Laser Ranging Beyond Lunar Distances

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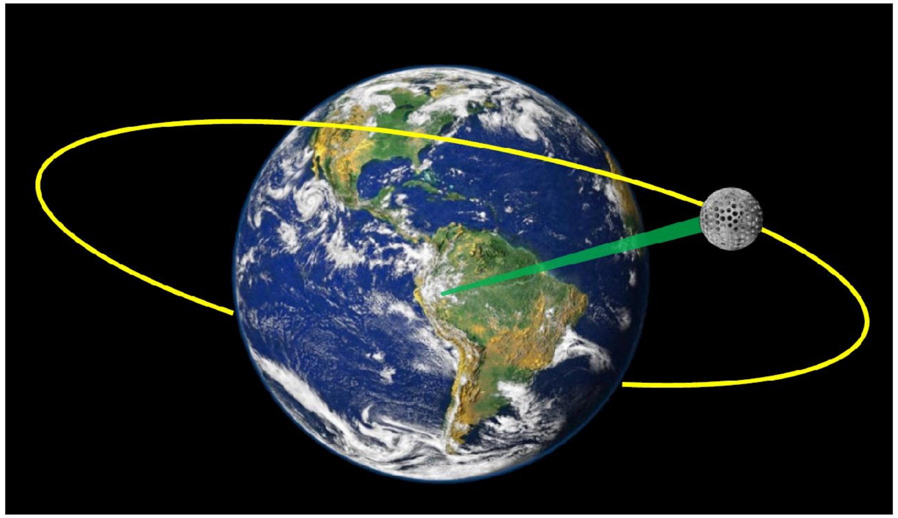
Satellite Laser Ranging

- Fire a short laser pulse to a satellite equipped with a retro-reflecting mirror
- Time when the laser pulse leaves the station
- Laser pulse reflects off the mirror back towards the station
- Time when the laser pulse is received
- Correct for atmospheric delay, system delay, measurement reference point
- Range measurement!

