Laser-Enabled Tests of Gravity:

Recent Advances, Technology Demonstrations, and New Ideas

Slava G. Turyshev, Michael Shao, James G. Williams, Dale H. Boggs
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91009 USA

Thomas W. Murphy, Jr.
University of California, San Diego,
9500 Gilman Dr., La Jolla, CA 92093USA

Kenneth L. Nordtvedt, Jr.
Northwest Analysis, 118 Sourdough Ridge Rd.
Bozeman MT 59715 USA

International Workshop on
"Advances in Precision Tests and Experimental Gravitation in Space"
Galileo Galilei Institute
Arcetri, Firenze (Italy), September 25-27, 2006

Deep Space Network

Navigation Tracking Requirements (2006)

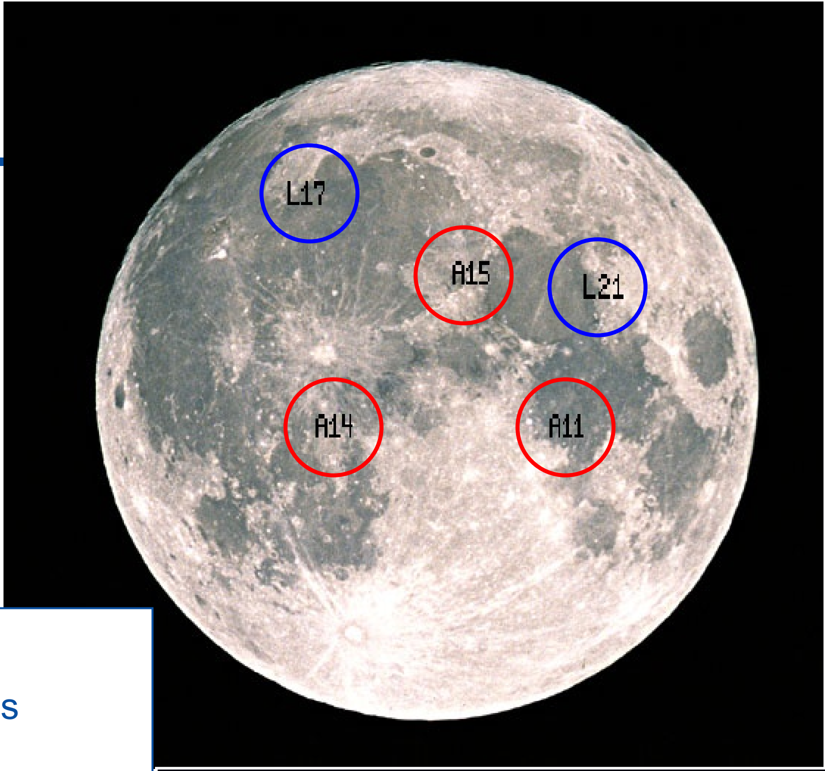
*Based on the current (2006) set of anticipated missions

Tracking Error Source (1σ Accuracy)	Units	current capability	2010 reqt*	2020 reqt*	2030 reqt*
Doppler/random (60s)	μm/s	30	30	30	20
Doppler/systematic (60s)	μm/s	1	3	3	2
Range/random	m	0.3	0.5	0.3	0.1
Range/systematic	m	1.1	2	2	1
Angles	deg	0.01	0.04	0.04	0.04
ΔVLBI	nrad	2.5	2	1	0.5
Troposphere zenith delay	cm	0.8	0.5	0.5	0.3
Ionosphere	TECU	5	5	3	2
Earth orientation (real-time)	cm	7	5	3	2
Earth orientation (after update)	cm	5	3	2	0.5
Station locations (geocentric)	cm	3	2	2	1
Quasar coordinates	nrad	1	1	1	0.5
Mars ephemeris	nrad	2	3	2	1

Interplanetary laser ranging is a very natural step to improve the accuracy

Lunar Laser Ranging

It is all begun 37 year ago…



Laser Ranges between observatories on the Earth and retroreflectors on the Moon started by Apollo in 1969 and continue to the present

- 4 reflectors are ranged:
  - Apollo 11, 14 & 15 sites
  - Lunakhod 2 Rover

- LLR conducted primarily from 3 observatories:
  - McDonald (Texas, USA)
  - OCA (Grasse, France)
  - Haleakala (Hawaii, USA)

- New LLR stations:
  - Apache Point, (NM, USA)
  - Matera (Matera, Italy)
  - South Africa, former OCA LLR equipment

Excellent Legacy of the Apollo Program

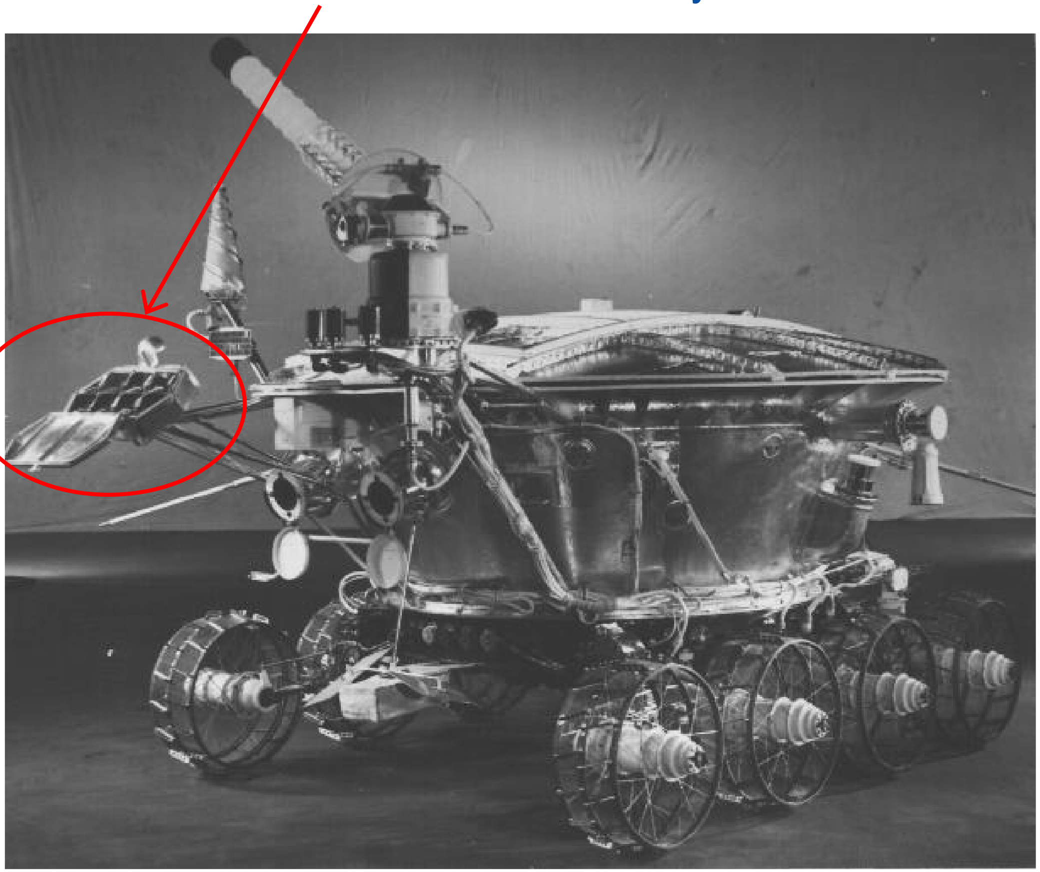
The Apollo 11 retroreflector initiated a shift from analyzing lunar position angles to ranges.
Today LLR is the **only** continuing experiment since the Apollo-Era


Edwin E. Aldrin, Apollo 11


Apollo 11


Apollo 14

Lunar Retroreflectors

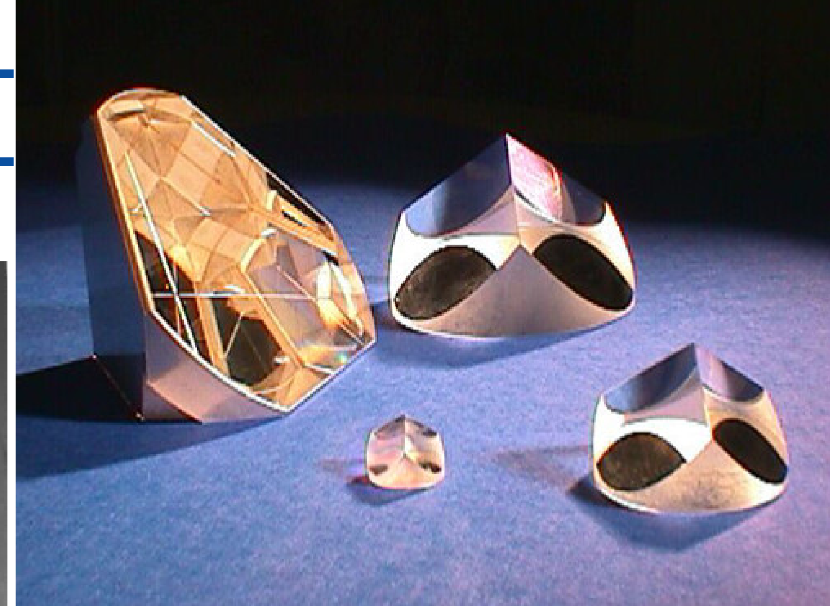


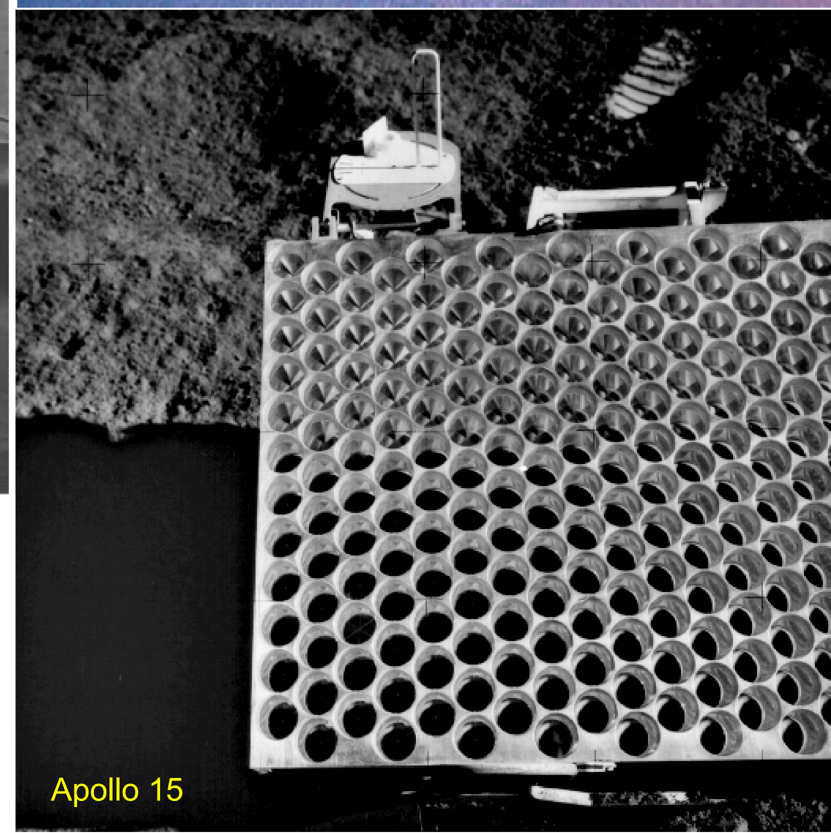
Lunokhod Rover (USSR, 1972)

Beginning of the laser ranging technology.

Today, laser ranging has many applications:

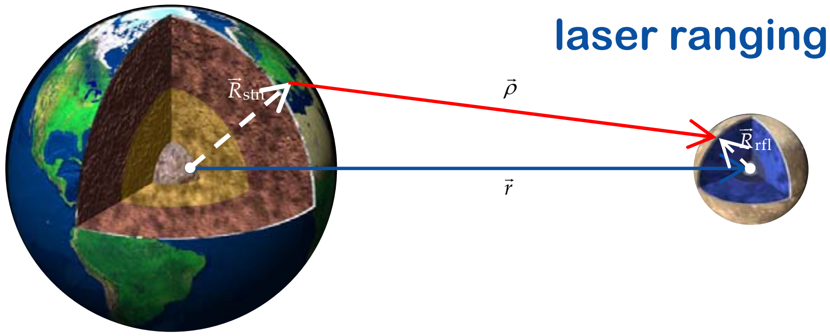
- Satellite laser ranging, communication systems, metrology, 3-D scanning, altimetry, etc.





Historical Accuracy of LLR

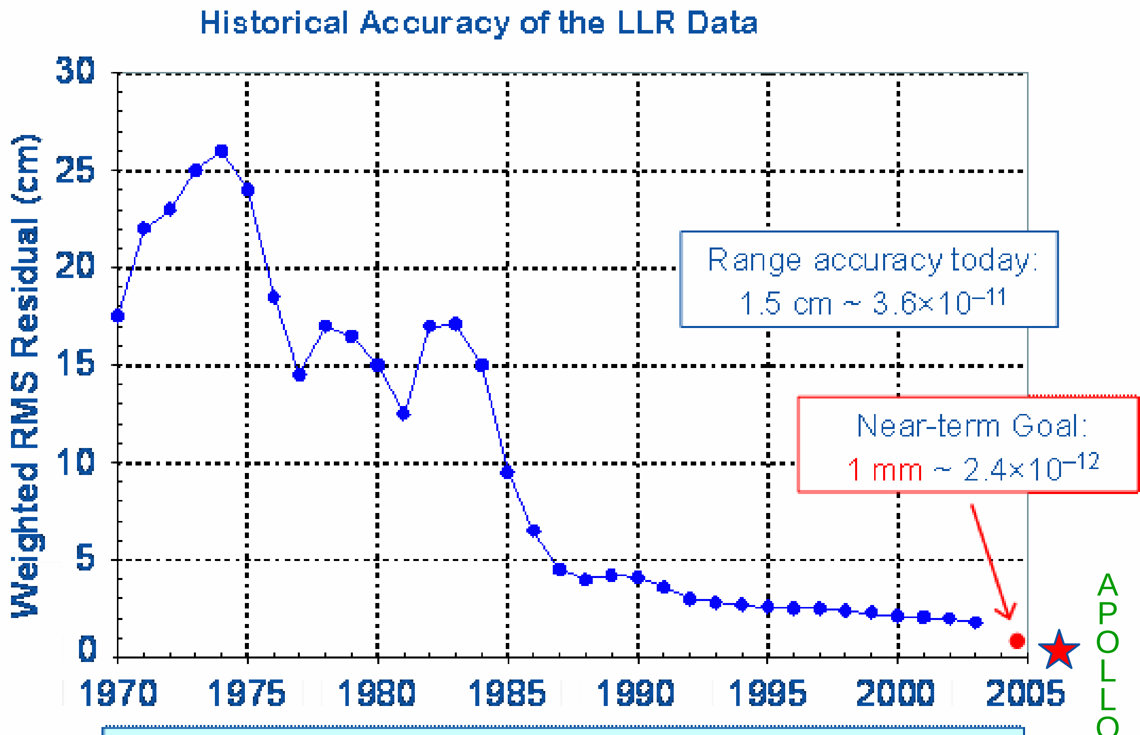
Schematics of the lunar laser ranging experiment



- Raw ranges vary by ~1,000s km
- Present range accuracy ~1.5cm

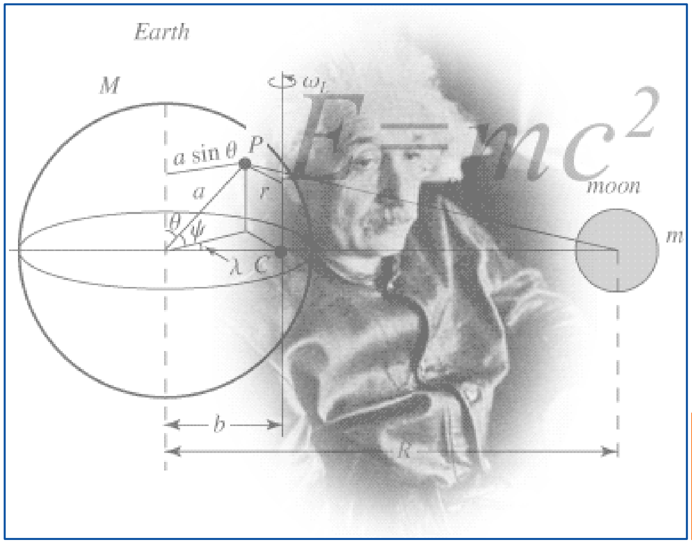
Solution parameters include:

- Dissipation: tidal and solid / fluid core mantle boundary (CMB);
- Dissipation related coefficients for rotation & orientation terms;
- Love numbers k_2, h_2, l_2;
- Correction to tilt of equator to the ecliptic – approximates influence of CMB flattening;
- Number of relativity parameters.



