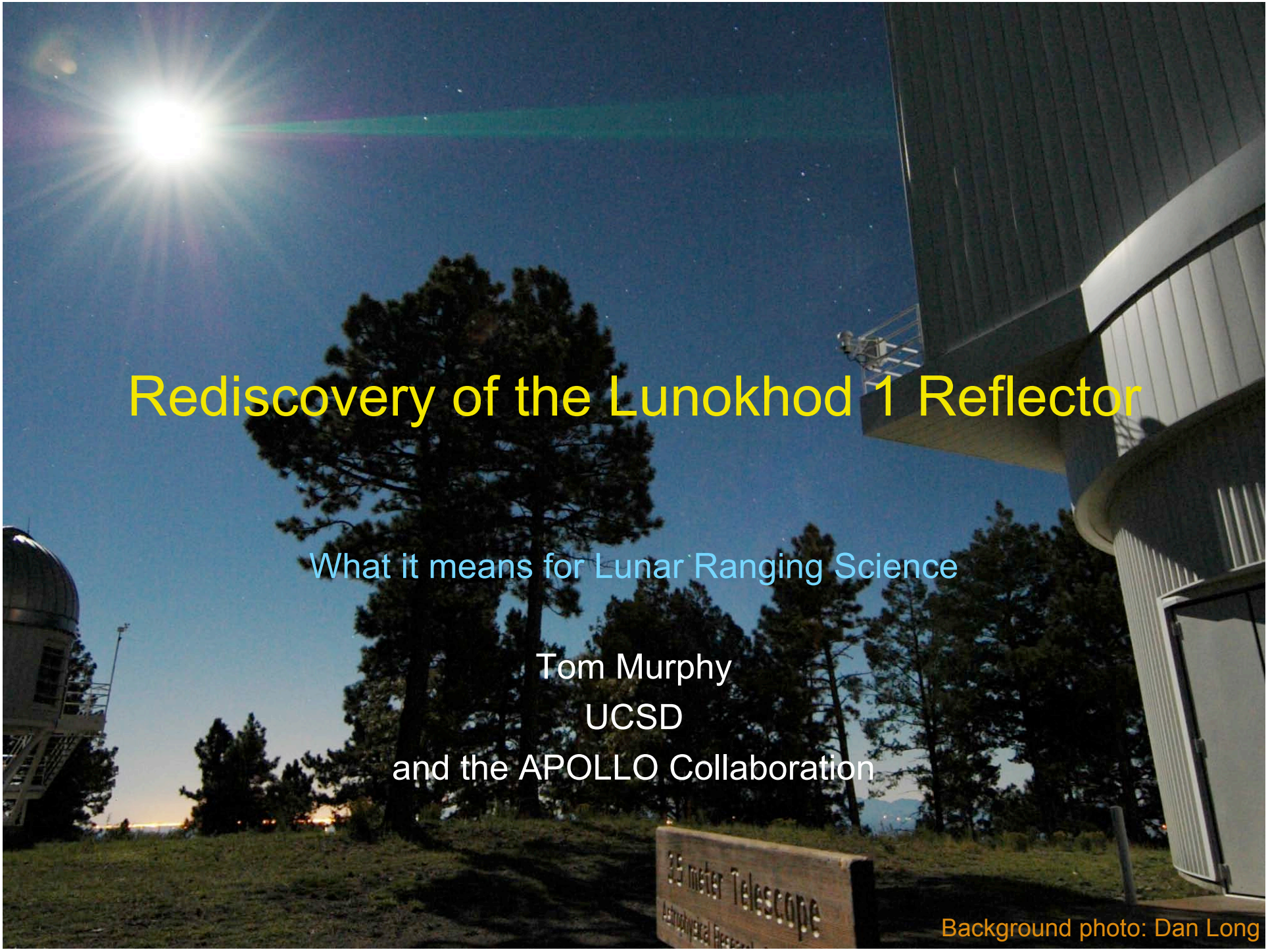


Rediscovery of the Lunokhod 1 Reflector

What it means for Lunar Ranging Science

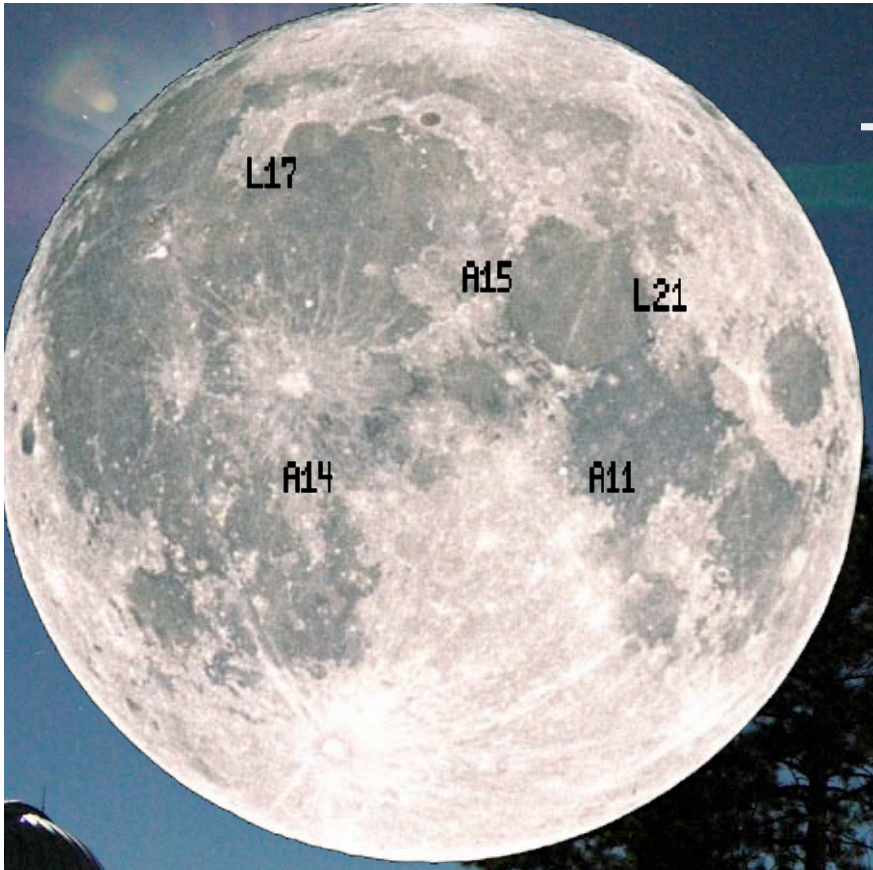
Tom Murphy
UCSD
and the APOLLO Collaboration

Background photo: Dan Long

Intro to APOLLO

- APOLLO (Apache Point Observatory Lunar Laser-ranging Operation) is a one-millimeter-capable lunar laser ranging (LLR) experiment using the 3.5 m telescope at Apache Point in southern New Mexico
- Main goal is precision tests of gravity
  - strong equivalence principle
  - time-rate-of-change of Newton's *G*
  - gravitomagnetism, inverse square law, geodetic precession, etc.
- Accomplish millimeter goal via big telescope, good atmospheric seeing, APD array → lots of return photons