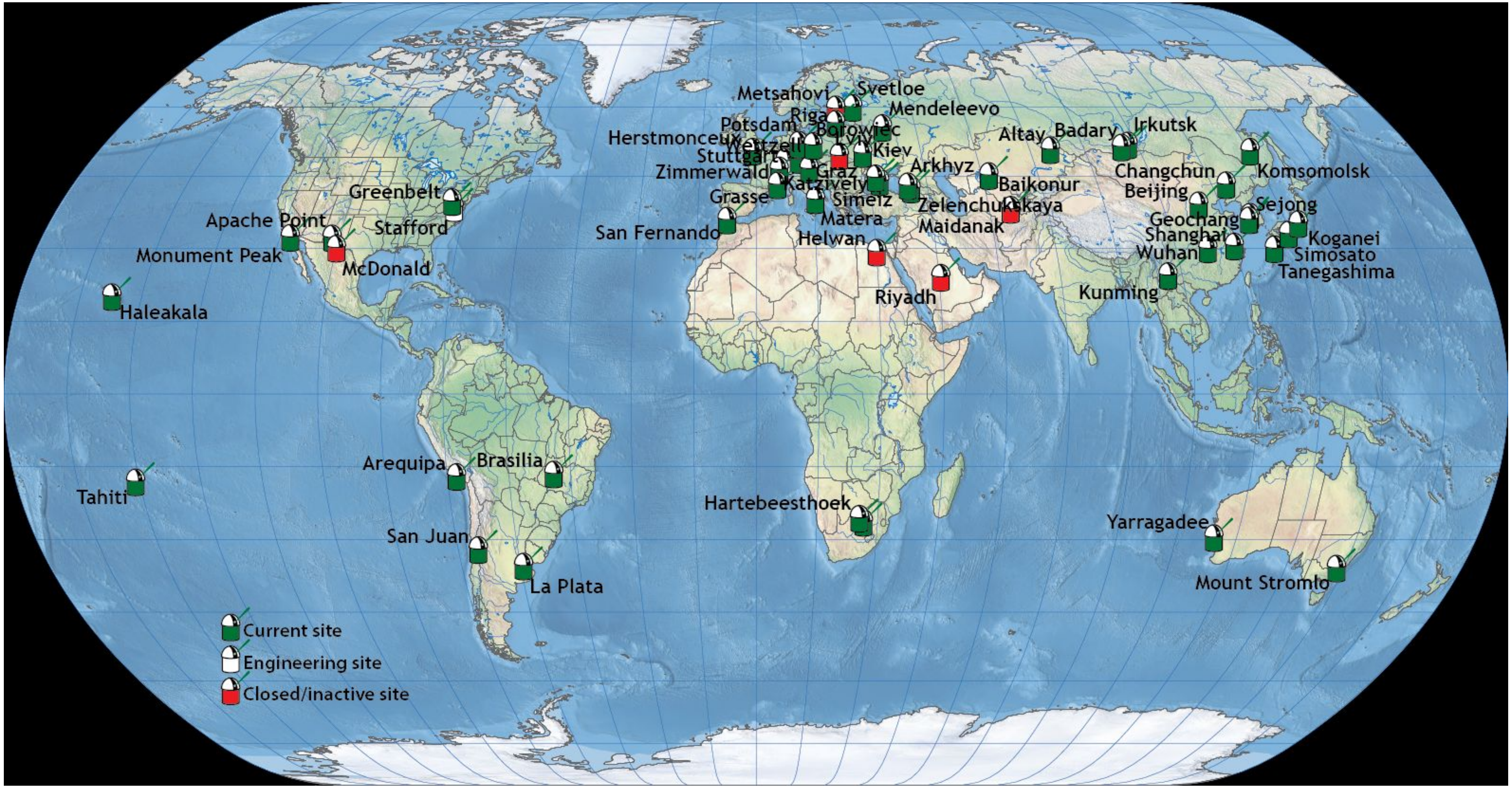


No electronics on the space segment

1-2 mm precision measurements

Centimeter-level accuracy orbits

SLR Network


Metsahovi
Svetloe
Riga
Mendeleevo
Potsdam
Borowiec
Herstmonceux
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Graz
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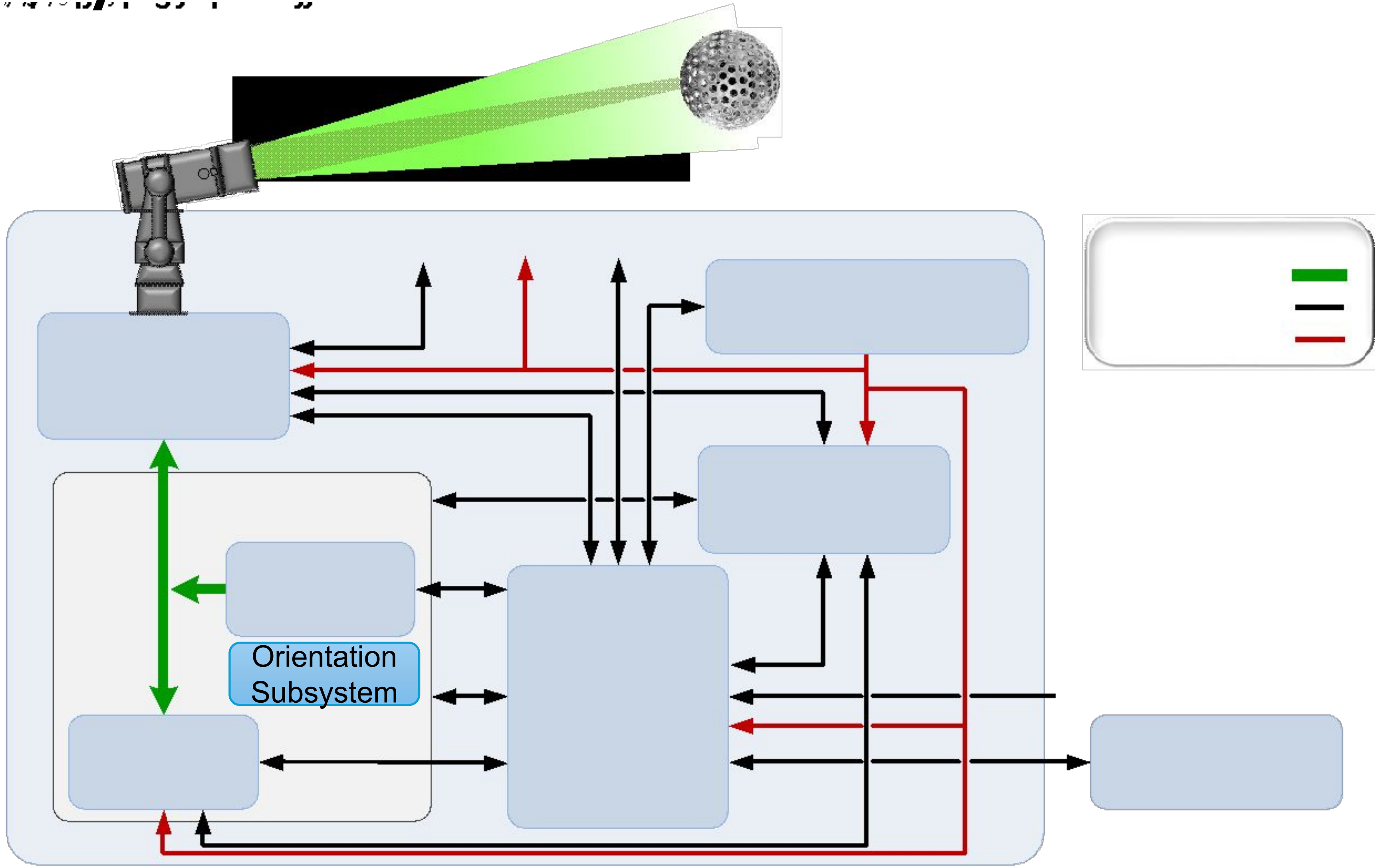
Matera
Arkhyz
San Fernando
Helwan
Altay
Badary
Irkutsk
Baikonur
Maidanak
Riyadh
Changchun
Beijing
Komsomolsk
Sejong
Geochang
Shanghai
Wuhan
Koganei
Simosato
Tanegashima
Kunming
Greenbelt
Stafford
Apache Point
Monument Peak
McDonald
Haleakala
Tahiti
Arequipa
Brasilia
San Juan
La Plata
Hartebeesthoek
Yarragadee
Mount Stromlo
Current site
Engineering site
Closed/inactive site

Typical Parts of an SLR System



2-Way Link Equation from Ground Station

The mean number of photons detected (n_s) can be modeled as:

$$n_s = \frac{E_t}{h\nu}\eta_t \frac{2}{\pi(\theta_d R)^2} e^{-2(\frac{\Delta\theta_p}{\theta_d})^2} \frac{1}{1 + (\frac{\Delta\theta_j}{\theta_d})^2} \frac{\sigma A_r}{4\pi R^2} \eta_r \eta_c T_a^2 T_c^2$$

2-Way Link Equation from Ground Station

The mean number of photons detected (n_s) per laser pulse can be modeled as:

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Photons in laser pulse
E_t -> energy (joules) of laser pulse
h -> Planck's constant
ν -> frequency of light

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Efficiency of transmitting optics (%)

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Transmitter (laser) gain
θ_d -> half angle divergence of laser
$\Delta\theta_p$ -> beam pointing error
R -> range

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Pointing Jitter factor

θ_d -> half angle divergence of laser

$\Delta\theta_j$ -> laser pointing jitter

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Return energy factor

σ > optical cross-section of reflector

A_r -> effective receiver area

R -> range

2-Way Link Equation from Ground Station

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Receiver efficiency factors
η_r -> receiver optics efficiency
η_c -> detector counting efficiency

2-Way Link Equation from Ground Station

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Atmospheric Factors
T_a -> Atmospheric attenuation
T_c -> cirrus cloud attenuation