LLR contributes significantly to astrometry, geodesy, geophysics, lunar planetology, and gravitational physics

Testing General Relativity with LLR



The EEP violation effect in PPN formalism:

$$\frac{\Delta a}{a} \equiv \frac{2(a_1 - a_2)}{(a_1 + a_2)} = \left(\frac{M_G}{M_I}\right)_1 - \left(\frac{M_G}{M_I}\right)_2, \qquad \frac{M_G}{M_I} = 1 + (4\beta - \gamma - 3)\frac{U}{Mc^2}$$

$$\frac{\Delta a}{a} = \eta \cdot \left(\frac{U_e}{M_e c^2} - \frac{U_m}{M_m c^2}\right) = -\eta \cdot 4.45 \times 10^{-10}, \qquad \eta \equiv 4\beta - \gamma - 3.$$

If η =1, this would produce a 13 m displacement of lunar orbit. By 2006, range accuracy is ~1.5 cm, the effect was not seen.

Recent LLR results (September 2006):

16,250 normal points through Jan 11, 2006, including 3 days of APOLLO data (2005)

$$\Delta\left(\frac{M_G}{M_I}\right) = (-0.8 \pm 1.3) \times 10^{-13}$$ – corrected for solar radiation pressure.

$$\frac{\Delta a}{a} = (-1.8 \pm 1.9) \times 10^{-13}$$ – Strong Equivalence Principle $\eta = 4\beta - \gamma - 3 = (4.0 \pm 4.3) \times 10^{-4}$

Using Cassini '03 result $\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5} \Rightarrow \beta - 1 = (1.0 \pm 1.1) \times 10^{-4}$

$$\dot{G}/G = (6 \pm 7) \times 10^{-13} \ \mathrm{yr}^{-1}$$

Geodetic precession $K_{gp} = -0.0005 \pm 0.0047$

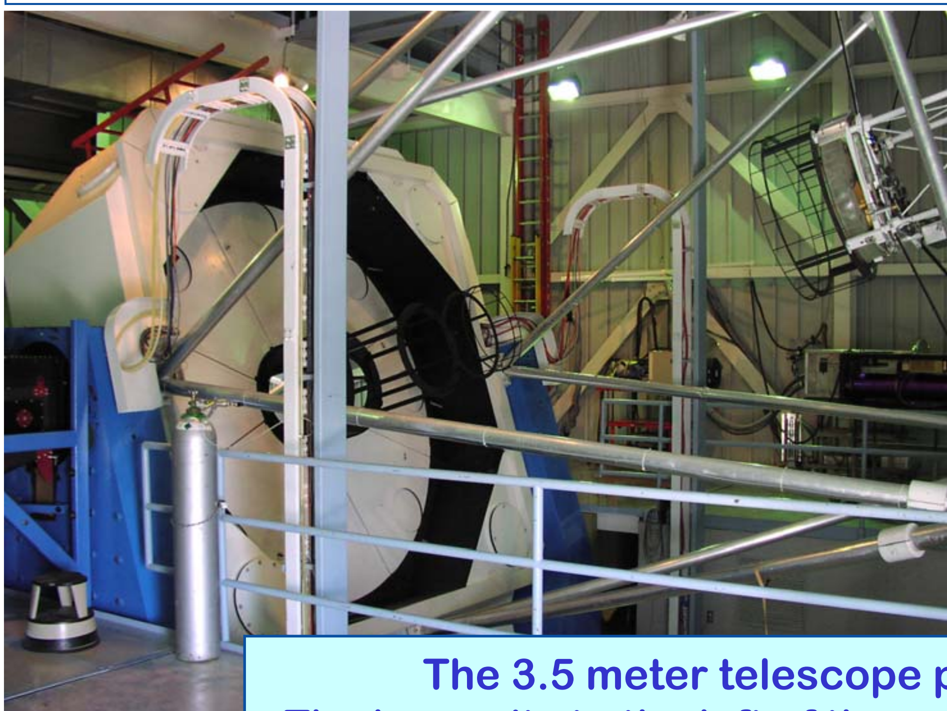
$1/r^2$ force law: 10^{-10} times force of gravity; Gravitomagnetism (frame-dragging): 0.1%

The APOLLO Project & Apparatus:

Apache Point Observatory Lunar Laser-ranging Operation

- Move LLR back to a large-aperture telescope
  - 3.5-meter: more photons!
- Incorporate modern technology
  - Detectors, precision timing, laser
- Re-couple data collection to analysis/science
  - Scientific enthusiasm drives progress

- Uses 3.5-meter telescope at 9200-ft Apache Point, NM
- Excellent atmospheric “seeing”: 1as
- 532 nm Nd:YAG, 100 ps, 115 mJ/pulse, 20 Hz laser
- Integrated avalanche photodiode (APD) arrays
- Multi-photon & daylight/full-moon



The 3.5 meter telescope prior to laser installation.
The laser sits to the left of the red ladder attached to the scope.

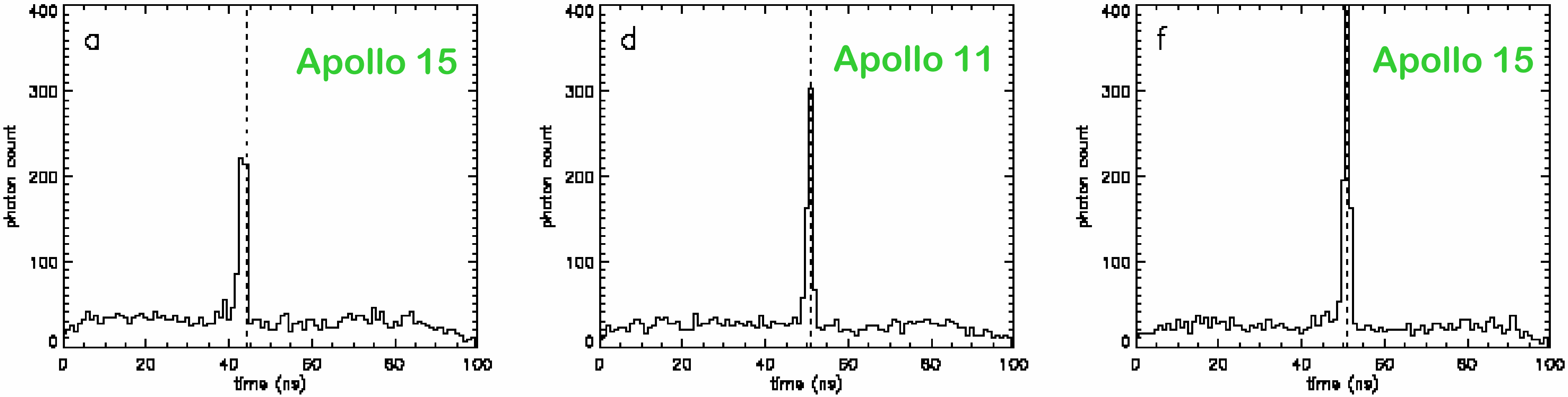
Laser Mounted on Telescope

First Light: July 24, 2005

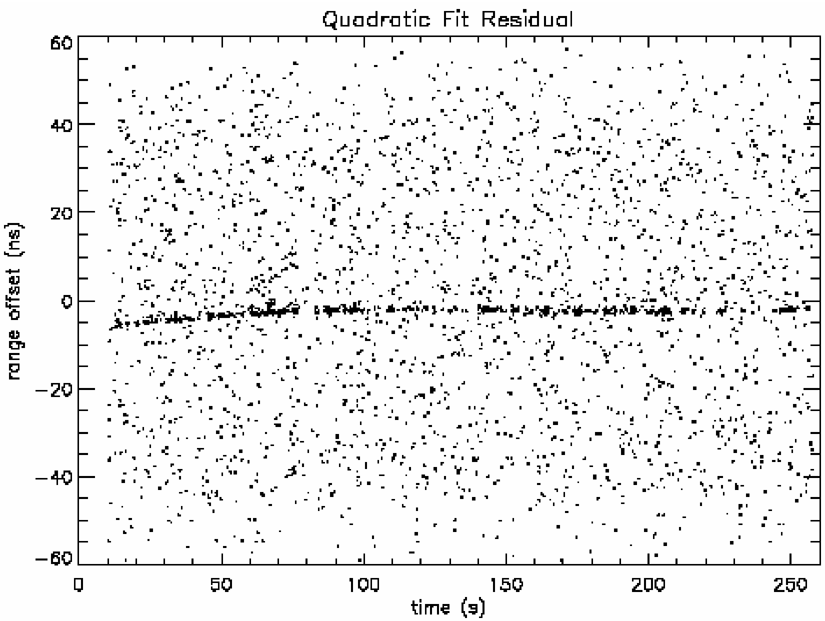
First Light: July 24, 2005

Blasting the Moon

First Lunar Returns: October 19, 2005



30 min: 5 consecutive 5 min runs – 2,400 protons; MLRS got as many for 2000-2002.
APOLLO can operate in full-moon; no other LLR station can do that.

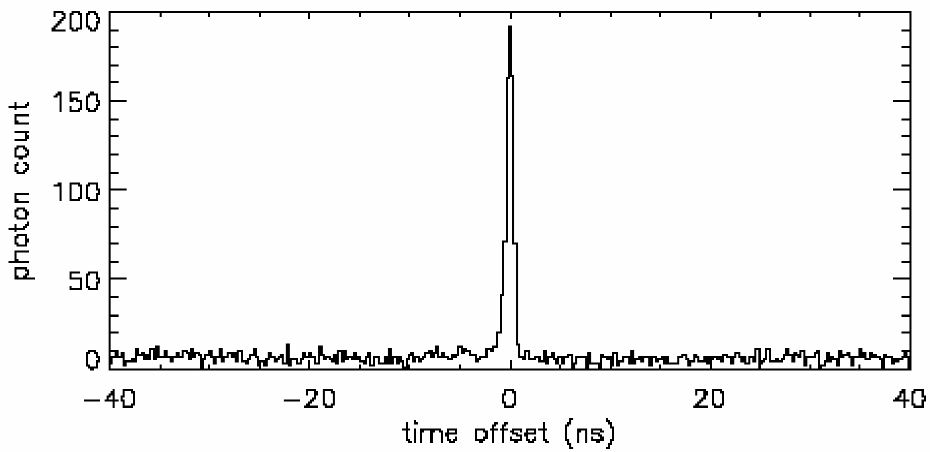


Error Source	Round-Trip Time Uncertainty, [ps]	One-Way Range Error, [mm]
Retro Array Orientation	100–300	15–45
APD Illumination	60	9
APD Intrinsic	<50	< 7
Laser Pulse Width	45	6.5
Timing Electronics	20	3
GPS-slaved Clock	7	1
Total Random Uncert.	136–314	20–47

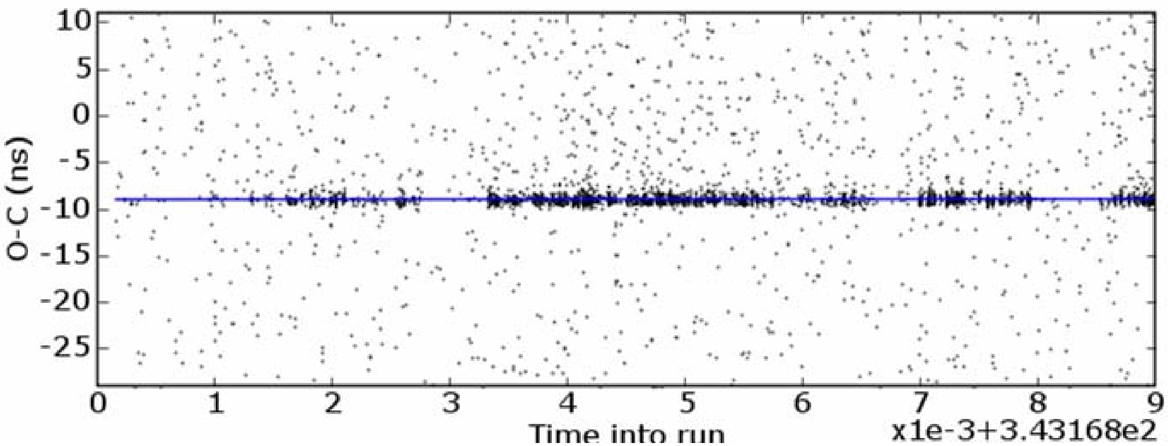
Single-photon random error budget

Good Start for APOLLO

Results of the runs with Apollo 15



Residuals computed with new data



APOLLO Recipe for a mm-range:

- 7 ps round-trip travel time error
- ~0.5 m lunar reflectors at ±7° tilt → up to 35 mm RMS uncertainty per photon
- 95 ps FWHM laser pulse → 6 mm RMS
- Need $\sim 40^2 = 1600$ photons to beat error
- Calculate ~5 ph/pulse return for APOLLO
- "Realistic" 1 photon/pulse → 20 ph/sec → mm statistics on few-minute timescales

