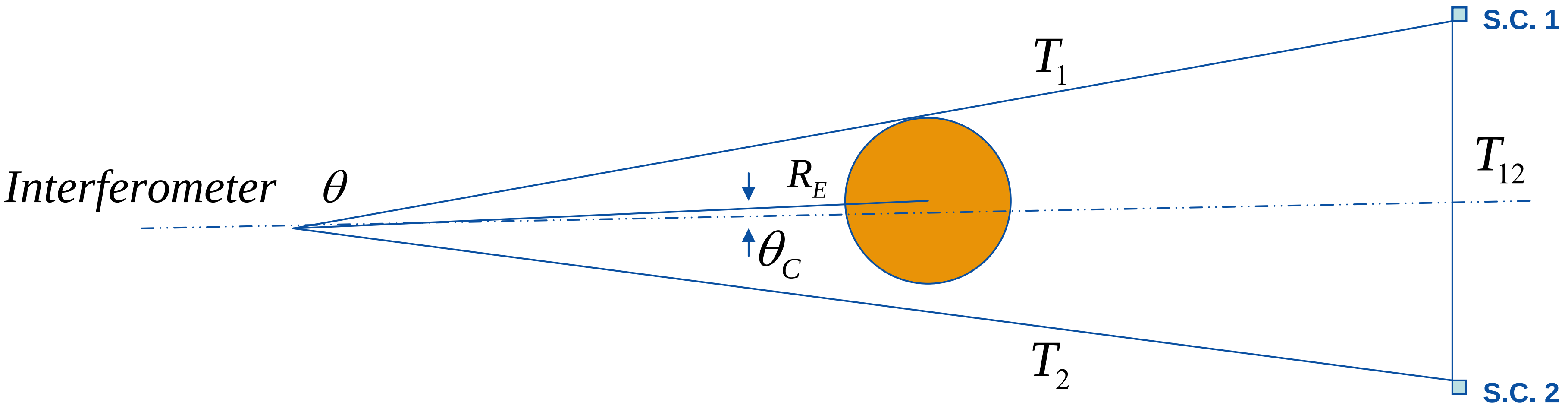
Technology solutions:

- Signal acquisition on the solar background: full-aperture narrow band-pass filer & coronagraph
- ISS vibration: micro-g accelerometers [first devised for SIM – not needed; KI used extensively]
- Fringe ambiguity: LATOR’94 needed variable baselines lengths; for LATOR ’03 the ISS orbit provides variable baseline projection – not an issue

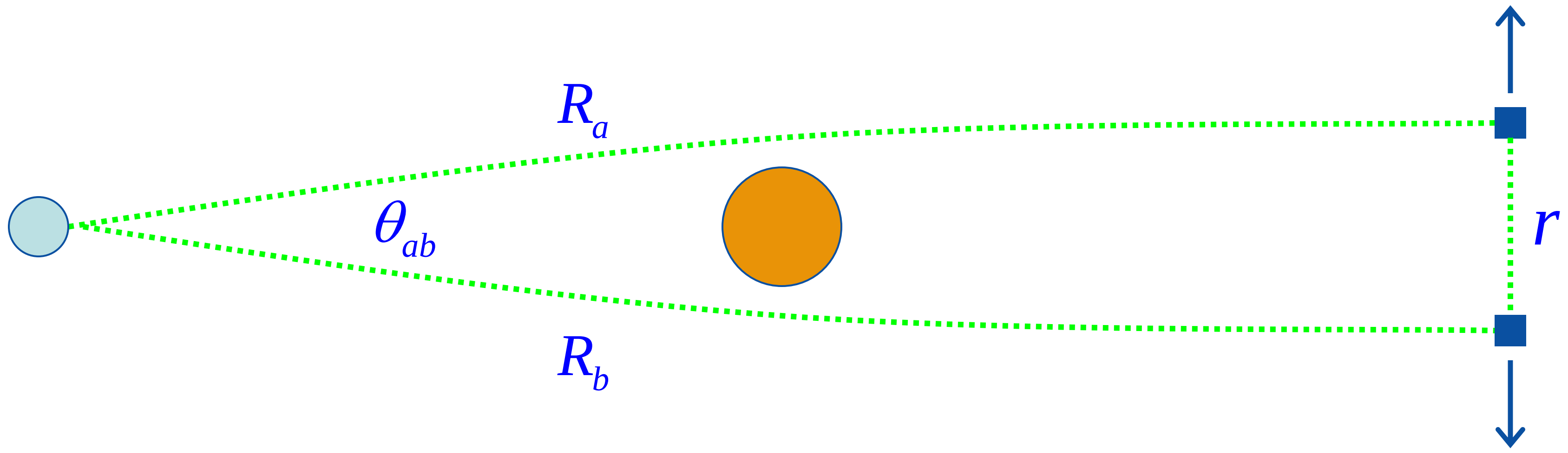
Measure Light Triangle's T_1, T_2, T_{12} with Laser Ranging
Measure θ using Interferometer θ_c with Navigation