Assumption: Photon detection is a Poisson process

$$P = \frac{\lambda^k e^{-\lambda}}{k!}$$

Probability of detecting k photons with an average detection rate of λ photons per laser shot

Return Rate		P(k=0) "No return"	P(k=1) "Single Photon detect"	P(k>=2) "Multiphoton detect"	% of detects that are Multiphoton
1%	0.010	0.99	0.010	0.00005	0.5%
5%	0.051	0.95	0.049	0.001	2.5%
10%	0.105	0.9	0.095	0.005	5.2%
20%	0.223	0.8	0.179	0.021	10.7%
40%	0.511	0.6	0.306	0.094	23.4%
60%	0.916	0.4	0.367	0.233	38.9%
80%	1.609	0.2	0.322	0.478	60.0%
99.9%	6.910	0.001	0.007	0.992	99.3%
99.99%	9.210	0.0001	0.001	0.999	99.9%

1-Way Link Equation from Ground Station

$$n_s = \frac{E_t}{h\nu}\eta_t \frac{2}{\pi(\theta_d R)^2} e^{-2(\frac{\Delta\theta_p}{\theta_d})^2} \frac{1}{1 + (\frac{\Delta\theta_j}{\theta_d})^2} \frac{\cancel{\sigma} A_r}{\cancel{4\pi R^2}} \eta_r \eta_c T_a^{\cancel{2}} T_c^{\cancel{2}}$$

Signal strength gains for 1 way links are very large

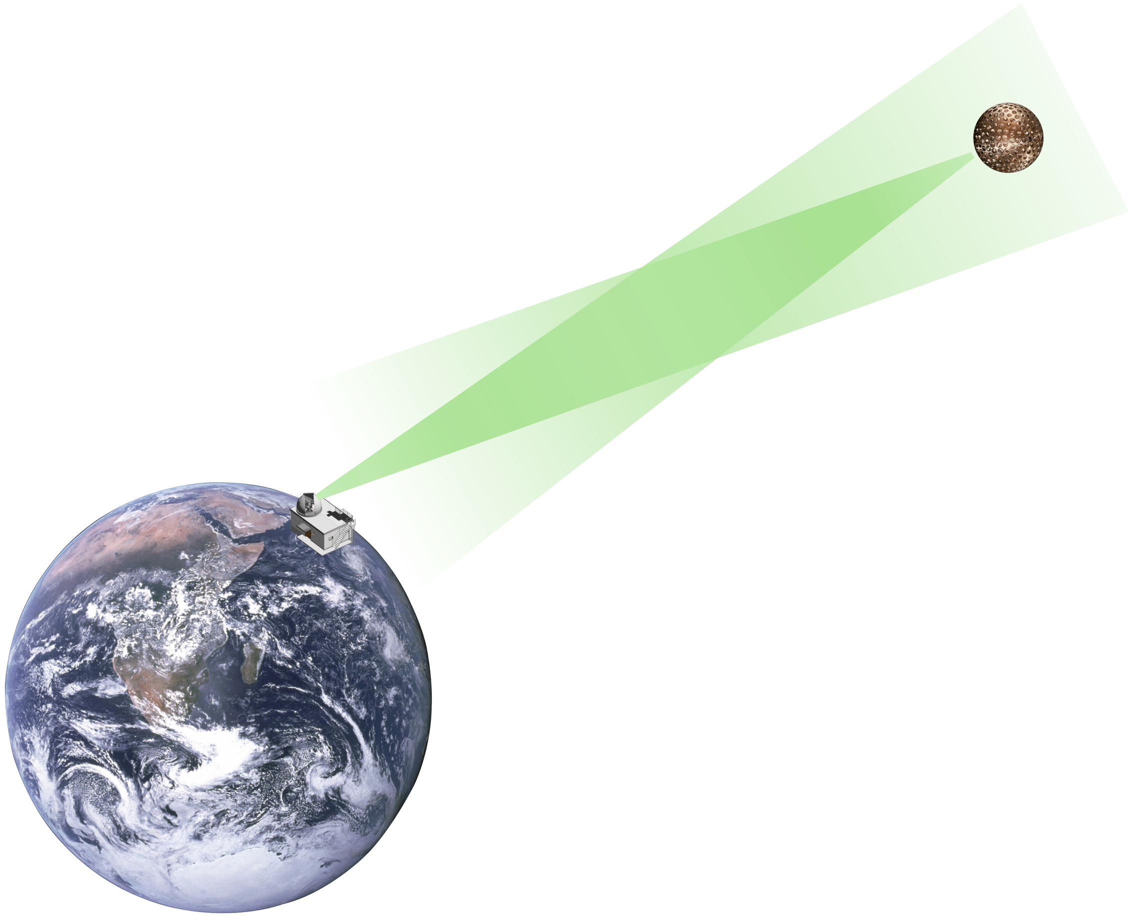
Instead of 1/r^4, becomes 1/r^2

1-Way Link Equation, Space to Space

$$n_s = \frac{E_t}{h\nu}\eta_t \frac{2}{\pi(\theta_d R)^2} e^{-2(\frac{\Delta\theta_p}{\theta_d})^2} \frac{1}{1+(\frac{\Delta\theta_j}{\theta_d})^2} \frac{\cancel{\sigma} A_r}{\cancel{4\pi R^2}} \eta_r \eta_c \cancel{T_a^2 T_c^2}$$

Neglecting atmospheric effects further increases signal

Link Example – Two Way



Laser Pulse Energy	1.5 mJ
Full Beam Divergence	20 arcseconds
Transmit Optics Efficiency	77%
Receive Optics Efficiency	54%
Detector Counting Efficiency	28%
Effective Receive Aperture	0.187m^2
Satellite Optical Cross Section	7.6 Mm^2
Satellite Range	**5995 km**
Mean Photons Received	**6.68**