- 1,500 photons in 13 min
- 1 mm statistical uncertainty

Interplanetary laser ranging is the next logical step

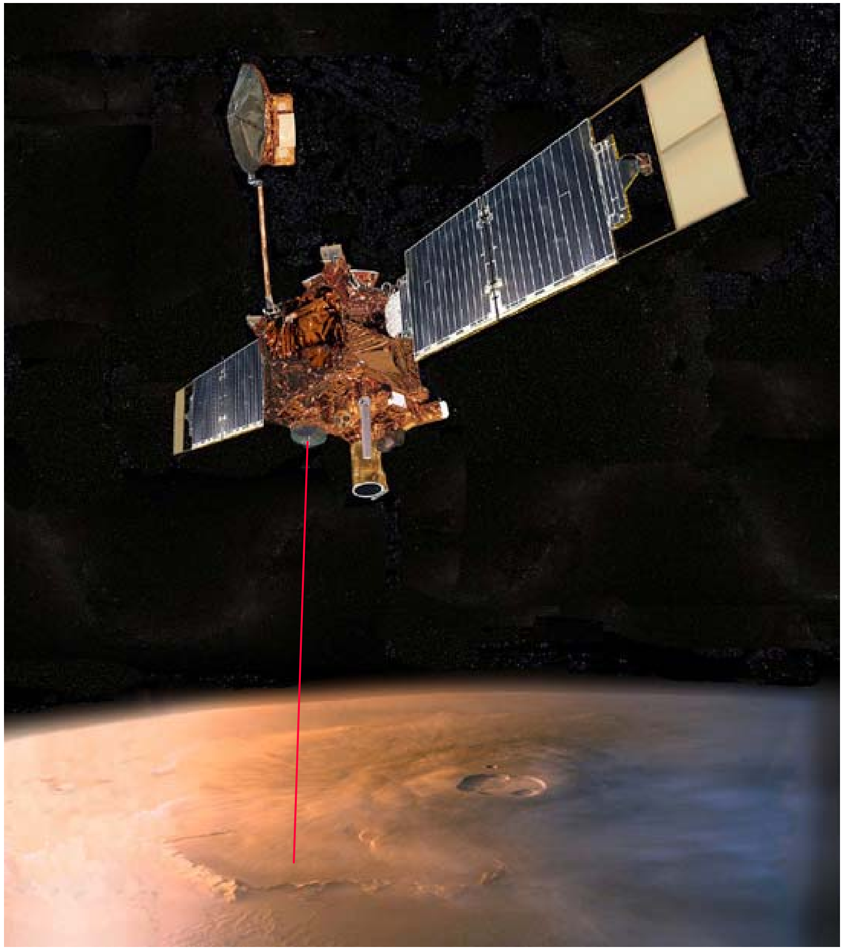
Pulsed Lidar Space Missions: History

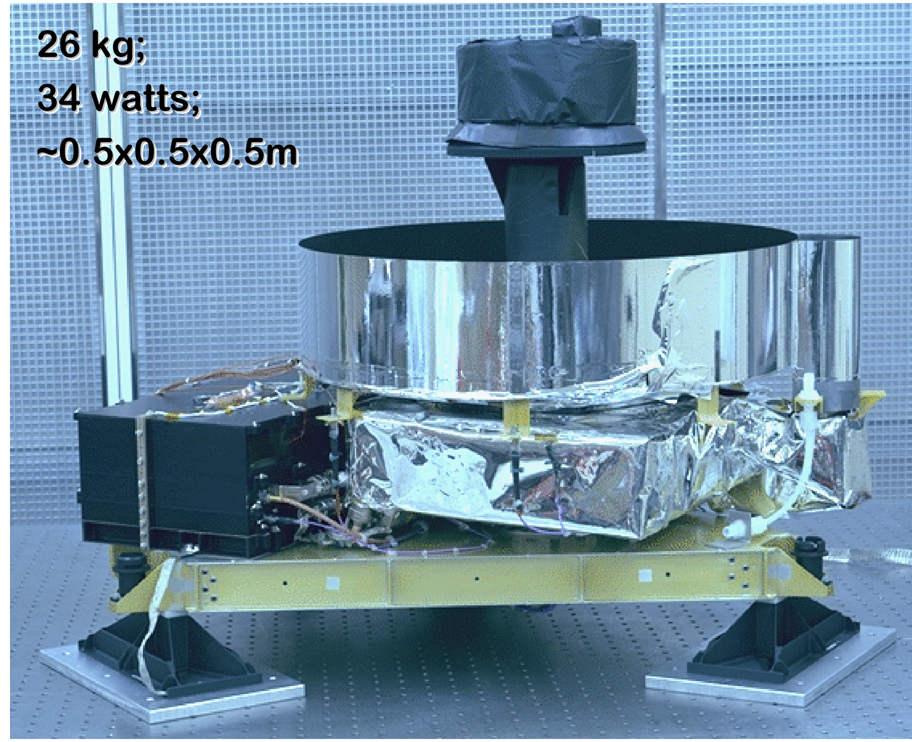
Mission	Launch	Objective	Performance
– Apollo 15, 16, 17	1971-2	Ranging, Moon	Success
– MOLA I	1992	Ranging, Mars	S/C Lost (Contamination)
– Clementine	1994	Ranging, Moon	Success (BDMO/NASA)
– LITE	1994	Profiling, Shuttle	Success (Energy Decline by 30%)
– *Balkan*	*1995*	*Profiling*	*Success (Russia)*
– NEAR	1996	Ranging	Success
– SLA-01	1996	Ranging, Shuttle	Success
– MOLA II / MGS	1996	Ranging, Altimeter	Success (Bar dropouts)
– SLA-02	1997	Ranging, Shuttle	Success
– MPL/DS2	1999	Ranging	S/C Lost
– VCL	2000	Ranging	Cancelled
– SPARCLE/EO-2	2001	Profiling, Shuttle	Cancelled
– Icesat/GLAS	2003	Ranging + Profiling	Laser 1, 2, 3 Anomalies
– Messenger/MLA	2004	Profiling, Mercury	Cost/Schedule Slips [Son of GLAS]
– Calipso	2006	Profiling	Launch delayed [Boeing strike]
– *T2L2/Jason 2*	*2007*	*TT, Altimeter, Ranging*	*Healthy program (CNES)*
– *ADM*	*2007*	*Wind Demo.*	*Was 2006 (ESA)*
– LOLA/LRO	2008	Altimeter, Moon	
– MLCD/MTO	2009	Lasercomm	Cancelled
– Mars Smart Lander	2009	Ranging, Mars	
– *BepiColombo*	*2011*	*Altimeter, Ranging*	*Being Decided (ESA)*

* (MOLA I through Calipso)

***Since 1990, NASA, launched & no reported problems, free-flyer: 1/8**

Mars Orbiter Laser Altimeter (MOLA)

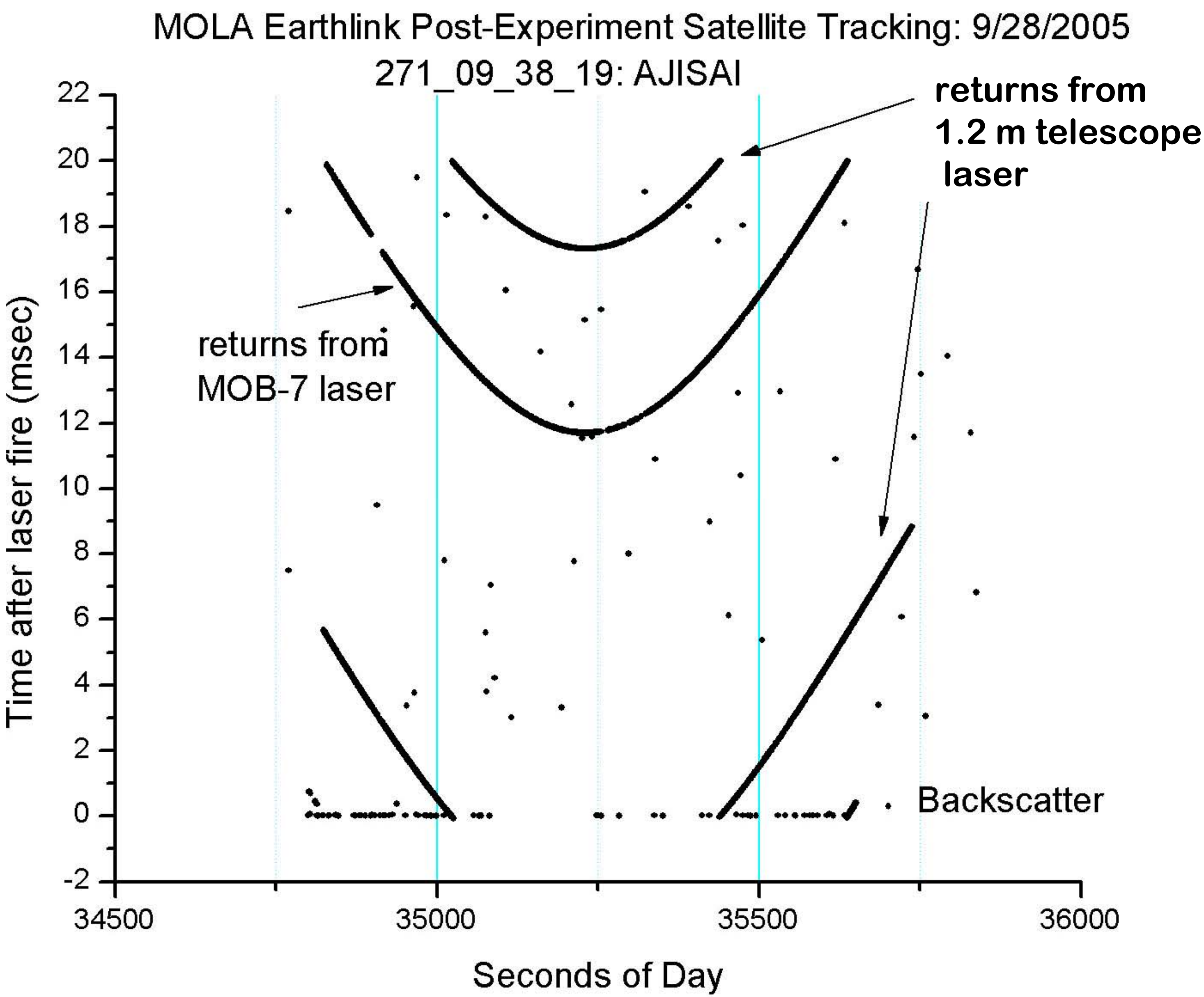




Lunch: Nov. 7, 1996.
Currently in circular orbits around Mars at 400km altitude and 2 hour orbit period.

- One of the science payload instruments on Mars Global Surveyor (MGS)
  - PI: David E. Smith, GSFC;
  - DPI: Maria T. Zuber, MIT
- Receiver field of view: 0.85 mrad
- Minimum detectable signal at telescope: ~ 0.1fJ/pulse at >90% detection probability.

MOLA-Earthlink Experiment



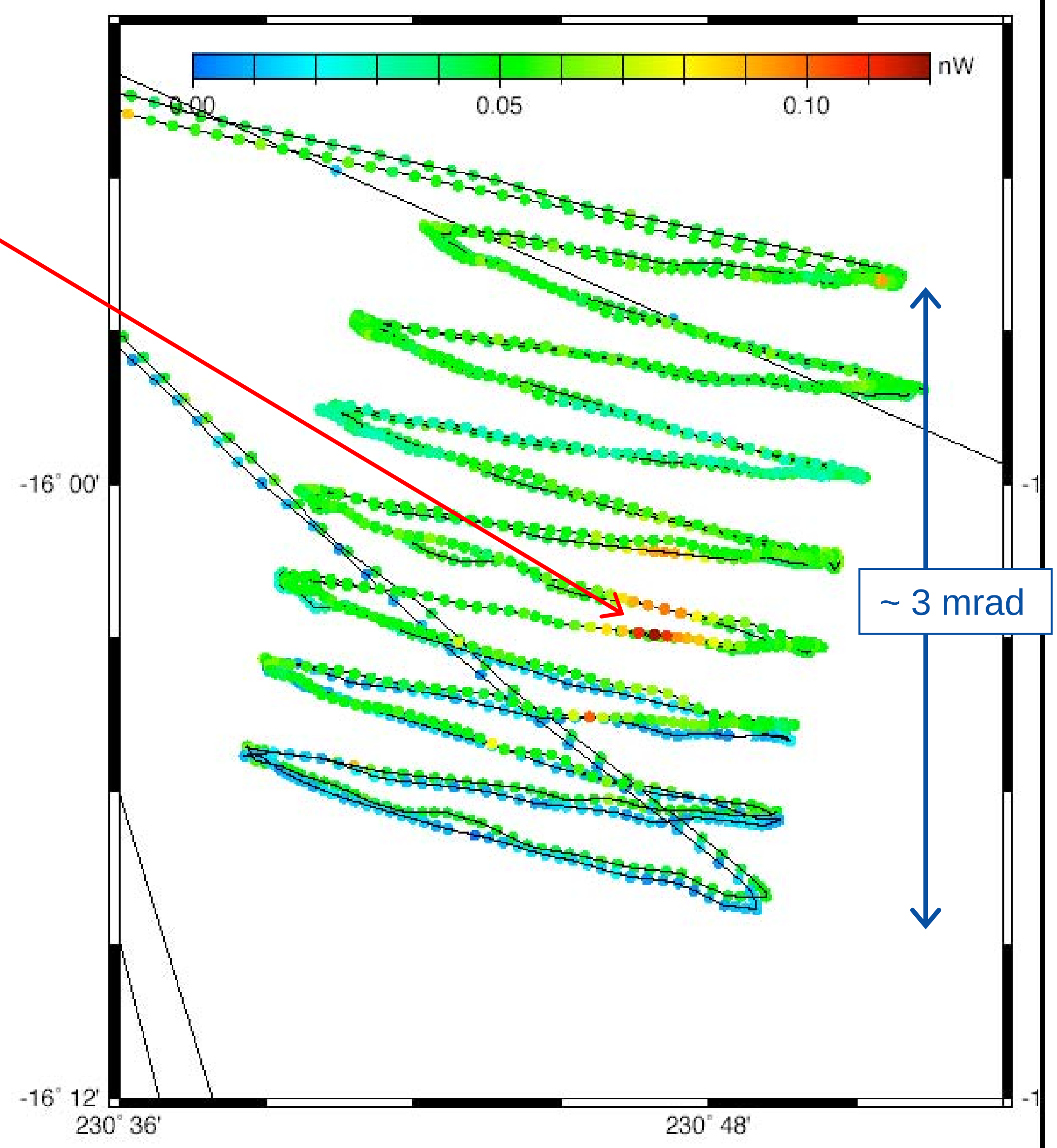
MOLA Earth Scan (2005)

MGS scans about Earth: Earthshine is seen in MOLA receiver ch#2 as red-orange-yellow in plot from 9/21/2005.

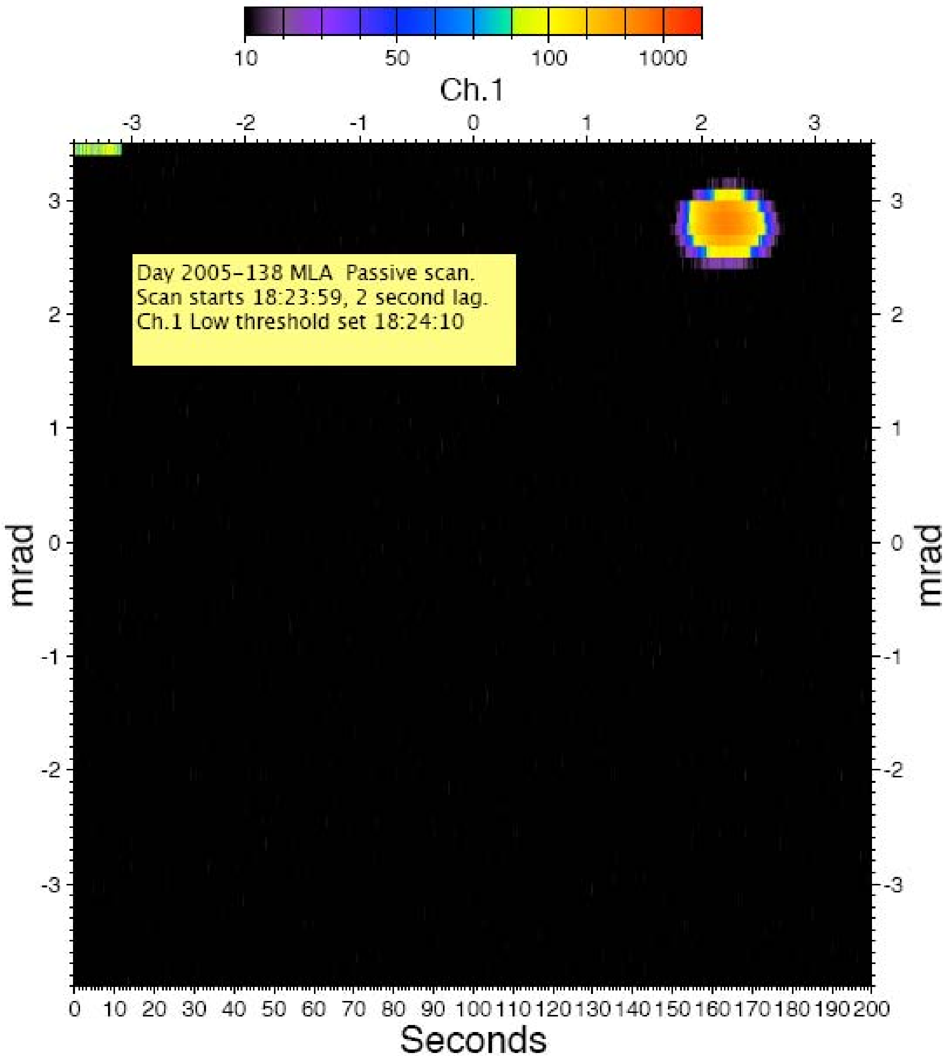
Each day's experiment consisted of two back-to-back scans.