- Collaboration includes: Eric Adelberger, James Battat, C.D. Hoyle, Nathan Johnson, Russet McMillan, Eric Michelsen, Chris Stubbs, Erik Swanson (UW, MIT, Humboldt State, UCSD, Apache Point Observatory, Harvard)
- Also involved in the NLSI LUNAR effort under Jack Burns

The Reflector Positions



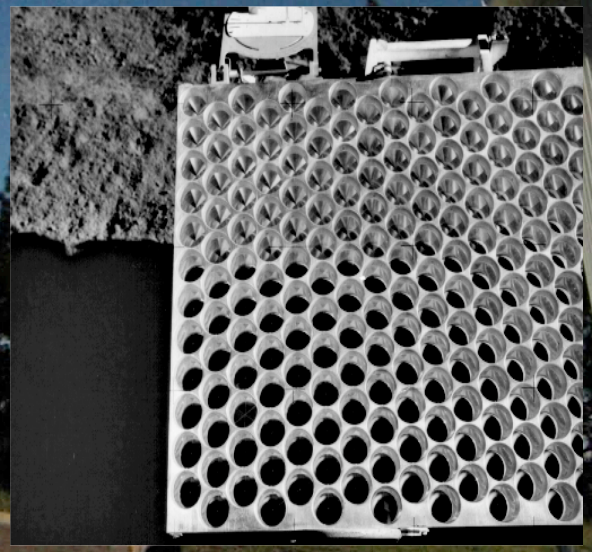
- Three Apollo missions left reflectors
  - Apollo 11: 100× 38 mm CCRs
  - Apollo 14: 100× 38 mm CCRs
  - Apollo 15: 300× 38 mm CCRs
- Two French-built reflectors were placed on rovers aboard the Soviet Luna 17 and Luna 21 landers
  - Lunokhod 1: 14 110 mm CCRs
  - Lunokhod 2: 14 110 mm CCRs
  - similar in cross-section to the Apollo arrays