Link Example – One Way

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Full Beam Divergence	20 arcseconds
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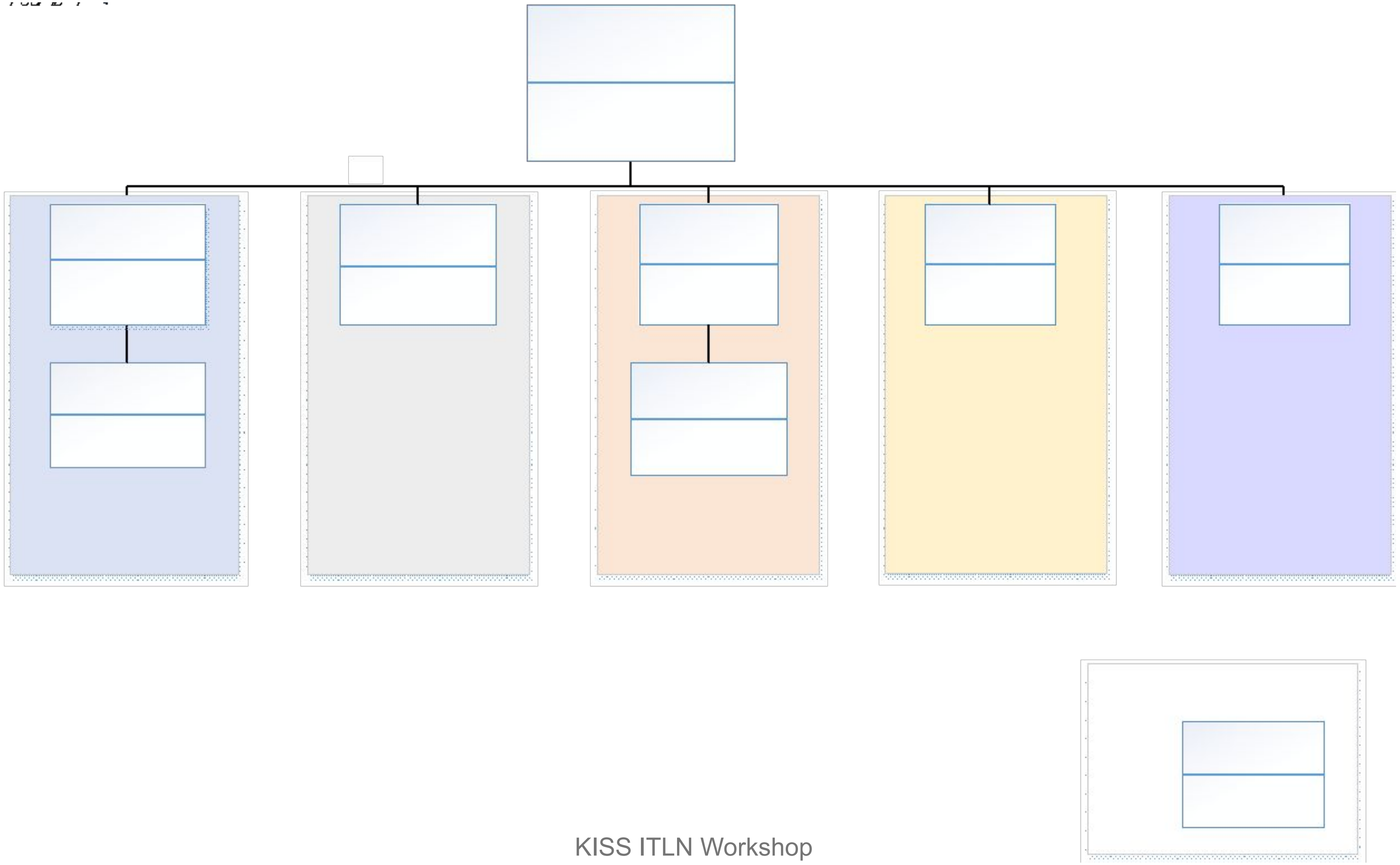
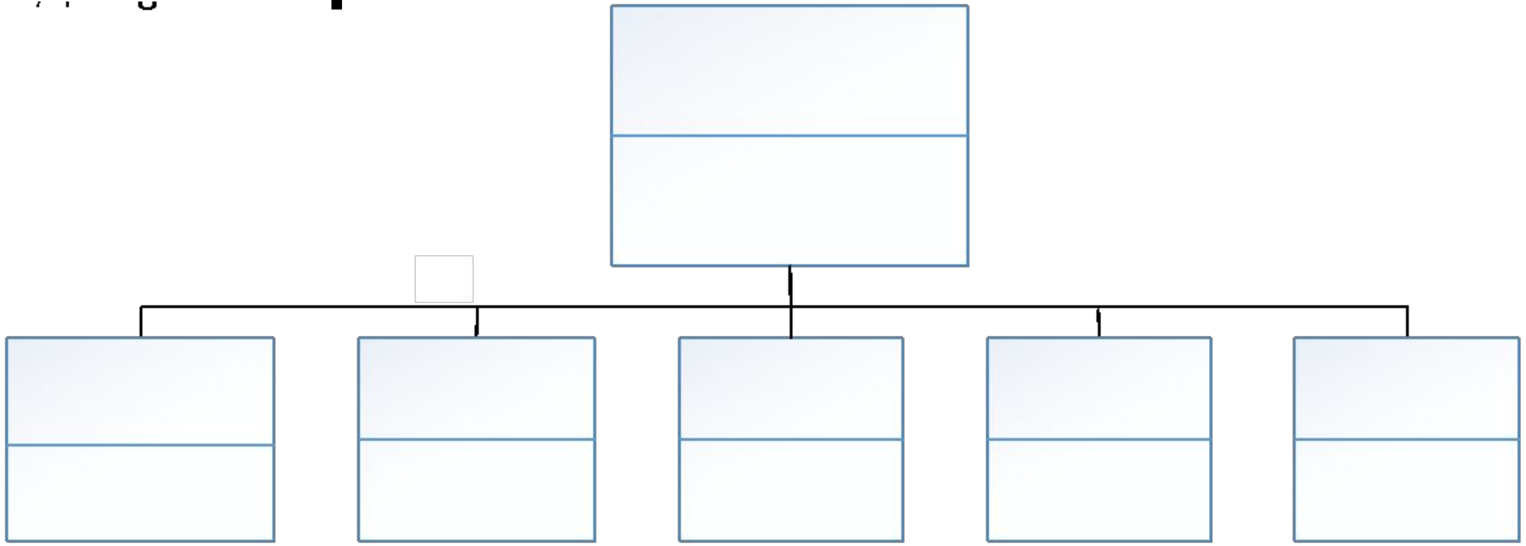
Error Budget Example for LAGEOS Satellite