Scans were very repeatable.

- Performed on 3 scheduled dates with spacecraft (9/21, 9/24, 9/28): at ~ 08:00 UTC.
- Each tested lasted ~ 45 min and involved 2 spacecraft scans of Earth.
- Maximum time Earth laser in MOLA FOV per scan line: ~8 sec
- MOLA saw earthshine in channel 2 detector on all 3 dates – very repeatable.



MLA-Earthlink Experiment Results:

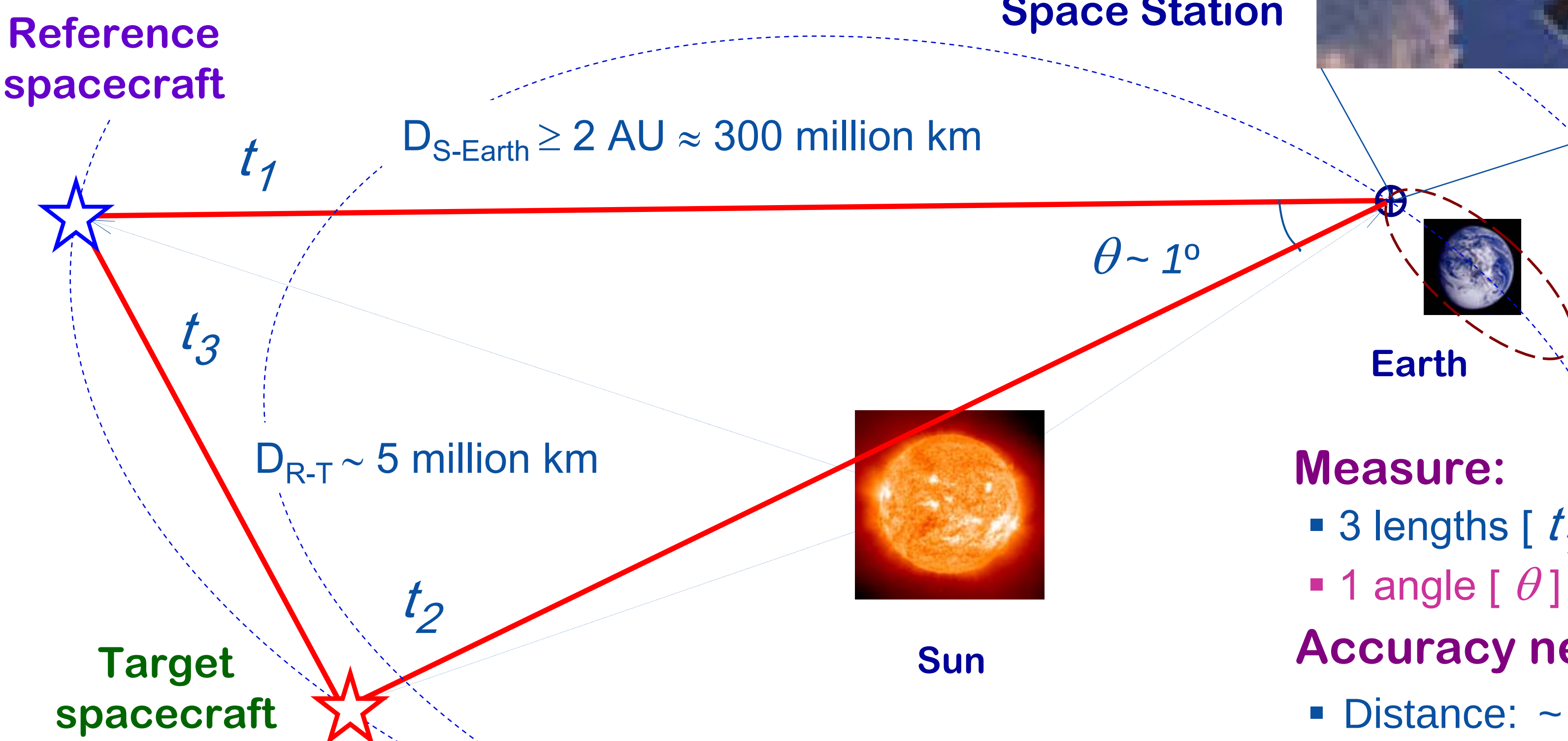


- Performed on 3 scheduled dates with spacecraft in May 2005 (5/26, 5/26, 5/31) at ~ 17:00 UTC
- Each test lasted ~ 5 hours and involved spacecraft scan of Earth over 7 x 7 mrad area.
- Maximum time earth laser in MLA FOV: ~ 5 seconds.
- Passive radiometry scan of earth by MESSENGER was performed earlier in the month and verified spacecraft pointing.
- MLA laser pulses were detected at the ground. MLA also detected laser pulses from ground laser.

First successful 2-way lasercomm at interplanetary distances 24 mln km (acc ± 12 cm).

LATOR Mission Concept

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



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:

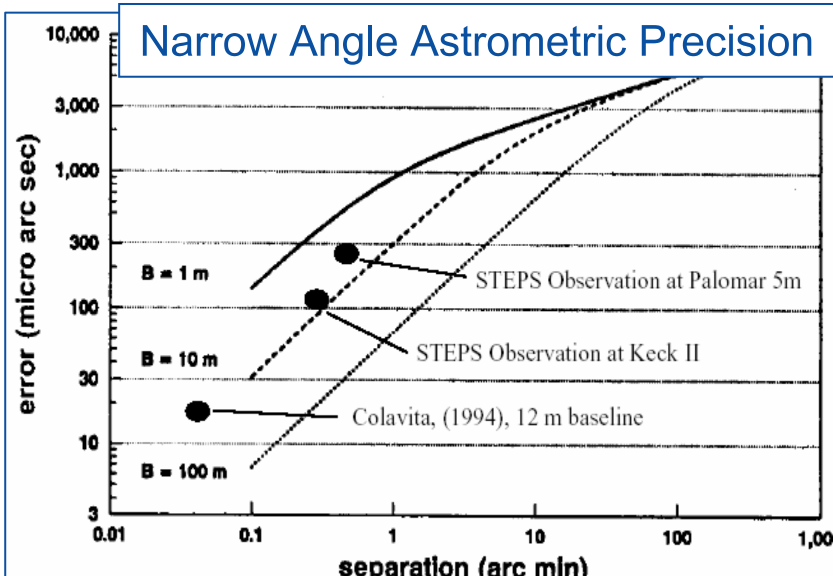
- Ground-based interferometer [B = 30km]
- Limited capabilities due to atmosphere

$(M/R)^2$ 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



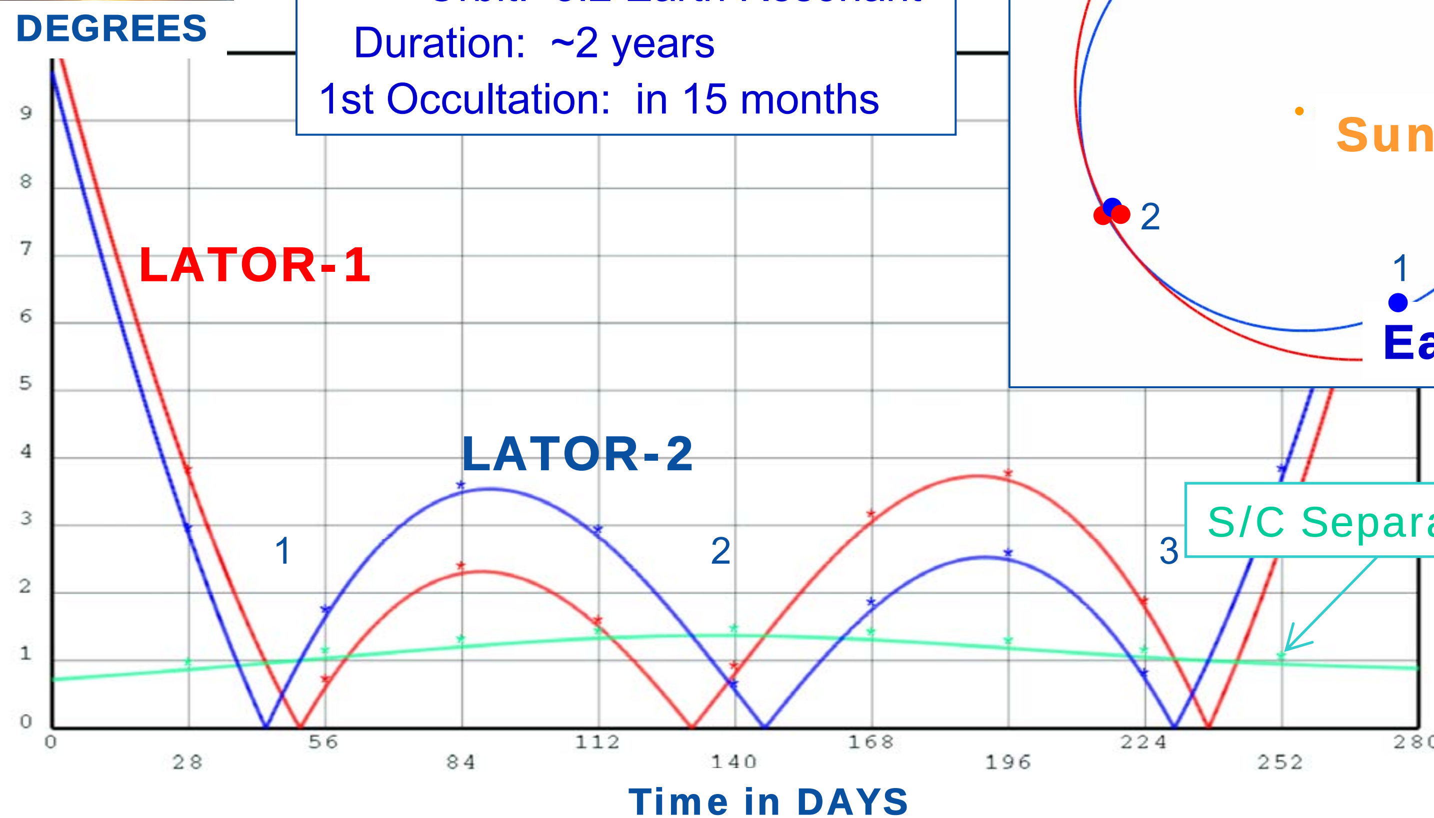
1 hour integration in 0.5 arcsec seeing

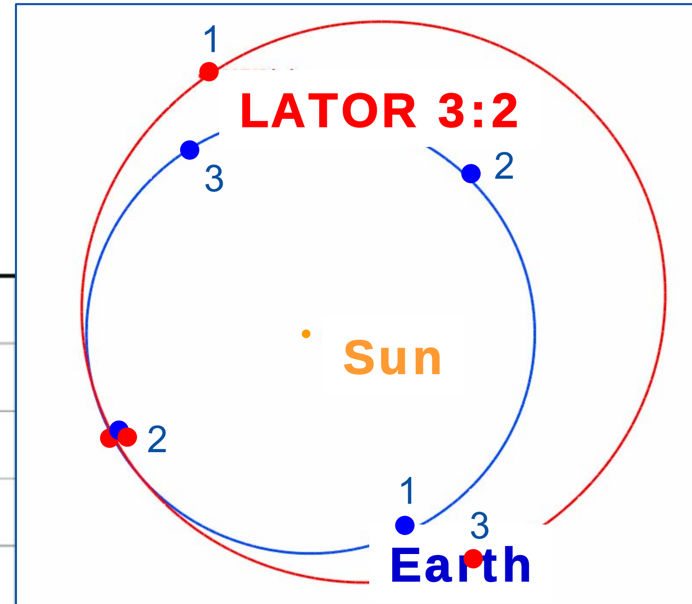
The key technologies are already available – SIM, TPF, Starlight, KI