Lunar Retroreflector Arrays

Corner cubes

Apollo 11 retroreflector array

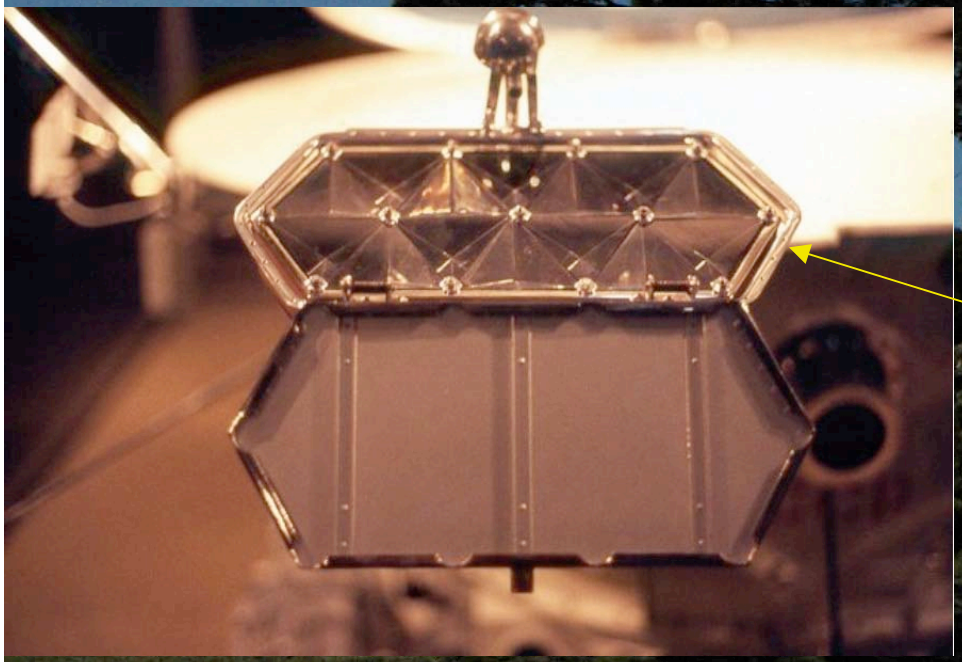
Apollo 14 retroreflector array

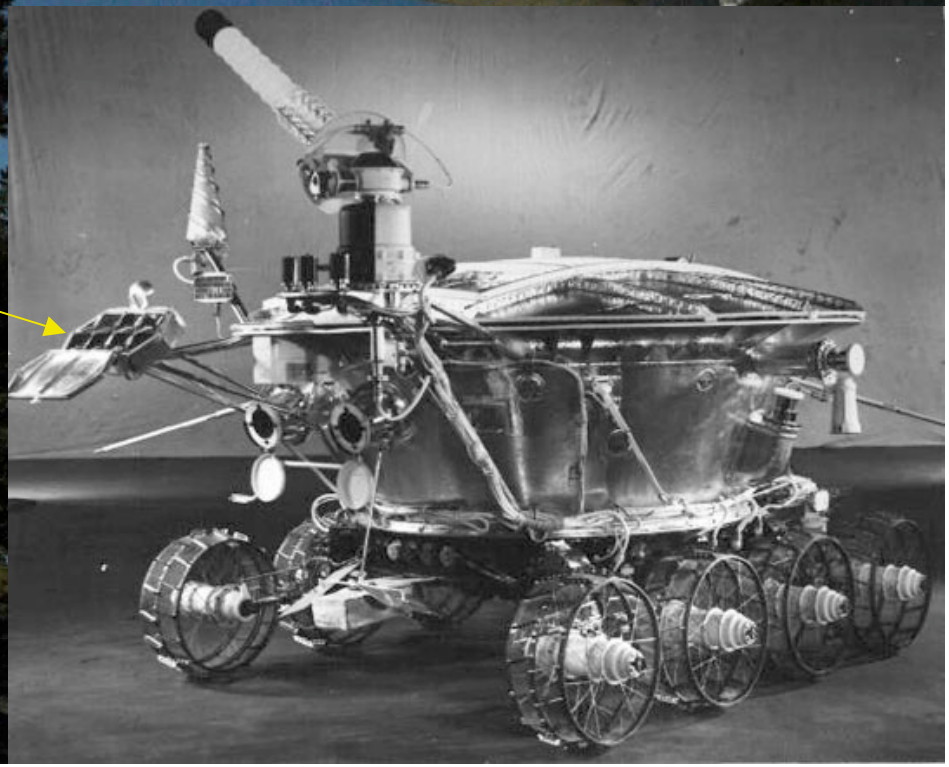


Apollo 15 retroreflector array

The Lunokhod Reflectors

- 14 triangular CCRs, 11 cm side length
- At 532 nm, expect response equivalent to ~200 Apollo 3.8 cm CCRs
  - between A11/A14 and A15
- L2 was once seen to be comparable to A15 in strength
- Now L2 is 1/10th the strength of A15
- Expected L1 to be comparable to L2 in strength, at best
  - or maybe lack of return indicated L1 would be weaker than L2, if found