Precision Error Budget Example



Single Shot Precision

$$\sigma_{NPT} = \frac{\sigma_{SS}}{\sqrt{N}} = 1\,mm \Rightarrow N = 1586 \Rightarrow \frac{N}{2000\,Hz * 10\%\,return\,rate} = 7.9\,seconds$$

Normal Point Precision

Number of Observations

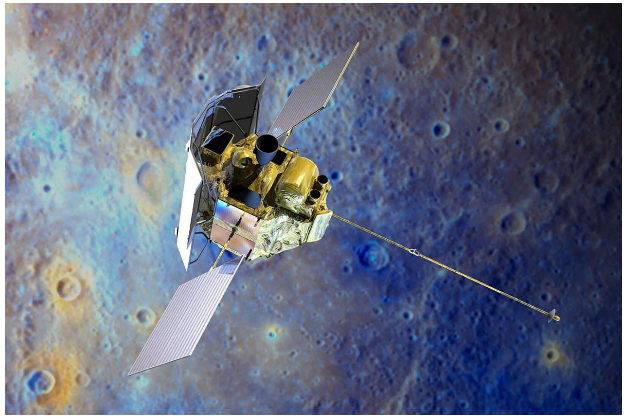
Challenges of Transponder Experiments

- Clock Synchronization and modeling
- Knowledge of spacecraft location in a reference frame
- Knowledge of laser pulse reference to center of mass of spacecraft
- Orientation/Pointing at AU distances
  - Point ahead/behind
  - Link feedback and correction
  - Possible attitude change of the spacecraft to move receiver field of view
- Instrument (Laser) Lifetime
- Sensitivity of, or Deconfliction with other instruments

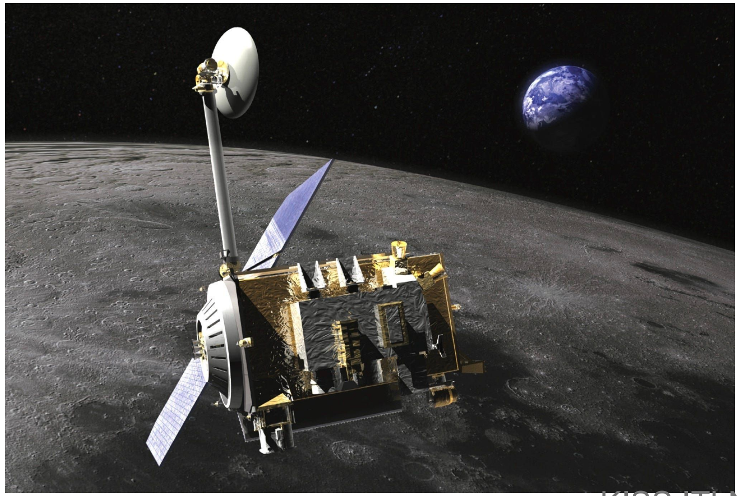
1 Way Ranging Experiments

Mars Global Surveyor (MGS)

MESSENGER

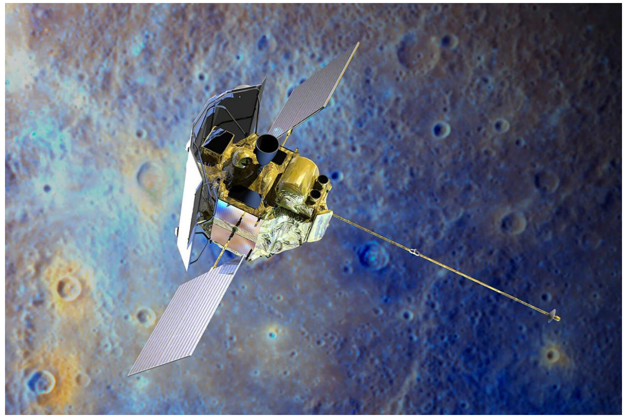


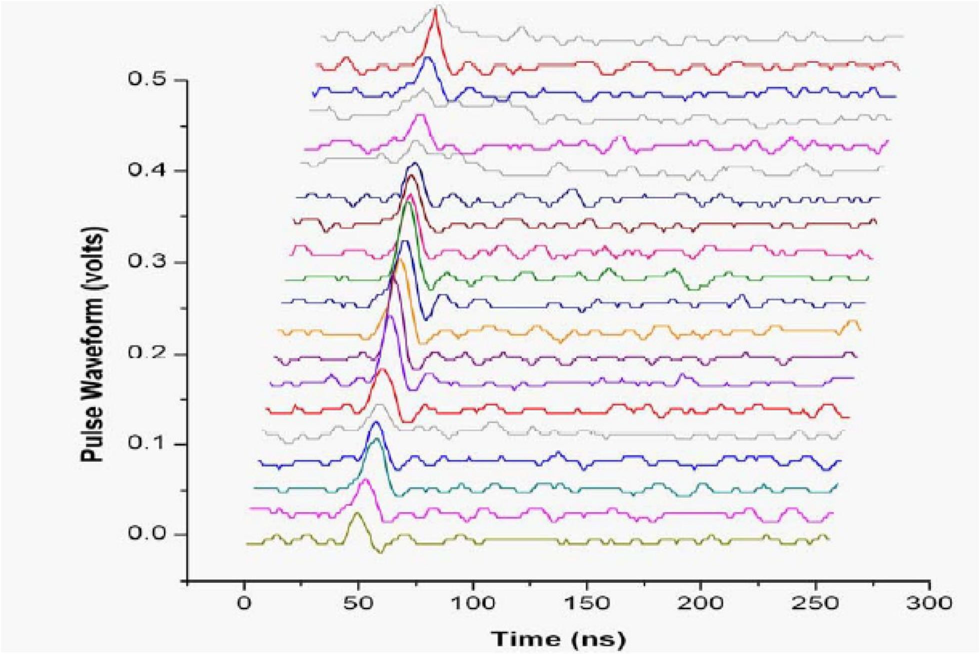
Lunar Reconnaissance Orbiter (LRO)