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



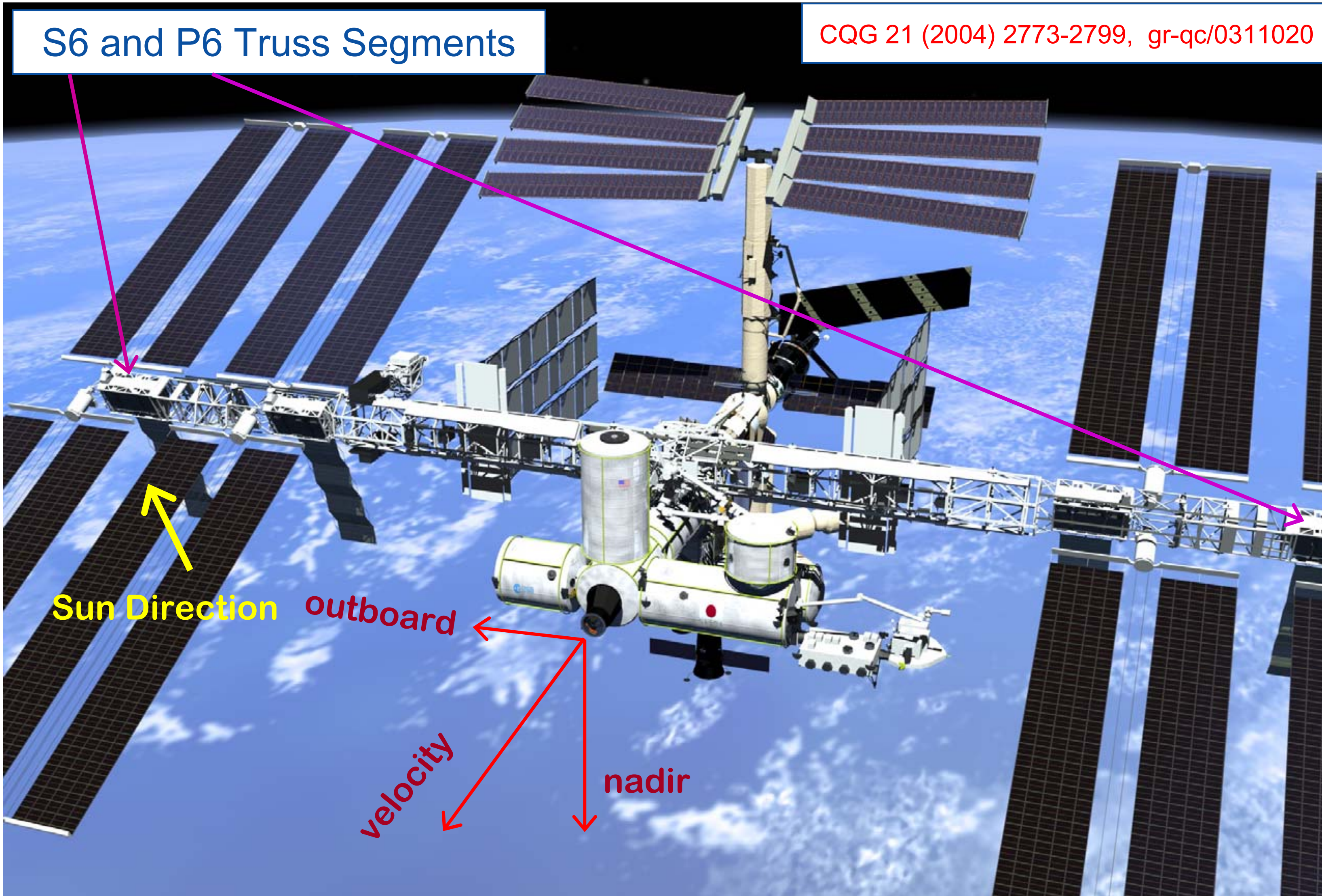


JPL Team X study demonstrates feasibility of LATOR as a MIDEX

LATOR Interferometer on the ISS

S6 and P6 Truss Segments

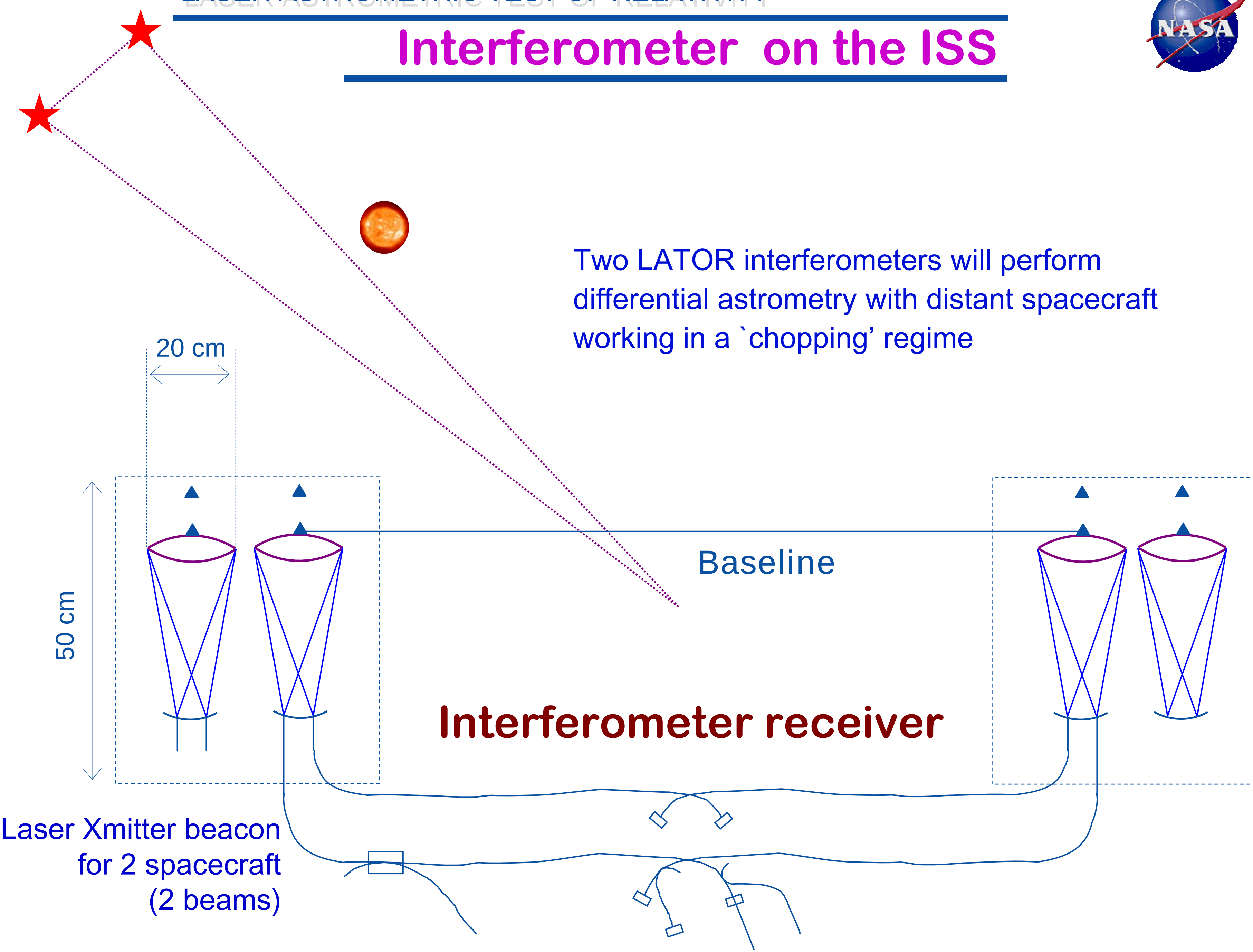
CQG 21 (2004) 2773-2799, gr-qc/0311020



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



Laser Xmitter beacon for 2 spacecraft (2 beams)

SIM Technology Components/Systems

Component Technology | Subsystem-Level Testbeds | System-Level

Picometer **Knowledge** Technology

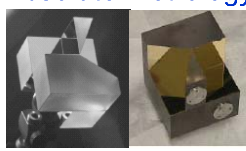
1999

Metrology Source

2001

Absolute Metrology

1999



Multi-Facet Fiducials

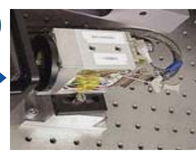
1:Aug2001

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)

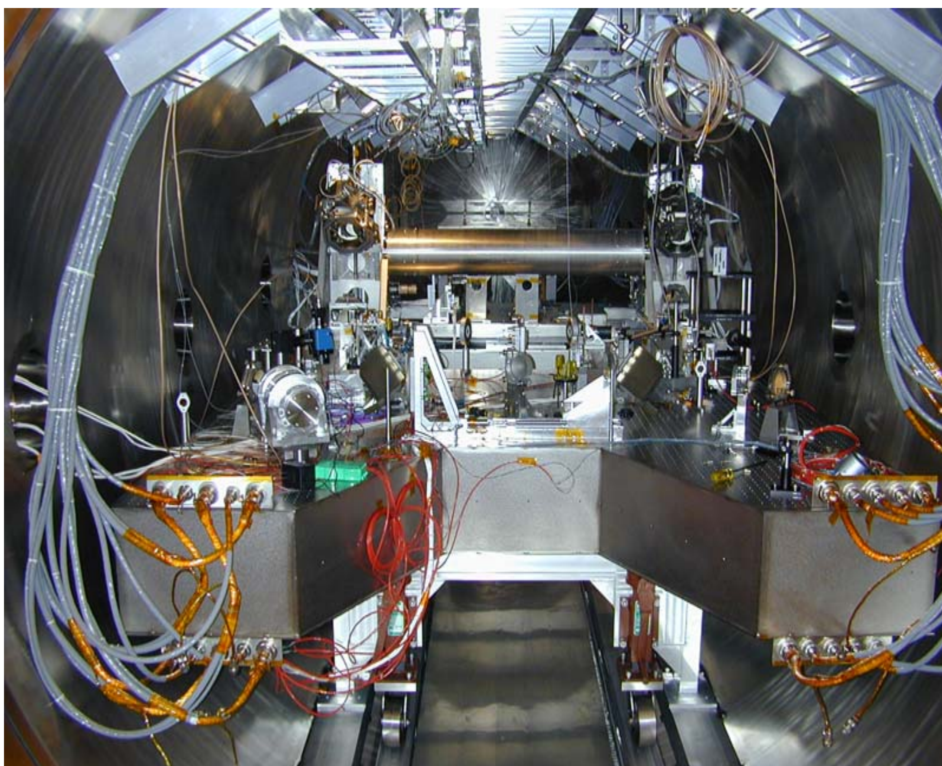
Success of SIM Enables LATOR: MAM Testbed

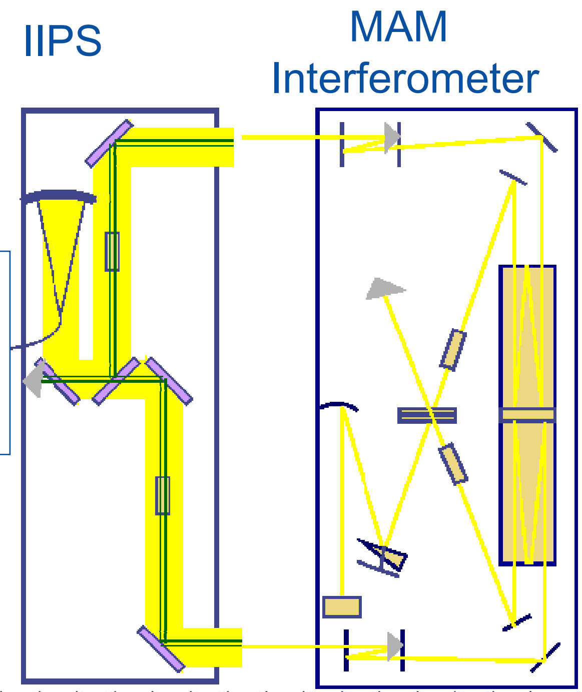
SIM is in Phase B: Aug 2003

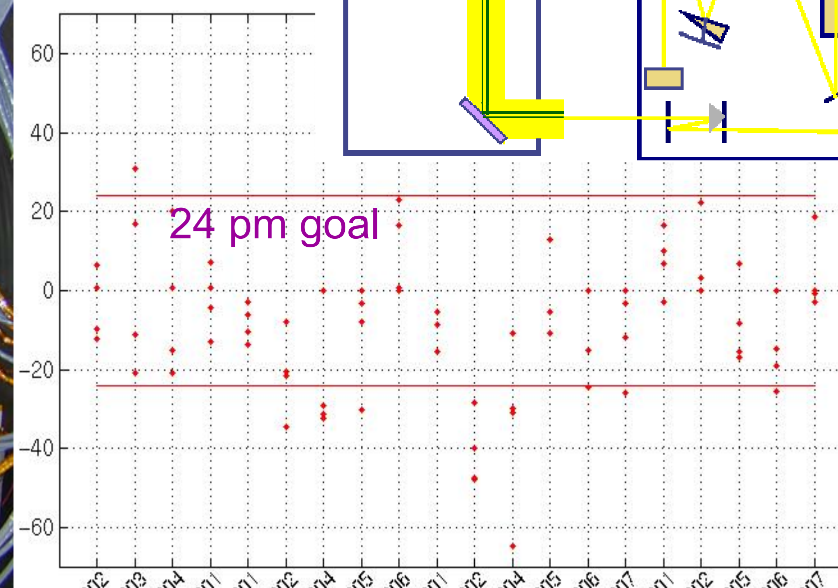
- After passing all 6 NASA technology gates
- Goal for Narrow Angle performance ~24 pm

MAM is a demonstration of SIM's Interferometer Sensor

- Single baseline interferometer test article
- Inverse Interferometer Pseudo-Star (IIPS)



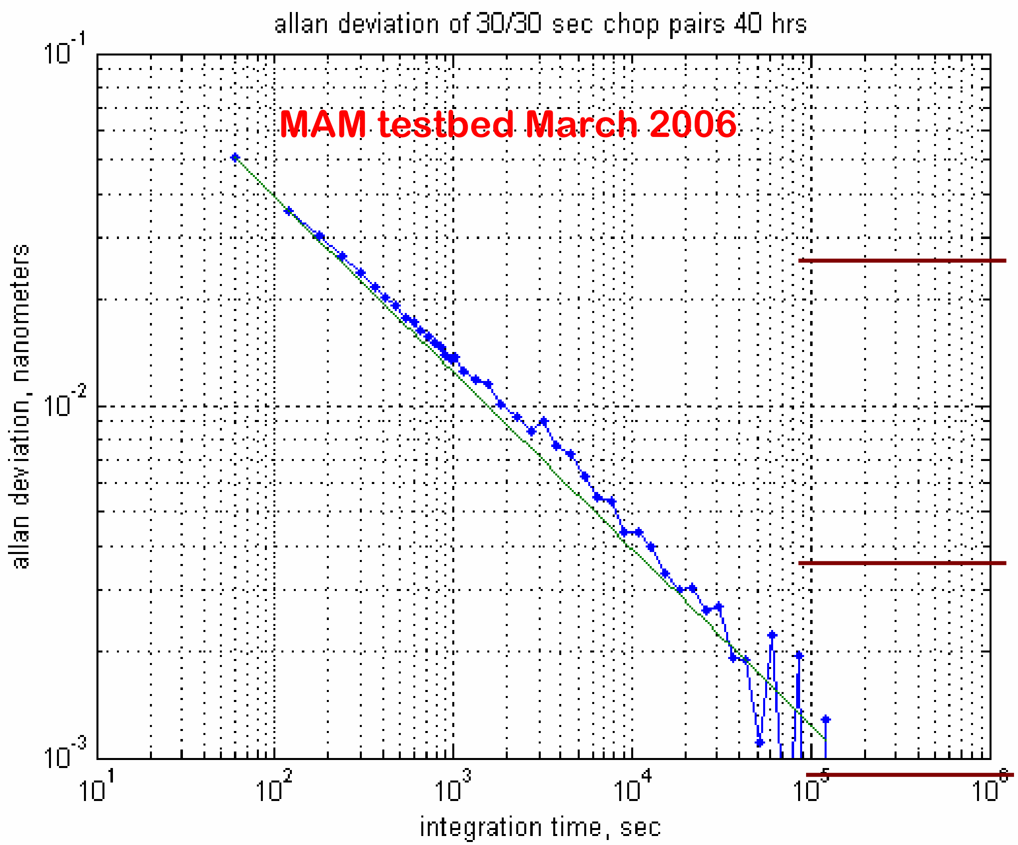




Performance of Microarcsecond testbed:
75.3% of data with uncertainty below 24 pm

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

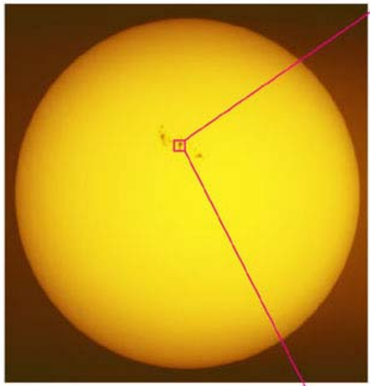


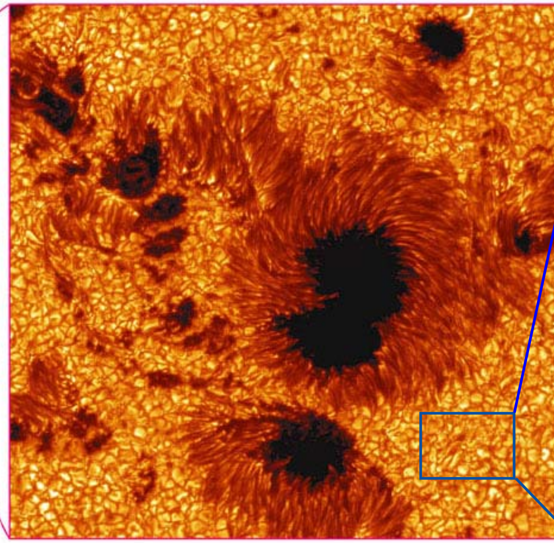
Terrestrial Planet search
Single epoch precision 1 µas

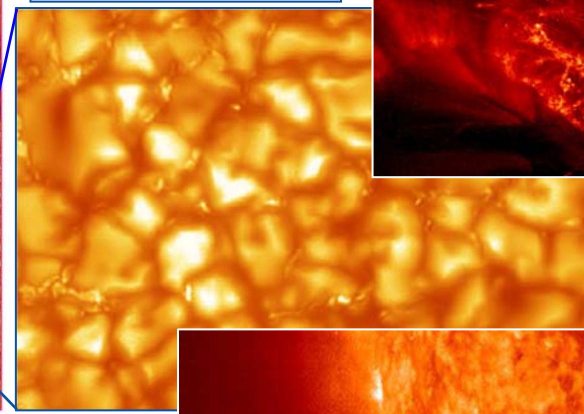
Terrestrial Planet search
5 yr mission precision 0.14 µas