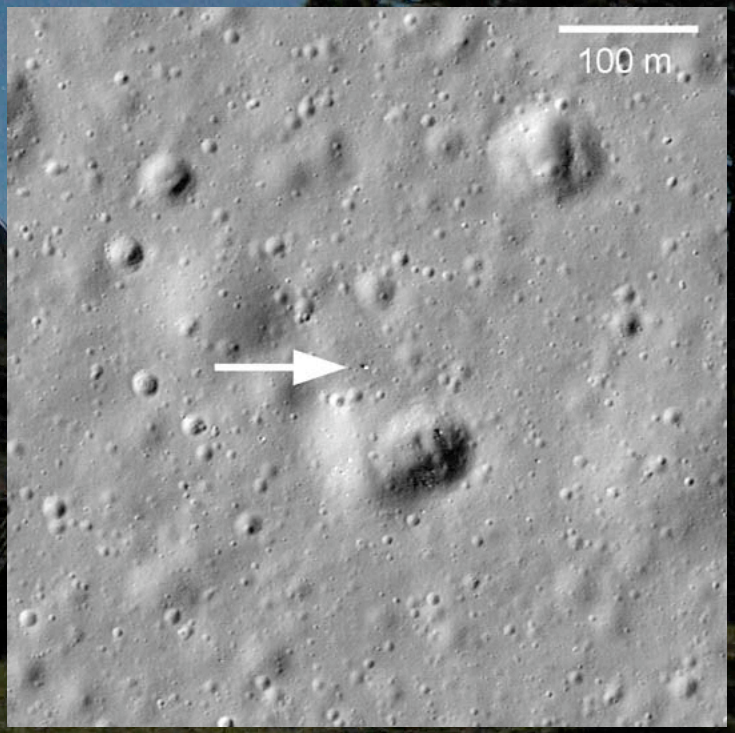


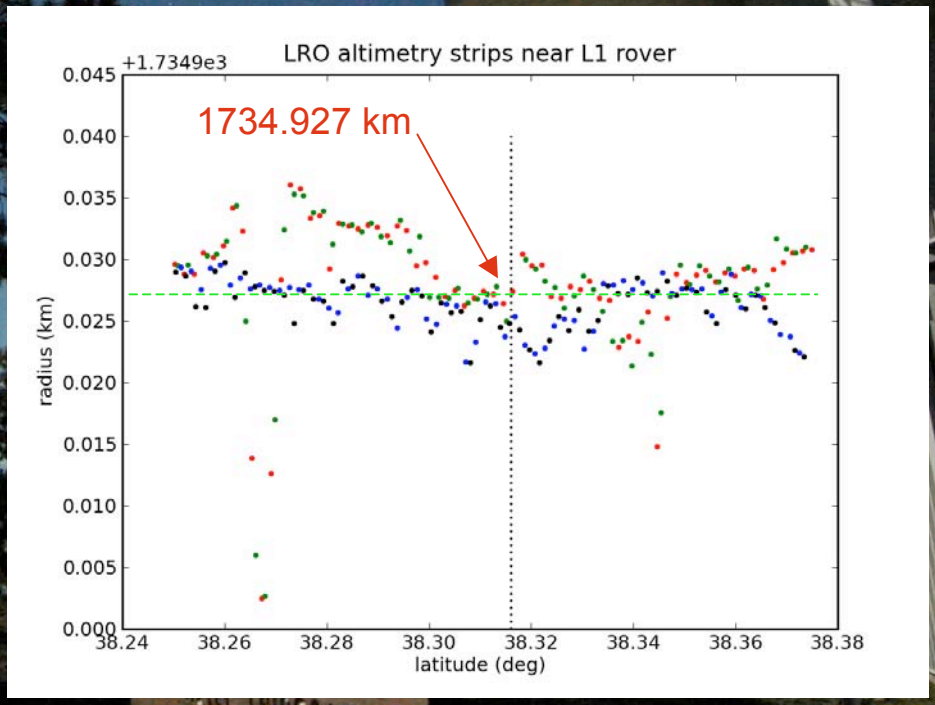
Lunokhod 1 History

- Landed 17 November, 1970
- Operated on surface through September 1971
- Parked during lunar nights; permitting ranging attempts
- Soviets and French *both* got returns December 1970, during first lunar night
  - but *both* failed in subsequent attempts, even after end of mission
- Americans (at McDonald 2.7 m) never convincingly found it
- A 1976 report states that Soviets found L1 again in May 1974
  - claims regular observations thereafter
  - not part of the international LLR dataset
  - attempts to recover these records were unsuccessful
- APOLLO tried occasionally, beginning April 2008
  - in hindsight, had no chance of success