JASON-2

MESSENGER (Earth to Mercury)





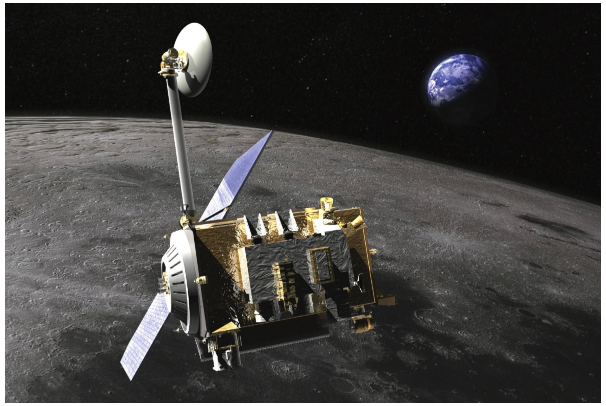
Parameter	Laser link solution	Spacecraft ephemeris	Difference
Range (m)	23,964,675,433.9 ± 0.2	23,964,675,381.3	52.6
Range rate (m s^{-1})	4,154.663 ± 0.144	4,154.601	0.062
Acceleration (mm s^{-2})	−0.0102 ± 0.0004	−0.0087	−0.0015
Time (s)	71,163.729670967 ± 6.6 × 10^{-10}	71,163.730019659	0.000348692
Clock drift rate (ppb)	1.00000001559 ± 4.8 × 10^{-10}	1.00000001564	−3.2 × 10^{-10}

Mars Global Surveyor

Transmitter, Signal and Link Summary

- Pulse width 10 nsec
- Pulse rate: 49 Hz
- Transmitted Pulse pattern:
  - –Scan 1 6 pulses on, 6 pulses off
  - –Scan 2 Continuous 49 Hz
- Beam divergence ~100 urad
- Pointing accuracy ~5-10 urad
- Earth to MGS distances: 80.107 -> 80.103 Mkm
- Light travel time: 267.2 seconds (4.45 minutes)
- Beam diameter at Mars 8100 km
- Transmitted Energy: 10 mJ, Scan 1
  11 mJ, Scan 2