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

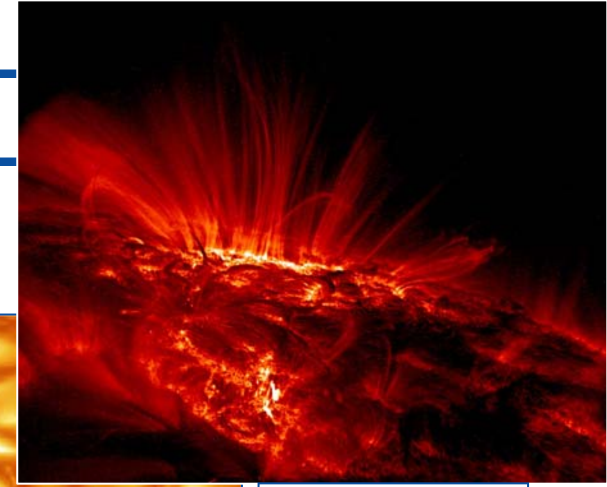
The Solar Boundary



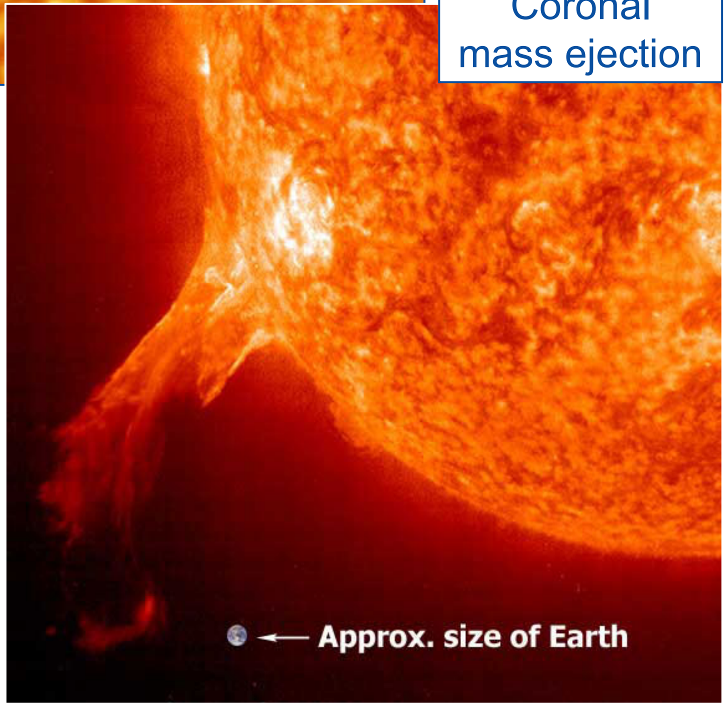




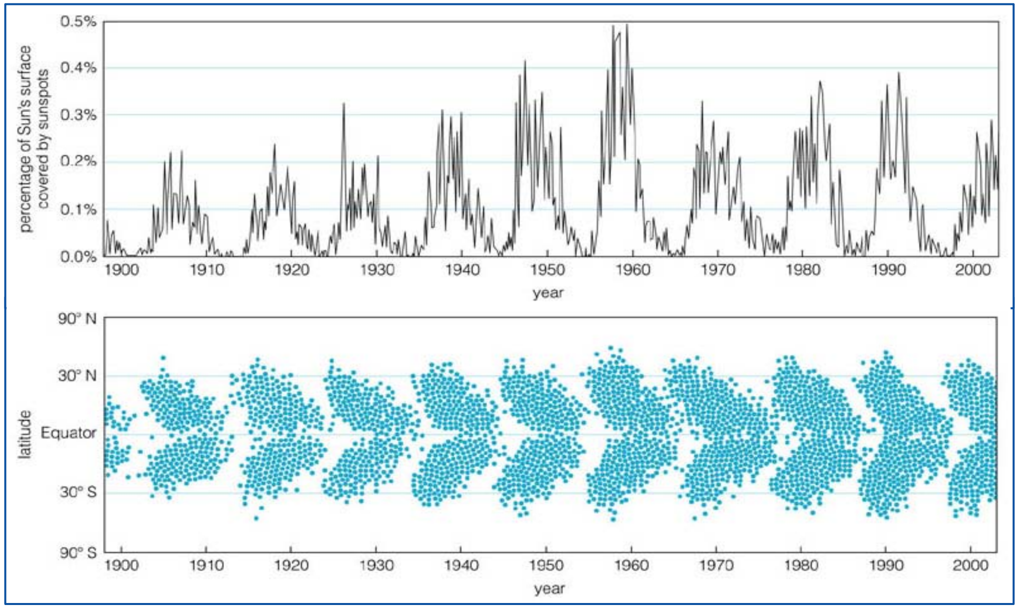
Granulation of solar surface



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)?

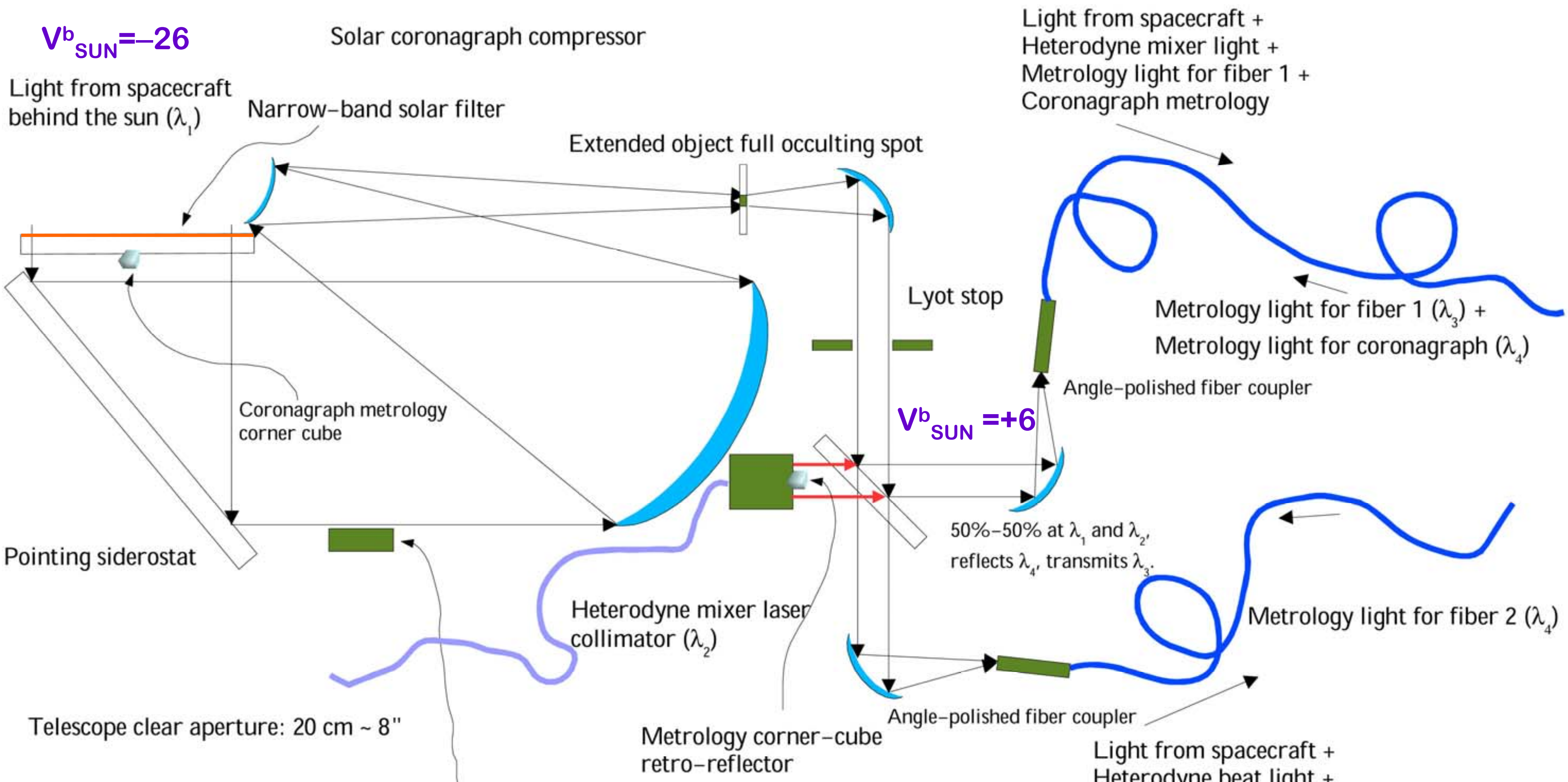
Optical Receivers Looking Next to the Limb of the Sun

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)

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})

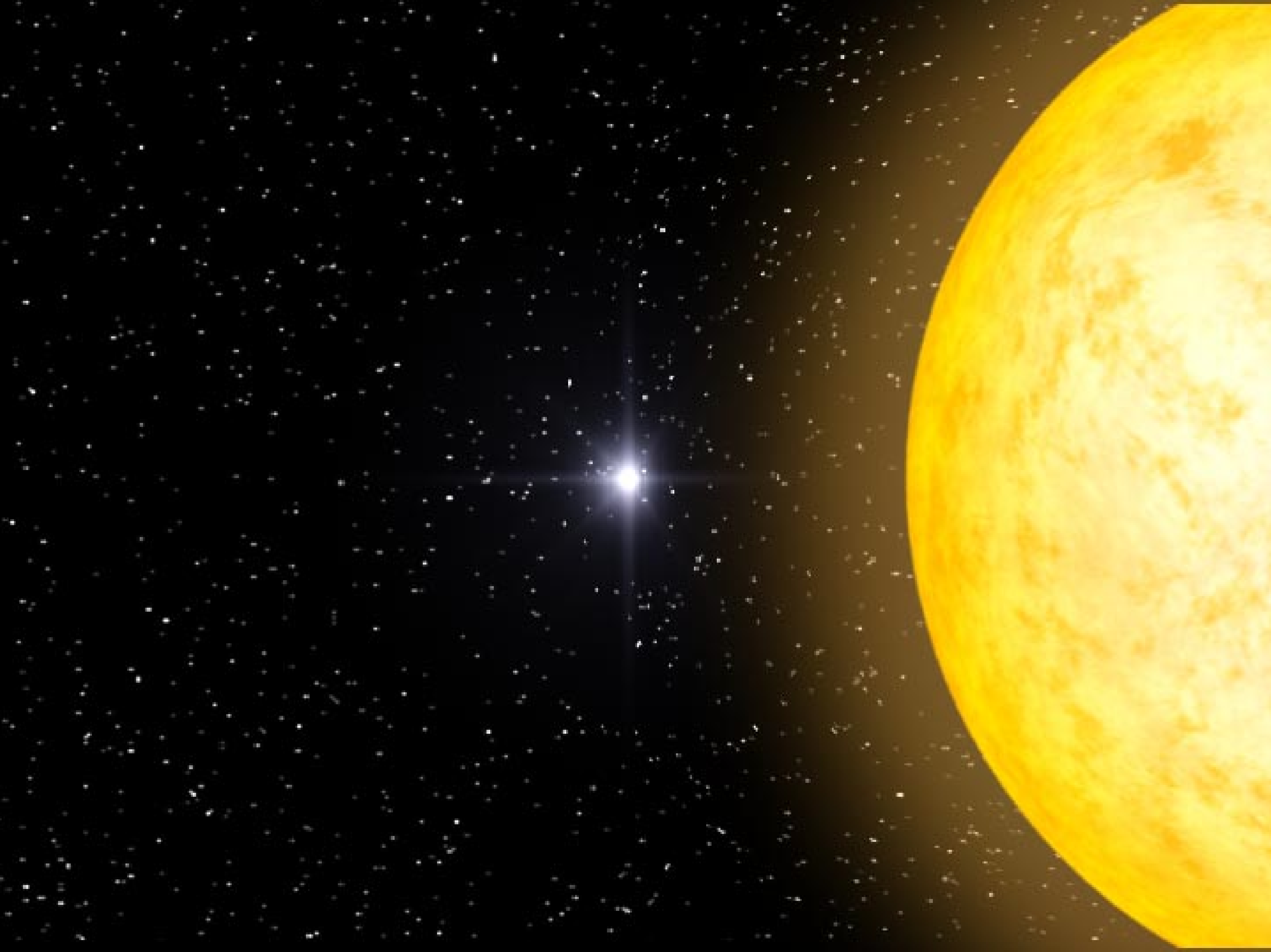
Possible rejection 10^{-17}, only need
10^{-10} ~ 10^{-11} rejection to be photon limited