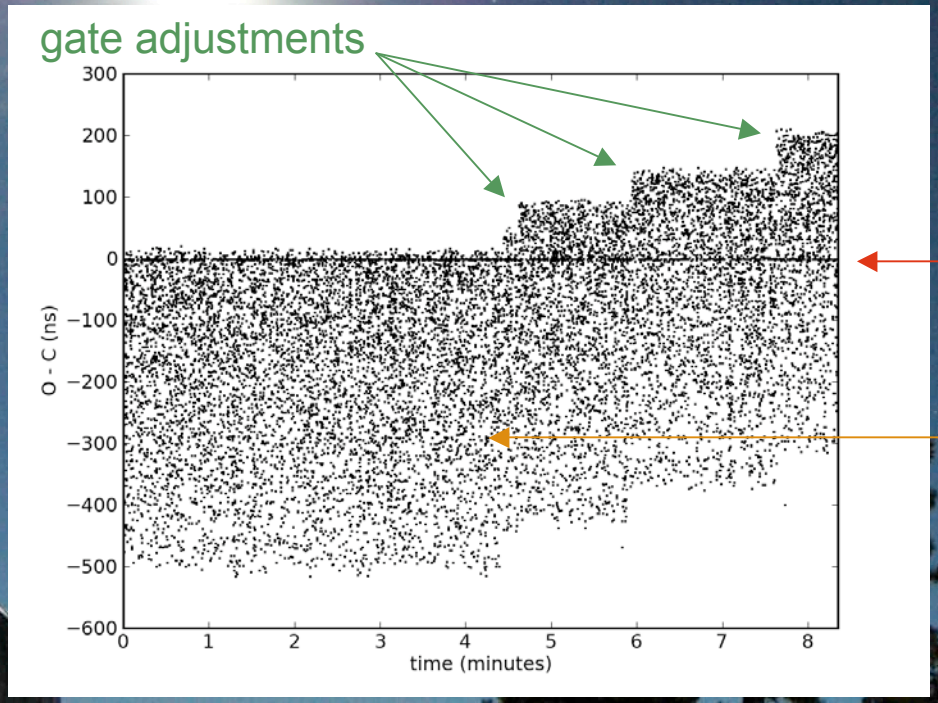
Enter LRO

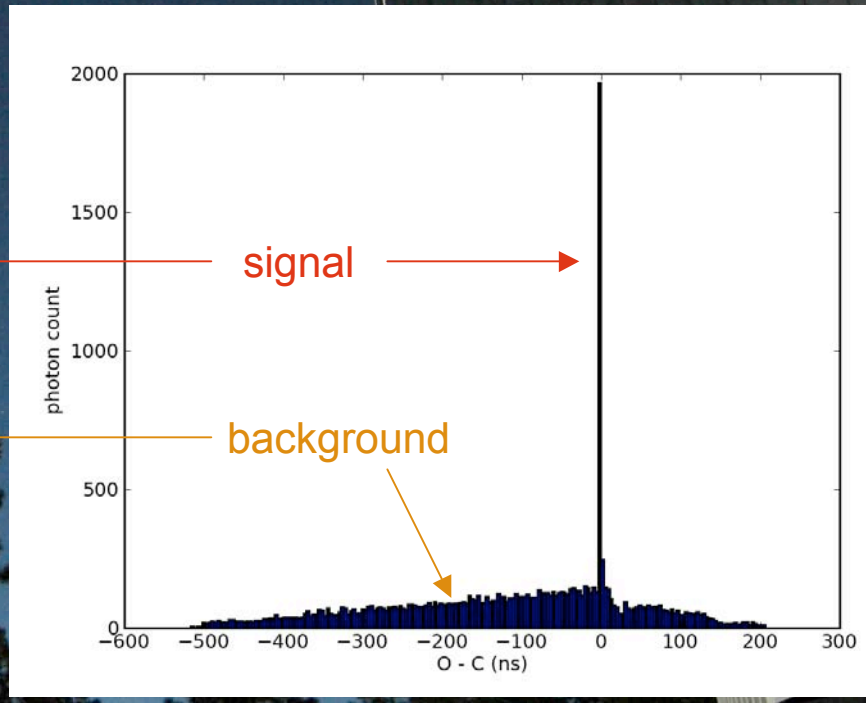
- The Lunar Reconnaissance Orbiter (LRO) helped in three ways:
  - LROC imaging (March 2010) found the rover and provided coordinates (thanks to Mark Robinson & Jeff Plescia)
  - LOLA altimetry fixed the site radius (thanks to Greg Neumann)
  - A CCR array on LRO prompted APOLLO to develop a wide-gate capability, making searches easier (thanks to Dave Smith & Xiaoli Sun)