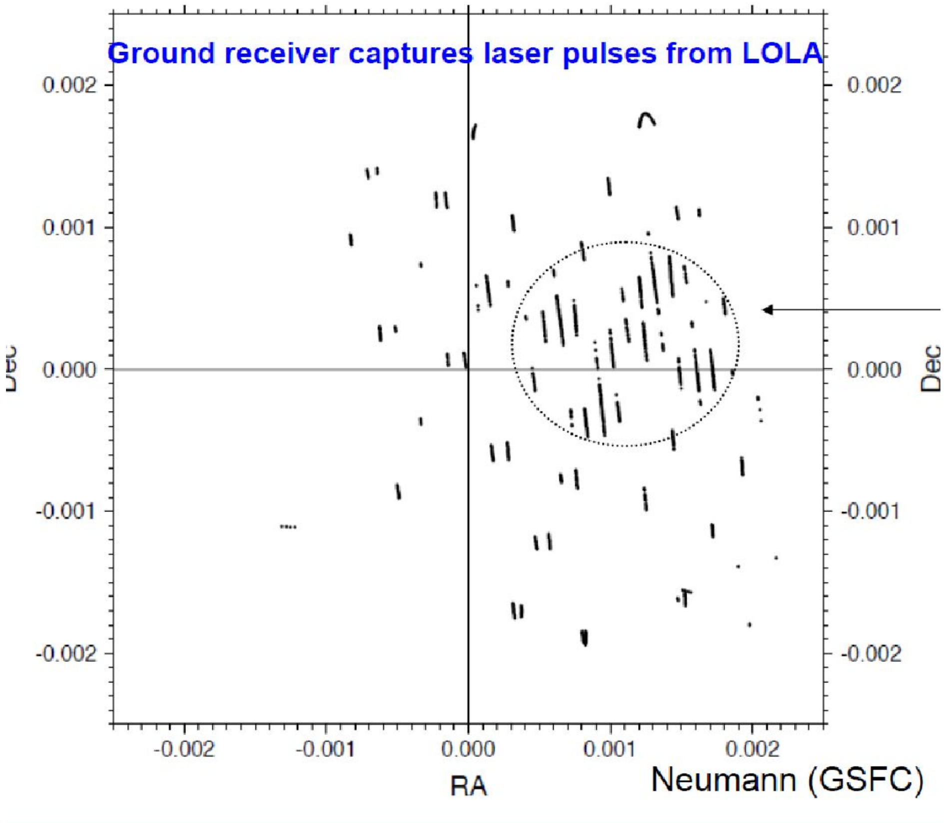
Lunar Reconnaissance Orbiter

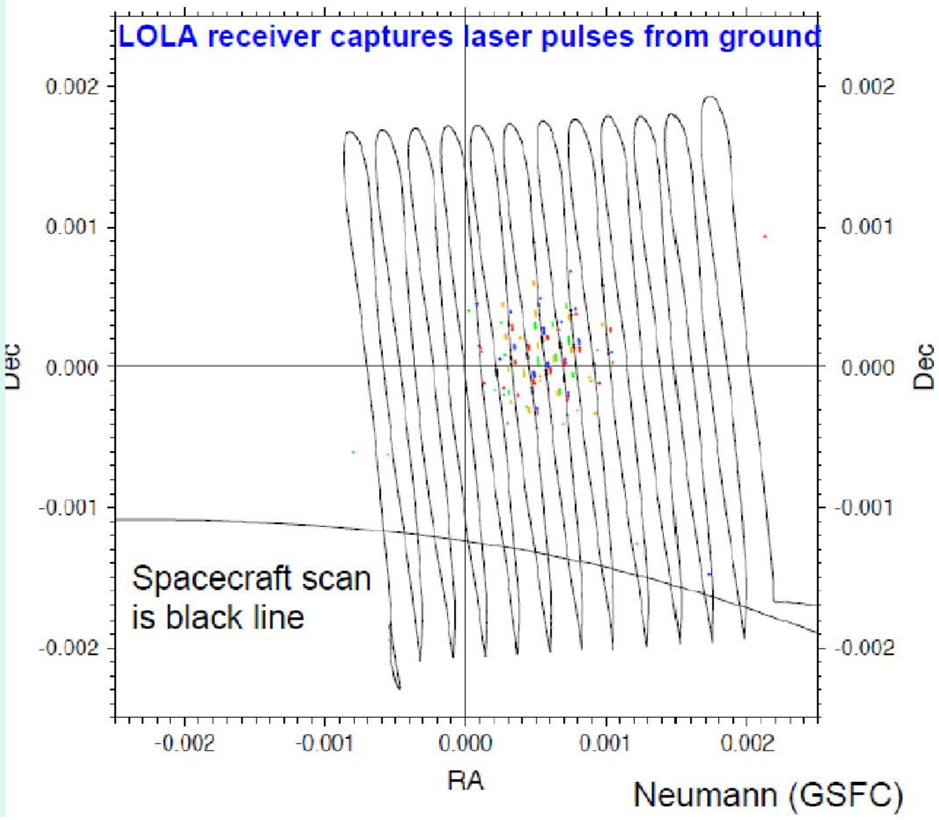


The mean RMS for the measurement residuals of the LR and radiometric data.

Data type	Gravity model	Mean RMS of S band range data (m)	Mean RMS of S band Doppler data (cm/s)	Mean RMS of LR data (m)
S band data only	GRGM900C	19.527	0.630	n/a
	LLGM-2	18.643	0.700	n/a
	SGM150J	21.337	0.668	n/a
LR data only	GRGM900C	n/a	n/a	0.251
	LLGM-2	n/a	n/a	0.334
	SGM150J	n/a	n/a	0.319
S-band and LR data	GRGM900C	35.132	0.697	2.757
	LLGM-2	34.794	0.861	6.412
	SGM150J	35.679	0.810	2.964

Lunar Reconnaissance Orbiter

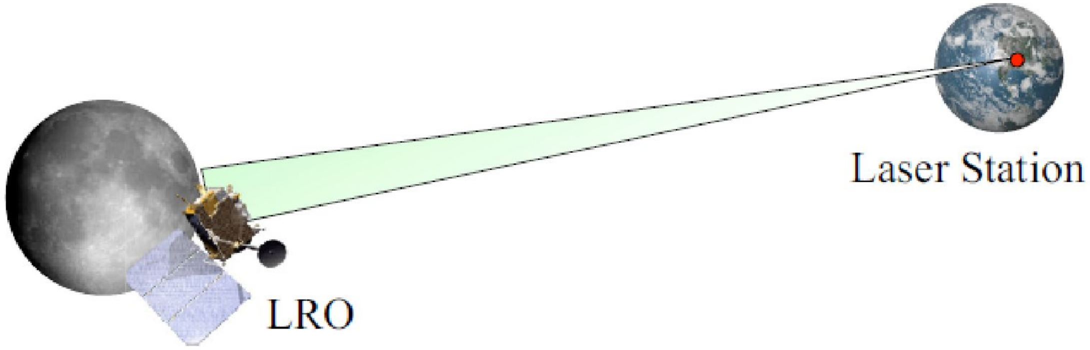




Clock Synchronization Example: LRO

Mao et al.

$$R = \left(T_{LOLA\_receive}^{MET} * \delta_f + {T_{LOLA\_receive}^{MET}}^2 * \alpha_f + \delta t_{offset} - T_{transmit}^{UTC} \right) * c$$