$$\sin\theta_{EUC} = \frac{\sqrt{2T_{12}^2\left(T_1^2 + T_2^2\right) - T_{12}^4 - \left(T_1^2 - T_2^2\right)^2}}{2T_1T_2}$$

$$\theta - \theta_{EUC} = \left(1+\gamma^*\right)\frac{GM(G)_S}{c^2R_E}\left(\frac{1}{\sin\left(\theta/2+\theta_C\right)} + \frac{1}{\sin\left(\theta/2-\theta_C\right)}\right) + \dots$$



Experimental Sensitivity



Euclid says: $$\sin\theta_{ab} = \frac{\sqrt{2r^2\left(R_a^2 + R_b^2\right) - \left(R_a^2 - R_b^2\right)^2 - r^4}}{2R_aR_b}$$

Doubles Experimental Sensitivity:

$$\delta\theta_{ab} \simeq 2(1+\gamma)\frac{GM}{c^2}\left(\frac{1}{D_A(t)} + \frac{1}{D_B(t)}\right) + \ldots$$

Results of Mission Simulations

$$\text{Multiply } \delta\gamma \text{ by } 10^{-8} / \sqrt{N(eff)}$$

$$\text{Multiply } \delta J_2 \text{ by } 6\ 10^{-9} / \sqrt{N(eff)}$$

$$\text{Multiply } \delta\beta \text{ by } 3\ 10^{-3} / \sqrt{N(eff)}$$

Z/R_{sun}	$\delta\gamma$	$\delta J2$	$\delta\beta$	$\delta\gamma^*$	$\delta J2^*$
0	23	55	73	3.7	6.9
.25	28	82	95	3.8	7.9
.50	15	131	87	4.8	13.7
.75	9	25	10	3.6	22.1
1	11	10	18	1.9	4.4

Sensitivity Study

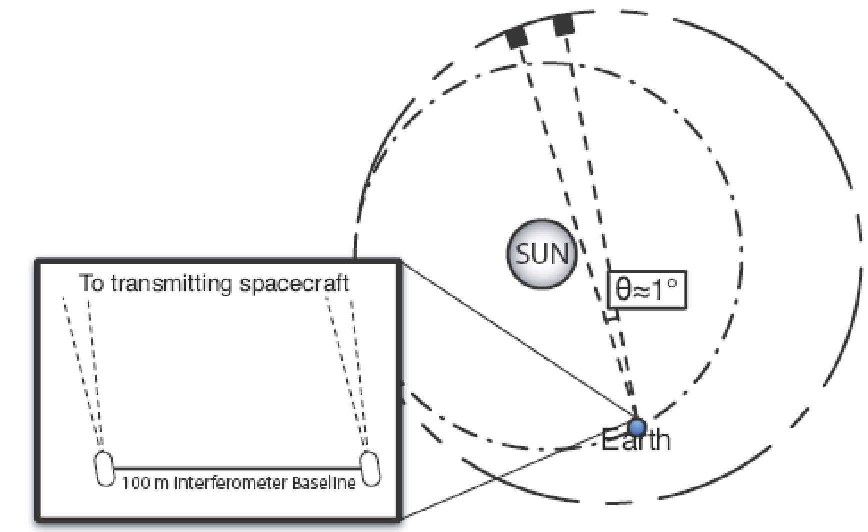
Plowman & Hellings, CQG (2005) subm., gr-qc/0505064