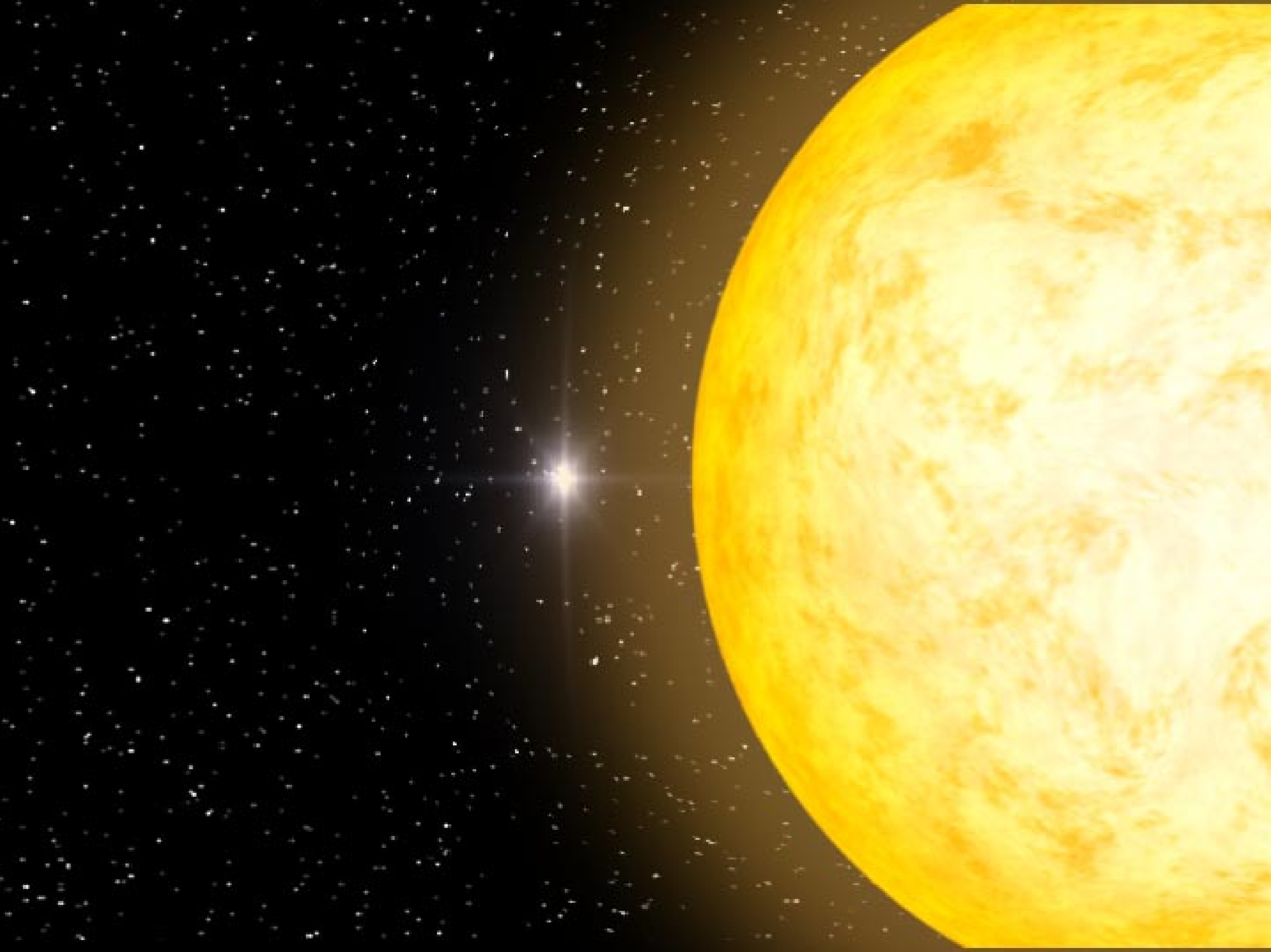
Fiber-Coupled Tracking Interferometer

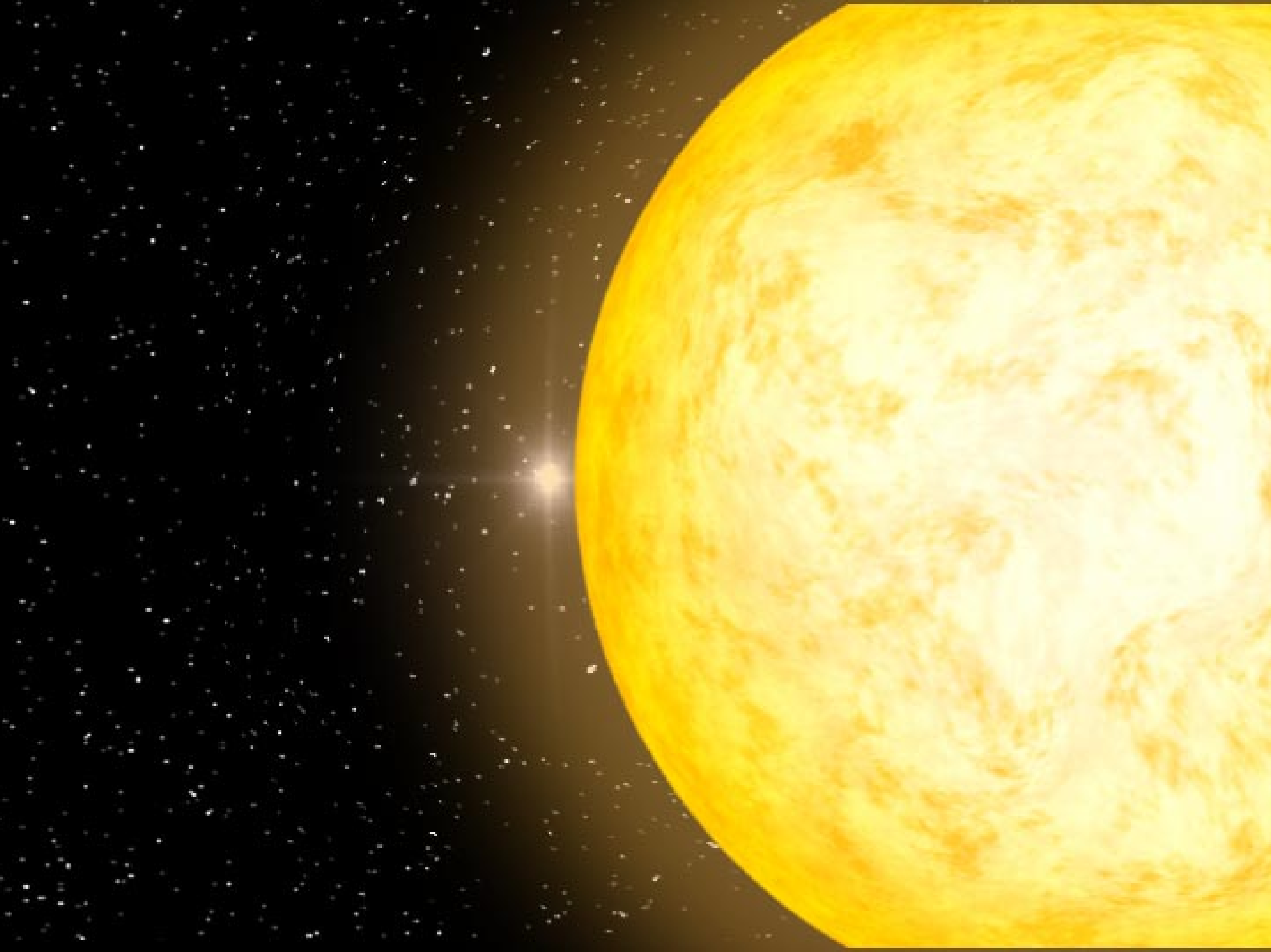


Basic elements:

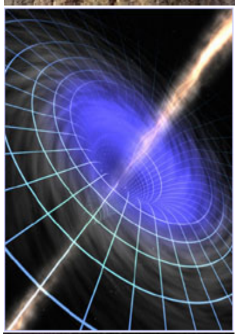
- Full aperture ~20cm narrow band-pass filter; corner cube [baseline metrology];
- Steering flat; off-axis telescope w/ no central obscuration [for metrology];
- Coronagraph; ½ plane focal plane occulter; Lyot stop;
- Fibers for each target (1 on S/C and 2 on the ISS).

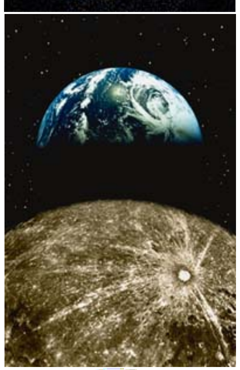


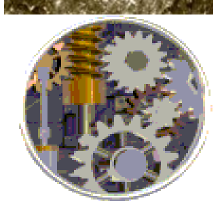




Eddington Experiment of the 21st Century







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):

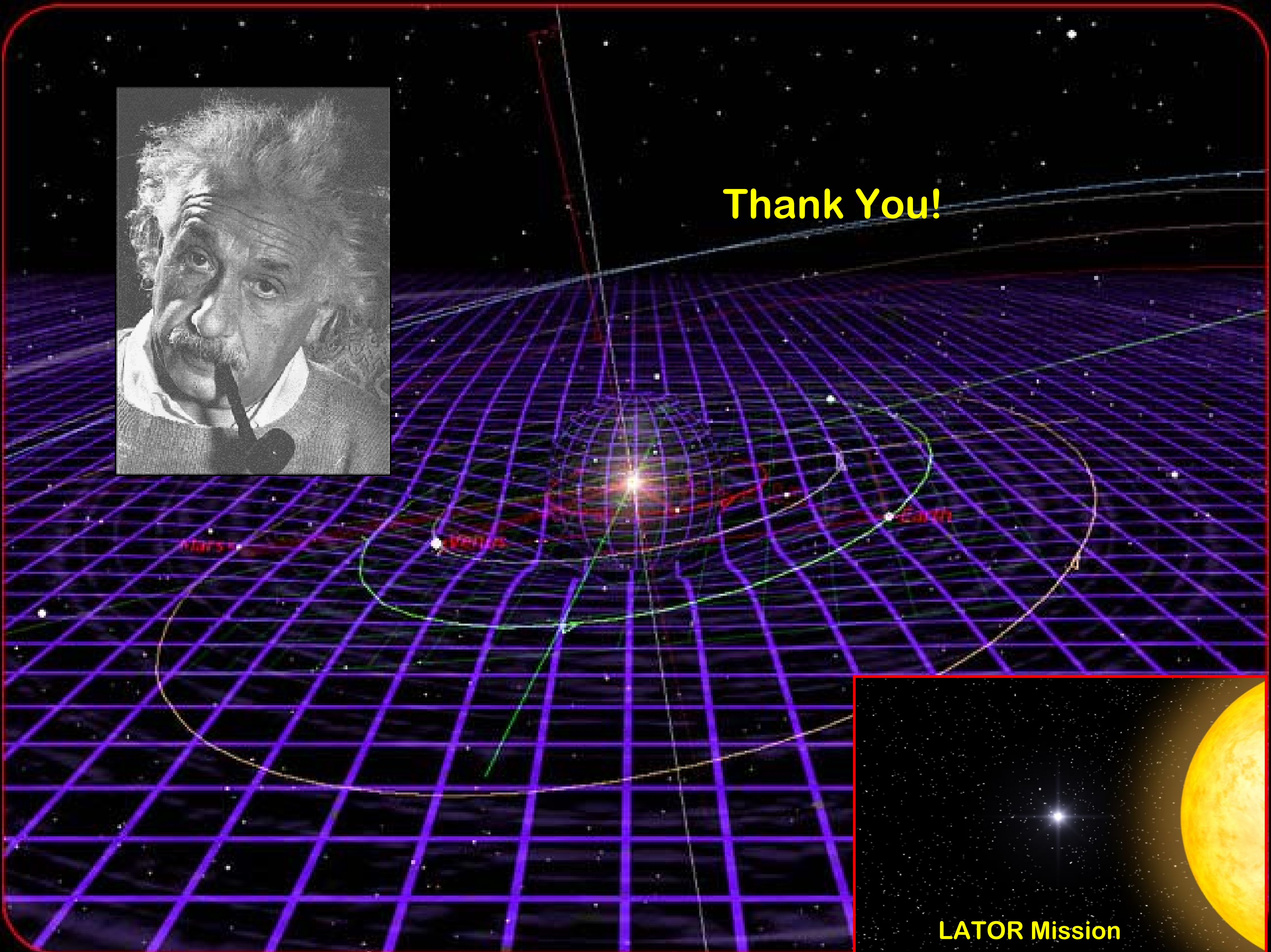
- No need for drag-free environment for LATOR spacecraft
- Redundant optical truss – alternative to ultra-precise OD

A Low Cost Experiment:

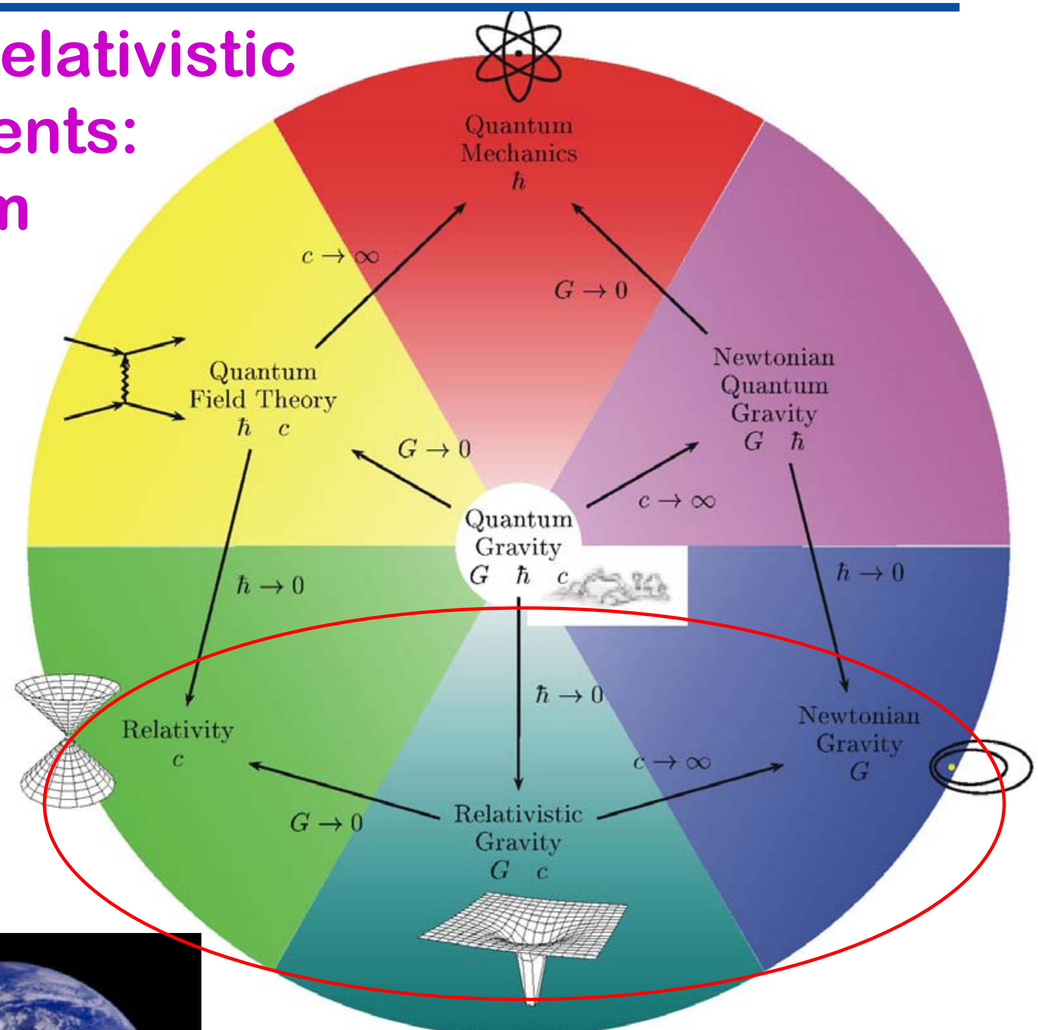
- Optical apertures ~15-25 cm – sufficient; high SNR ~1700
- Options exist for NO motorized moving parts
- Many technologies exist: laser components and spacecraft
- Possibilities for further improvements: clocks, accelerometers, etc.

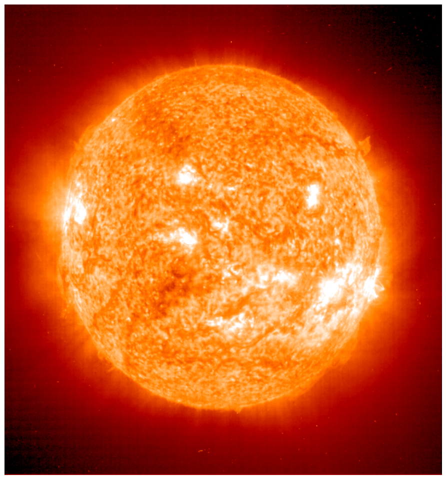
Toward Centennial of General Relativity (2015):

- 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}**


Thank You!
Mars
Venus
Earth
LATOR Mission

Laboratory for Relativistic Gravity Experiments: Our Solar System

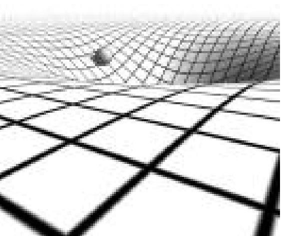




Strongest gravity potential

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

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



Most accessible region for gravity tests in space:

- ISS, LLR, SLR, free-fliers

Technology is available to conduct tests in immediate solar proximity

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.

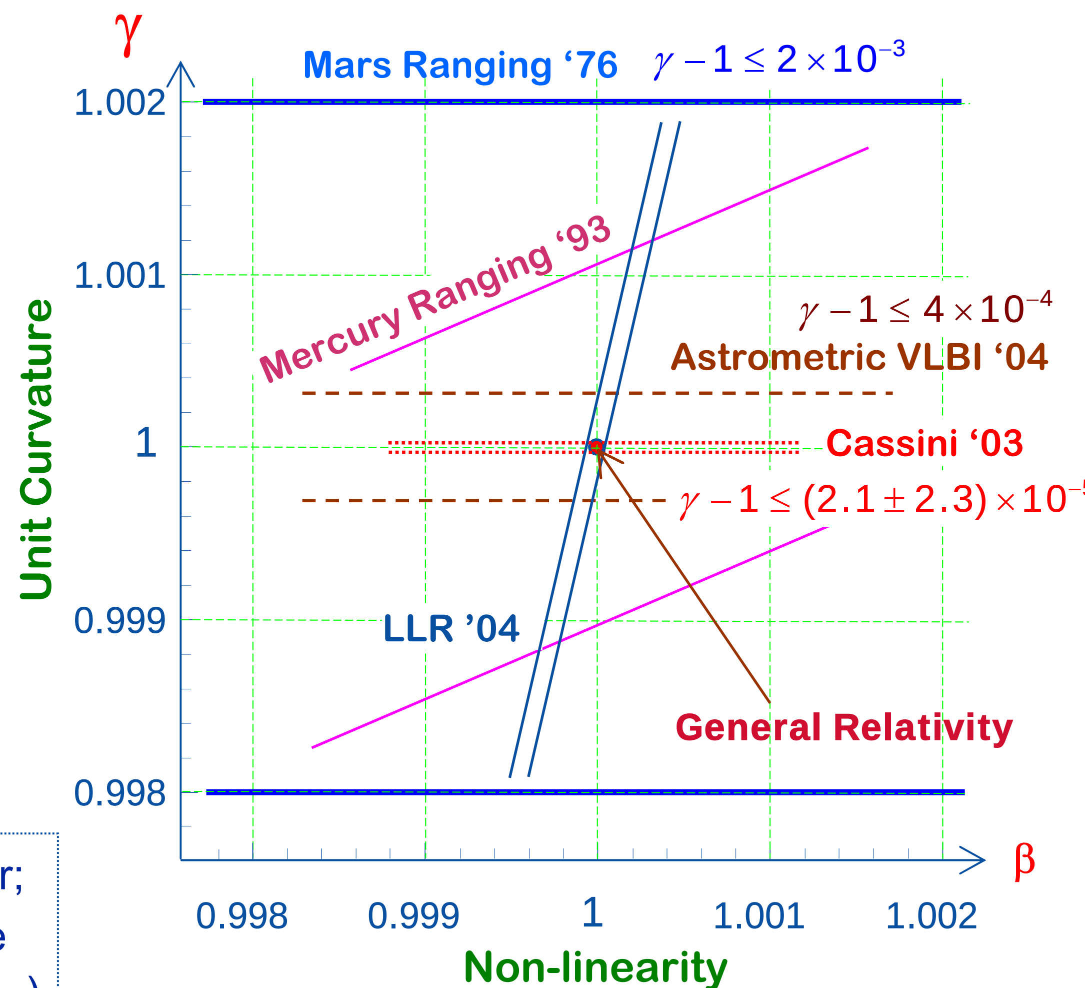
Laser:
- LLR, SLR, etc.