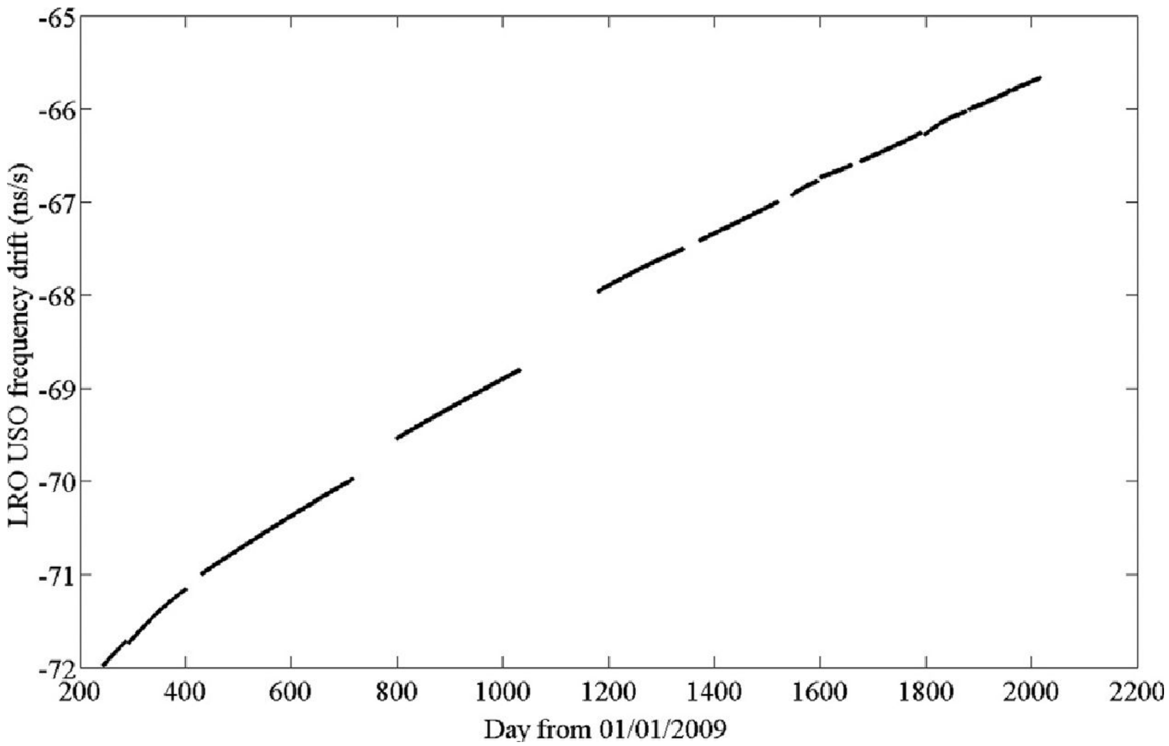
Clock Synchronization Example: LRO

$$T^{UTC}_{LOLA\_receive} = \left(T^{MET}_{LOLA\_receive} + \delta t_{range\_walk}\right) * \left(1 + \delta_f\right) + {T^{MET}_{LOLA\_receive}}^2 * \alpha_f + \delta t_{offset},$$

$$\delta t_{range\_walk} = 6 - \sqrt{6^2 + \left(p \times \left(\Delta t_{pulse\_width} - 1\right)\right)^2}$$

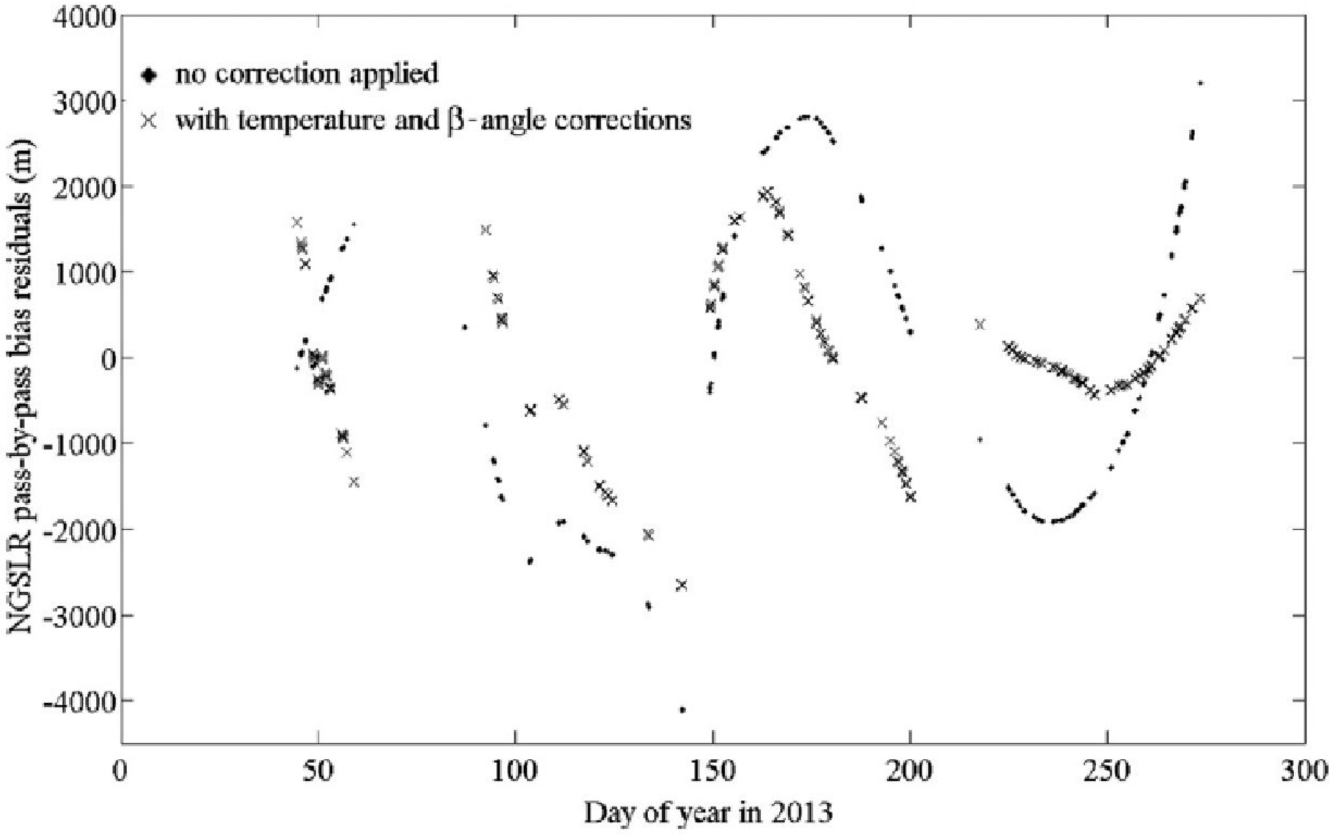
Clock Synchronization Example: LRO

- Oven-Controlled Crystal Oscillator < 10^12 per hour
- Offset from UTC and drift due to aging and temperature effects
- Events on the spacecraft (e.g. Ka-band data downlink) can influence temperature



Clock Synchronization Example: LRO

- Modeling temperature and B-angle reduced bias residuals in range from 1760m to 910m in this sample
- Still very large
- Lesson: Better models are not a replacement for more stable clocks



Summary

- One-way ranging presents several challenges (and a few benefits) over two-way ranging
- Beyond lunar distances, only one-way ranging is practical
- We need stable, traceable clocks
- We need robust lasers with a useful mission lifetime and ‘short enough’ pulse
- Defining proper science goals/requirements is key to assess feasibility

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Thank you!