APOLLO Find, 22 April, 2010





- Armed with 100 meter accurate coordinates and a wide gate capability, APOLLO's first favorable telescope time produced stunning results
- Offset was 40 m (270 ns) in projected range (100 m lateral), putting signal at edge of gate
- Gate adjustments in first run confirmed reality
- Almost 2000 photons in first try: so bright we thought we were being fooled

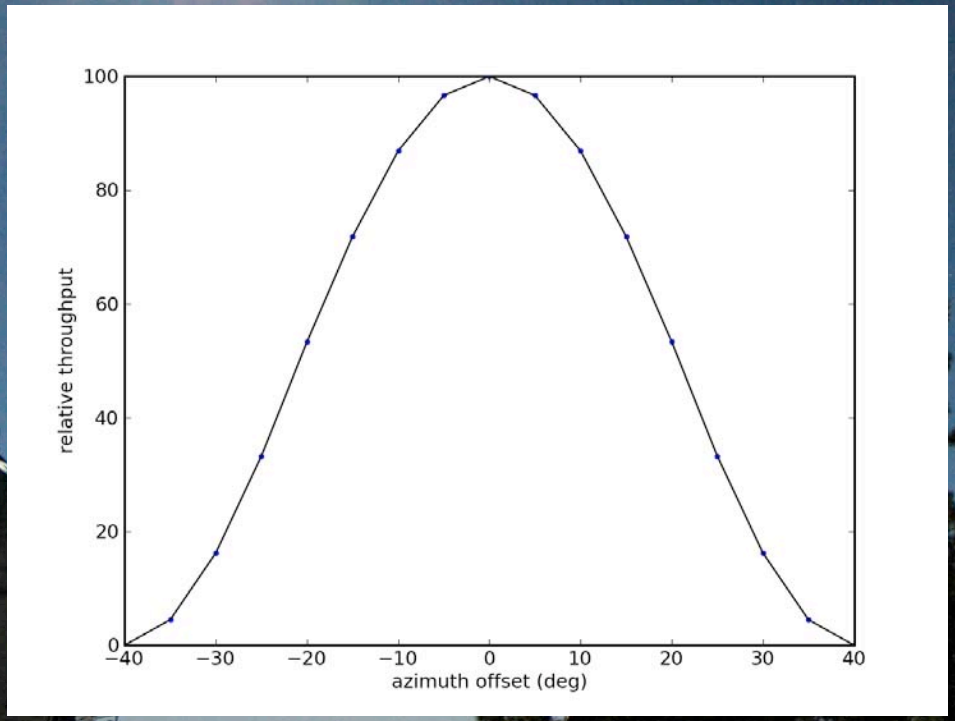
Comparative Reflector Performance

Date	Sun Angle at L1	Rate Factor (photons/shot)	A11	A14	A15	L1	L2
2010-04-22	–18°	0.0894	0.47	1.23	3.30	1.70	—
2010-04-26	22°	0.0383	0.08	1.24	3.76	0.06	—
2010-05-05	32°	0.1770	0.61	1.06	3.33	0.23	0.17
2010-05-23	–3°	0.0864	1.12	0.56	3.32	0.79	—
2010-05-24	7°	0.0116	1.19	0.61	3.20	1.08	—
2010-06-16	–45°	0.0426	0.96	1.08	2.96	0.59	0.14
2010-06-20	–16°	0.0077	2.34	0.78	1.88	1.49	—

- The return rate varies dramatically from night to night
- Normalized to make A11+A14+A15 = 5.0 as per 1:1:3 ratio
- Yellow numbers → in daylight; orange numbers → in the dark
- L1 is doing better in the dark, but still usable in daylight, unlike L2
- Summary table shows L1 as good as A11/A14 in dark; 5× better than L2