Difference:

1. X-band tracking.
2. No spacecraft-spacecraft link.

Drag-Free System (to enhance s/c orbit determination):

1. A 10^{-13}-radian angular accuracy at a distance of 3×10^{11} m corresponds to a position accuracy of 3 cm.
2. Position noise for a spacecraft suffering acceleration noise with noise spectral density S_a (at a frequency f) is $x_{\rm rms} = \sqrt{S_a/(16\pi^4 f^4)}$.
3. Therefore, if we require 3 cm accuracy at a frequency 1/month ($f = 4 \times 10^{-7}$ Hz), we derive a drag-free requirement of $S_a \approx 4 \times 10^{-26}$ $\rm m^2 s^{-4} Hz^{-1}$, or a root spectral density $\sqrt{S_a} \approx 2 \times 10^{-13}$ $\rm ms^{-2} Hz^{-1/2}$.
4. Two orders of magnitude less precise than the LISA drag-free requirement (though in a lower frequency band).



Parameter	Current best estimate	Uncertainty
γ	$1 + (2.1 \pm 2.3) \times 10^{-5}$	2.4×10^{-9}
β	$1 + (0.9 \pm 1.1) \times 10^{-4}$	Not solved for.
δ	Unmeasured. =1 in GR	1.2×10^{-3}
J_2	Umeasured. Estimated at $\sim 10^{-7}$ (from solar models).	6×10^{-9}

Various mission studies and sensitivity analyses are on-going

LATOR - II

Orbits:

- 80,000 km circular around Earth

Measure:

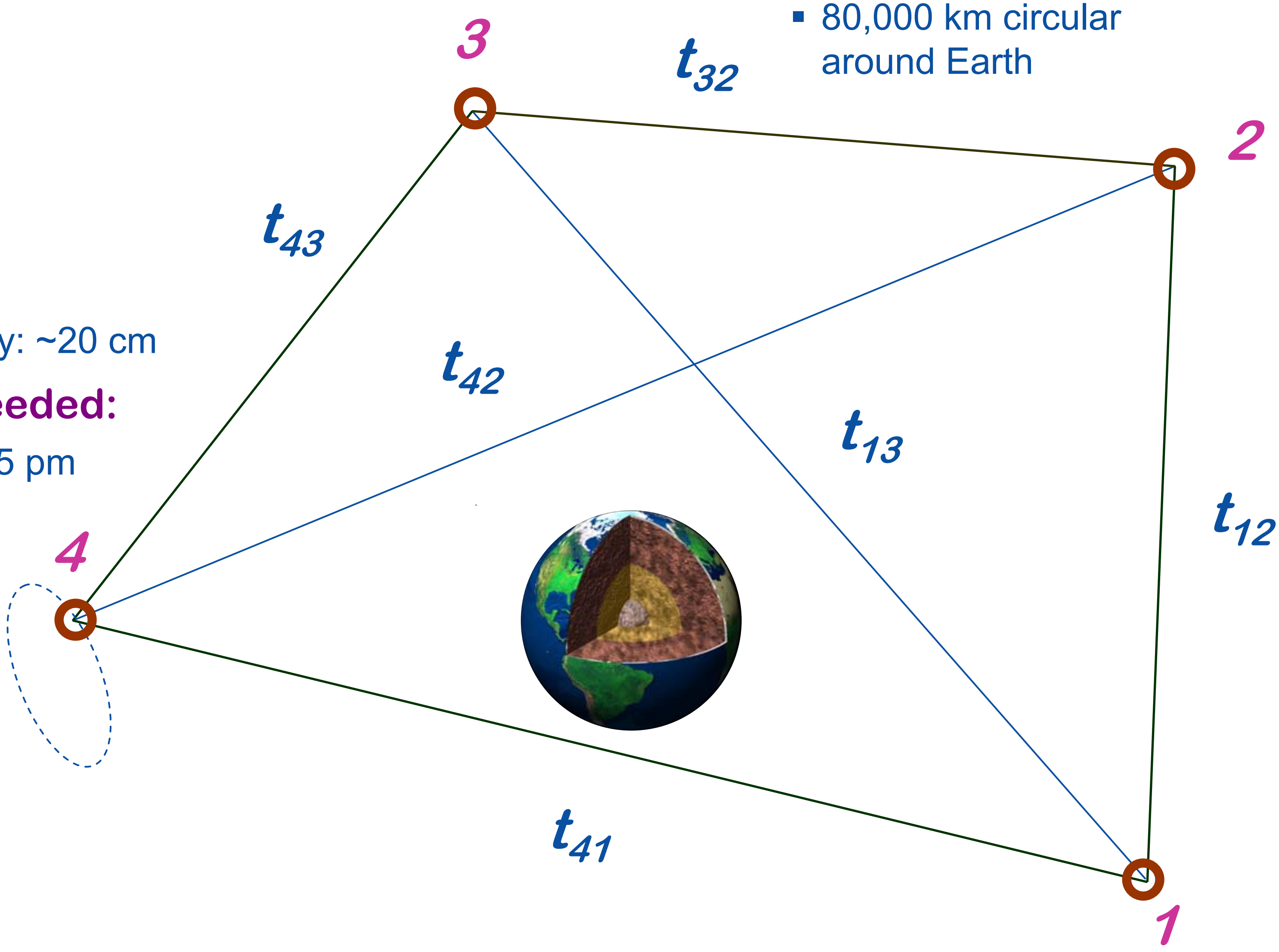
- 6 lengths

Main Effect:

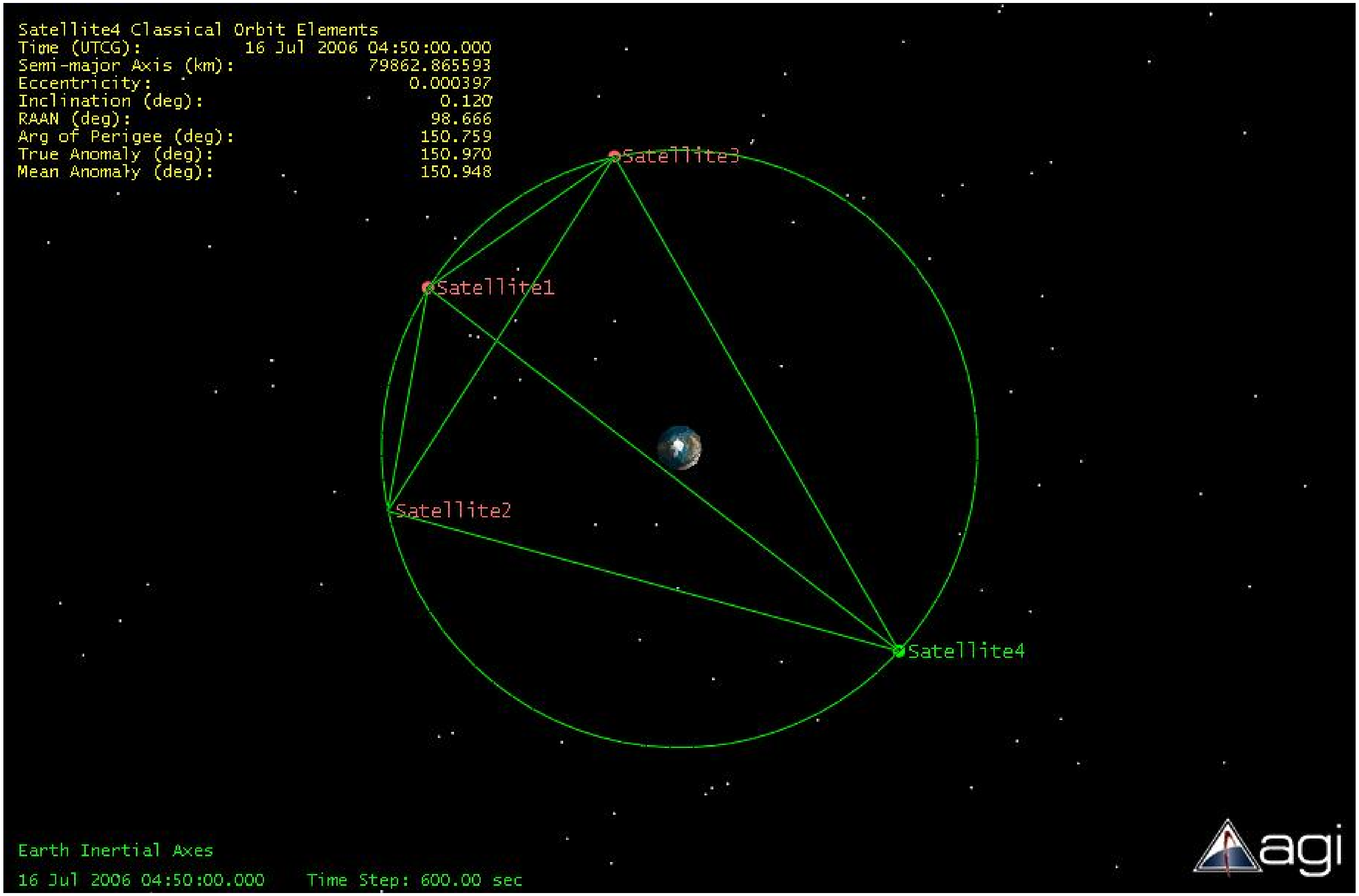
- Shapiro delay: ~20 cm

Accuracy needed:

- Distance: ~ 5 pm



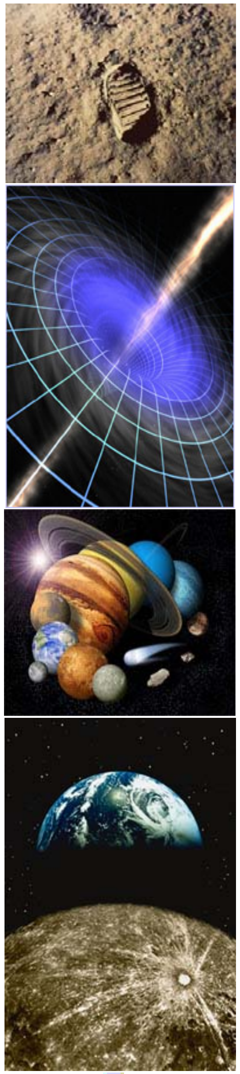
LATOR - II



```
Satellite4 Classical Orbit Elements
Time (UTCG):            16 Jul 2006 04:50:00.000
Semi-major Axis (km):                79862.865593
Eccentricity:                            0.000397
Inclination (deg):                          0.120
RAAN (deg):                                98.666
Arg of Perigee (deg):                     150.759
True Anomaly (deg):                       150.970
Mean Anomaly (deg):                       150.948
```

```
Earth Inertial Axes
16 Jul 2006 04:50:00.000     Time Step: 600.00 sec
```

Michelson-Morley Experiment of the 21st Century



Optical vs. Microwave:

- Solar plasma effects decrease as λ^2: from 10cm (3GHz) to 1 μm 300 THz is a 10^{10} reduction in solar plasma optical path fluctuations

Orbit Determination (OD):

- No need for drag-free environment for LATOR spacecraft
- Redundant optical truss – alternative to ultra-precise OD

A Low Cost Experiment:

- Optical apertures ~15-25 cm – sufficient; high SNR ~1700
- Options exist for NO motorized moving parts
- Many technologies exist: laser components and spacecraft
- Possibilities for further improvements: clocks, accelerometers, etc.

Toward Centennial of General Relativity (2015):

- 1919: Light deflection during solar eclipse: $|1-\gamma| \leq 10^{-1}$
- 1980: Viking – Shapiro Time Delay: $|1-\gamma| \leq 2 \times 10^{-3}$
- 2003: Cassini – Doppler [d(Time Delay)/dt]: $|1-\gamma| \leq 2.3 \times 10^{-5}$
- **2016:** LATOR – Astrometric Interferometry: $|1-\gamma| \rightarrow$ **10^{-8}–10^{-9}**

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Take-Away Message:

> *LATOR will lead to robust advances in Fundamental Physics.*
> *LATOR mission is technologically feasible and economically sound.*
> *LATOR experiment is unique and it must be done!*

Thank You!