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!

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: $\gamma = 1 + (2.1 \pm 2.3) \times 10^{-5}$

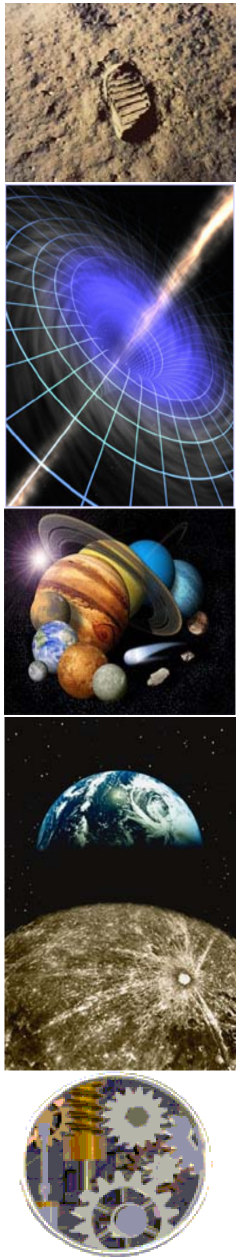
Possible with Existing Technologies?!

- VLBI [current $\gamma = 3 \times 10^{-4}$]: 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 $\sim 6 \times 10^{-6}$
- tracking of BepiColombo s/c at Mercury $\sim 2 \times 10^{-6}$
- Optical astrometry [current $\gamma = 3 \times 10^{-3}$]:

  SIM & GAIA $\sim 1 \times 10^{-6}$ (2015/16?)

We need a dedicated mission to explore accuracies better then 10^{-6} for both PPN parameters γ (and β). Optical and atom technologies show great promise.

MLA-Earthlink Experiment at 1.2 m telescope



Team from GSFC:
X. Sun, G. Neumann, J. Cavanaugh, J. McGarry, T. Zagwodzki, J. Degnan, + many others

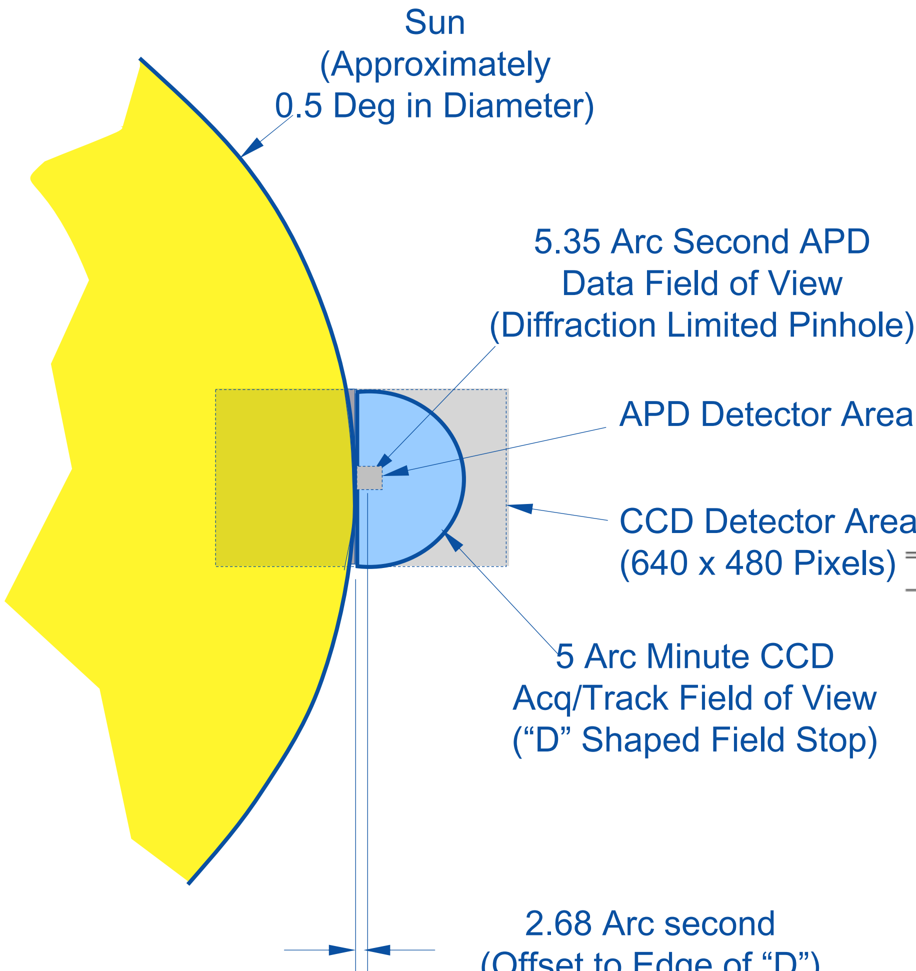
Experiment Objectives:

- In-flight calibration of instrument – determine instrument pointing relative to spacecraft and laser boresight, verify laser characteristics, verify ranging system performance.

Laser ground system characteristics:

- Laser PRF: 240 Hz
- Wavelength: 1064 nm
- Energy per pulse: 15 mJ
- Laser divergence: 55 urad
- Receiver FOV: ~260 urad
- Event time recording: 50 psec shot-to-shot, accurate to UTC to ~100 nsec
- Telescope pointing: 1 arcsec open-loop accuracy, several arcsec jitter during daylight.
- Detector: spare MOLA detector
- Laser: HOMER (B. Coyle Laser Risk Reduction Program developmental)

Focal Plane Mapping



(Diagram not to scale)

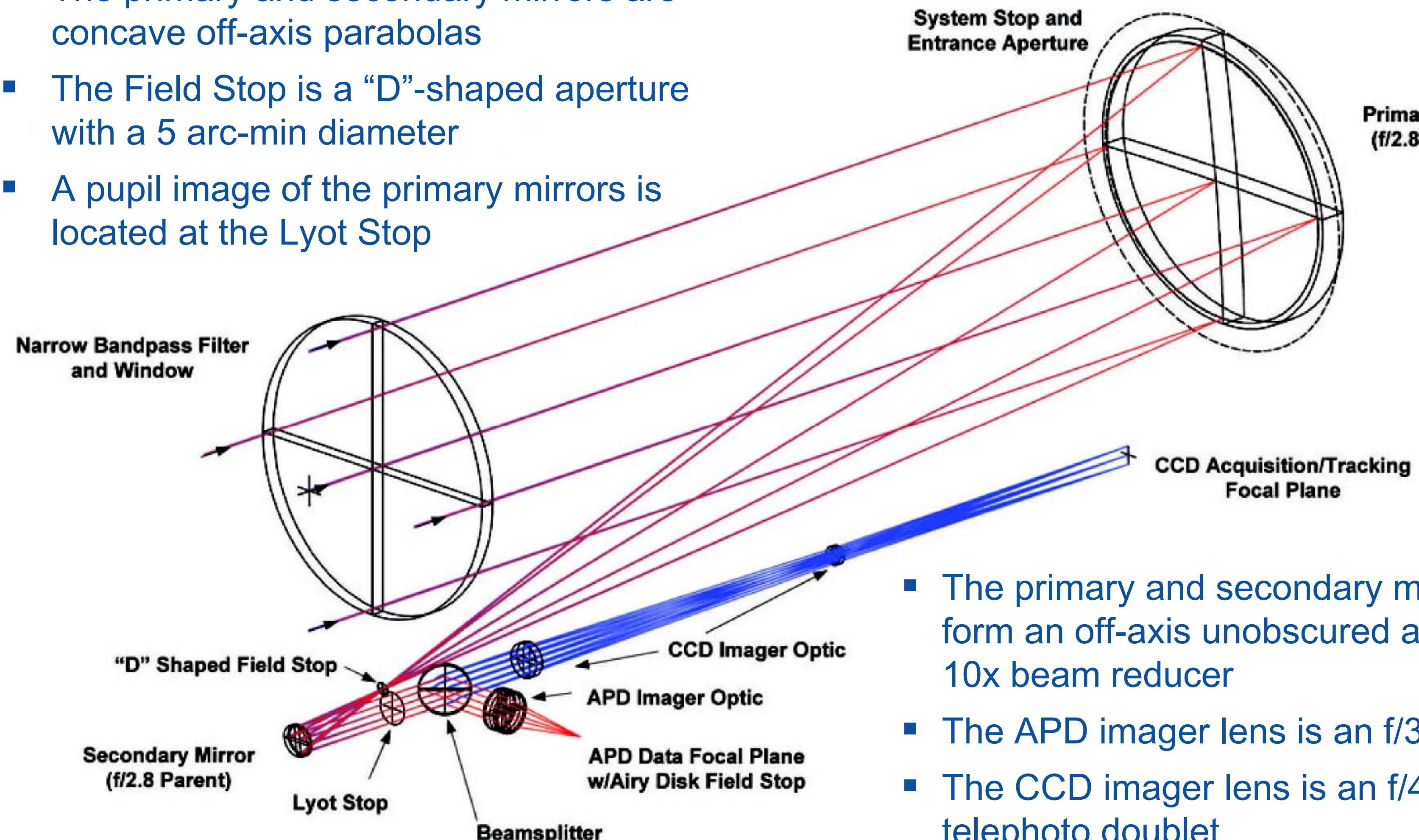
– The straight edge of the "D"-shaped CCD Field Stop is tangent to both the limb of the Sun and the edge of APD field stop (pinhole)
– There is a 2.68 arcsecond offset between the straight edge and the concentric point for the circular edge of the CCD Field Stop ("D"-shaped aperture)
– The APD field 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 $\times$ 480 pixels (9.6 mm $\times$ 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

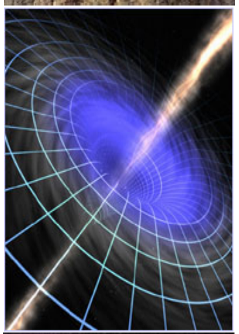
- The primary and secondary mirrors are concave off-axis parabolas
- The Field Stop is a “D”-shaped aperture with a 5 arc-min diameter
- A pupil image of the primary mirrors is located at the Lyot Stop

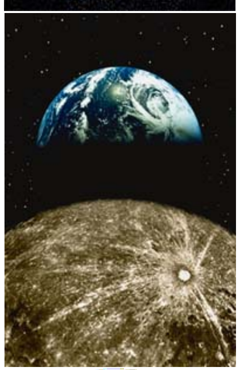
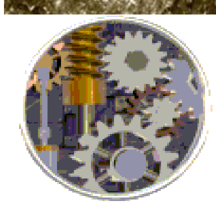


- The primary and secondary mirrors form an off-axis unobscured afocal 10x beam reducer
- The APD imager lens is an f/3.6 triplet
- The CCD imager lens is an f/45.5 telephoto doublet

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.

Summary of Recent Transponder Experiments

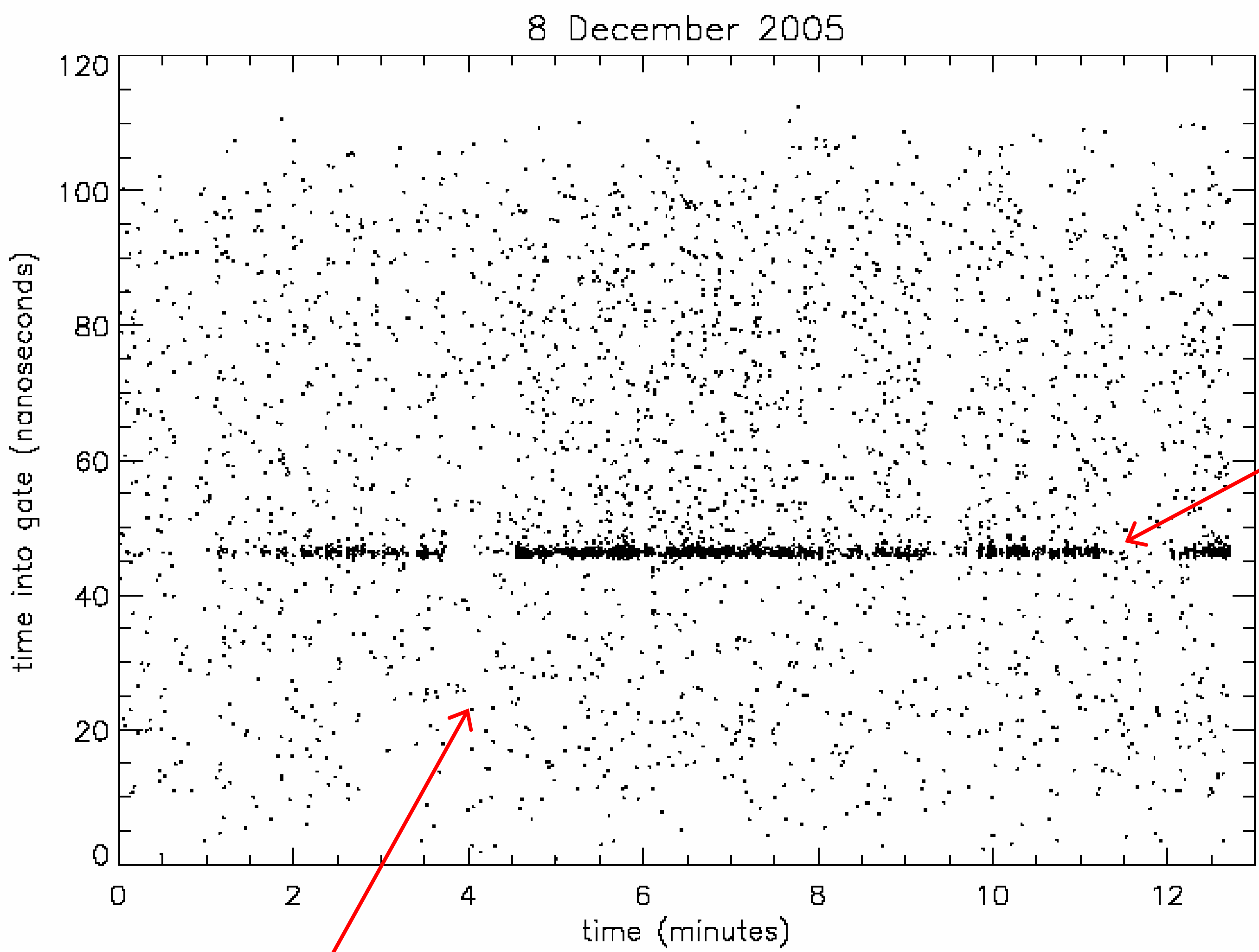



Experiment	MLA (cruise)		MOLA (Mars)
Range (10^6 km)	24.3		~80.0
Wavelength, nm	1064		1064
	Uplink	Downlink	Uplink
Pulsewidth, nsec	10	6	5
Pulse Energy, mJ	16	20	150
Repetition Rate, Hz	240	8	56
Laser Power, W	3.84	0.16	8.4
Full Divergence, μrad	60	100	50
Receive Area, m^2	0.042	1.003	0.196
EA-Product, J-m^2	0.00067	0.020	.0294
PA-Product, W-m^2	0.161	0.160	1.64

- Key instrument parameters for recent deep space transponder experiments at 1064 nm
- Note, these were experiments of opportunity and not design
- At the same time, the accuracy of MLA range determination was 12 cm at the distance of 24 mln km from the Earth (Sun et al., 2005, Smith et al., 2005)

Example Data From a 2005 Run



Return photons from reflector

width is < 30 cm

2150 photons in 14,000 shots

Randomly-timed background photons (bright moon)