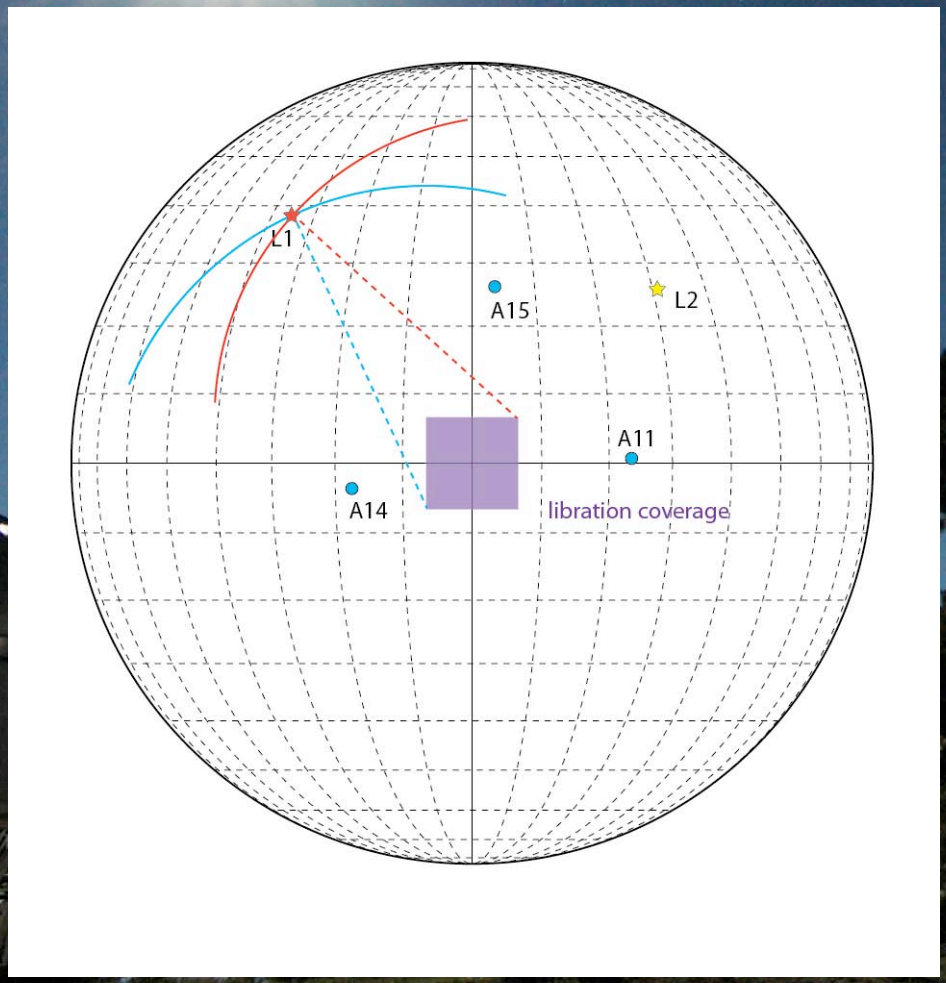
Condition	A11	A14	A15	L1	L2
All	0.96	0.94	3.10	0.85	0.16
Dark	—	—	—	1.14	—
Light	—	—	—	0.46	—

Good Parking



- A common speculation was that the Lunokhod 1 rover was poorly parked: the reflector not facing earth
- If the rover azimuth were off by as much as 40°, no return would be possible
- The fact that L1 is comparable to the Apollo arrays indicates a small azimuth offset

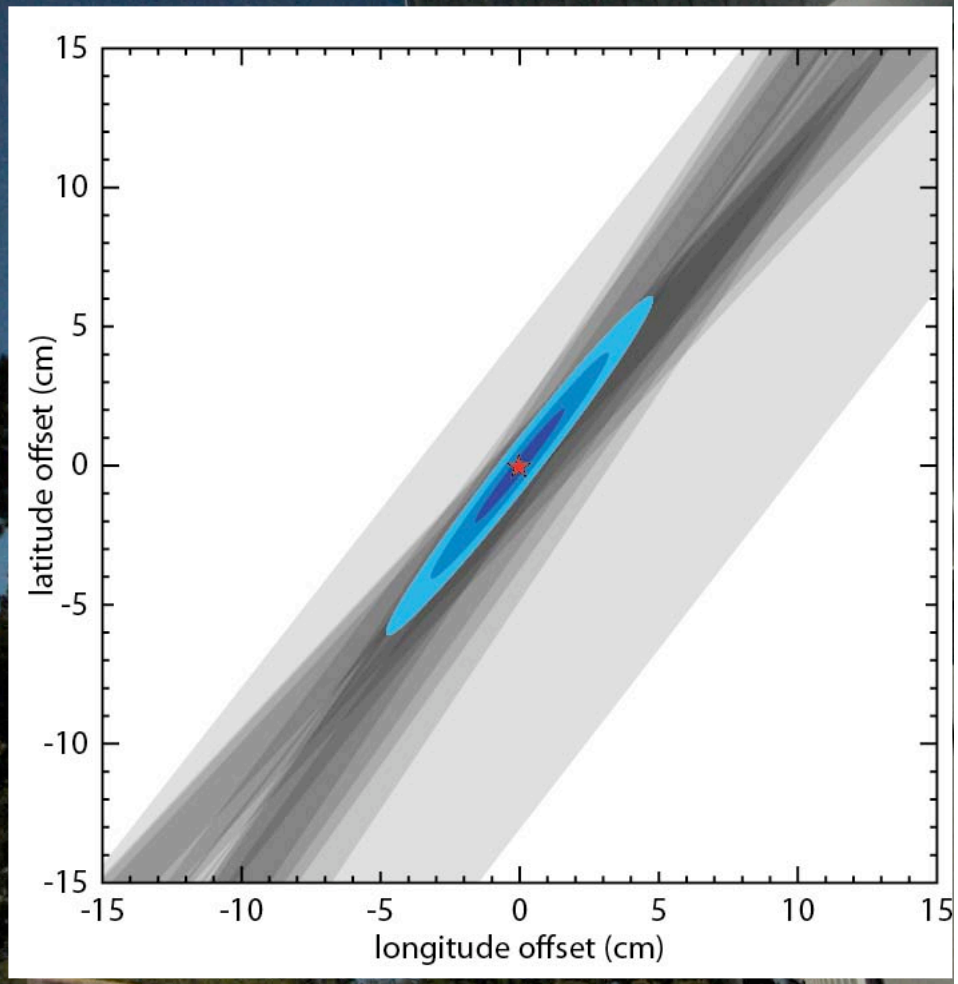
Location Determination



- Range measurements at different librations allow us to pinpoint the reflector location
- Each range measurement is a slice intersecting the moon in a “small” circle centered on the sub-earth point
- For L1, the arcs cross at a maximum of ~20°
- Our observations through June 2010 are enough to constrain the position in selenographic coordinates to about 0.1 m

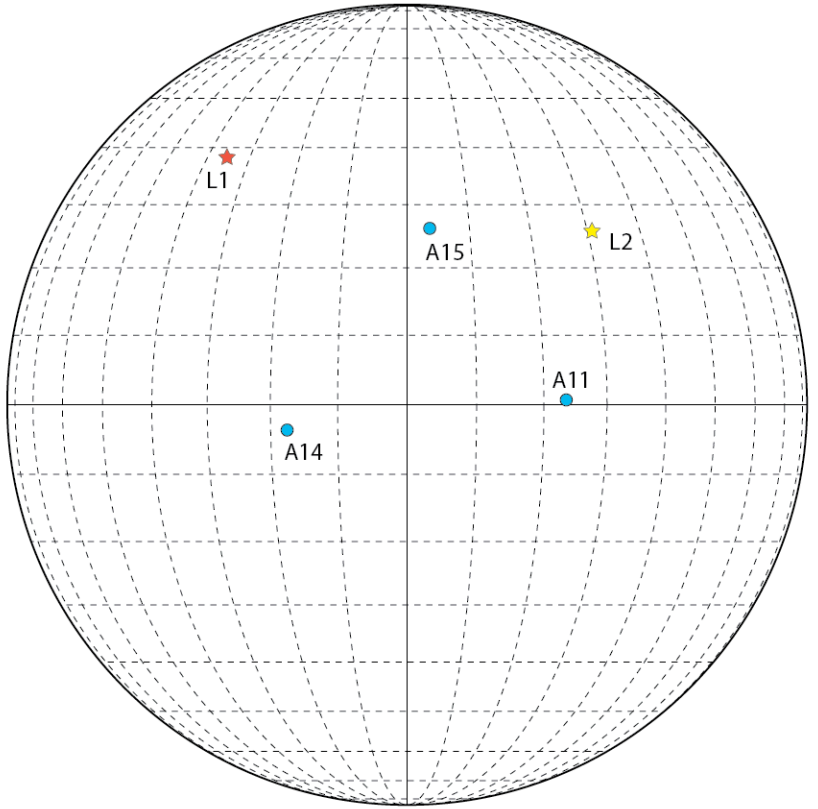
Current Error Ellipse

- Based on a few months of observation at a limited sampling of librations, we have a decimeter-level position determination
- Error ellipses are 1σ, 2σ, 3σ
- Lunar tidal deformation not considered in model for fit, so could have 0.1 m systematic offsets, still
- Best-fit position, in DE421 Principal-Axis coordinates:
  - r = 1734928.14
  - lat = 38.333072°
  - lon = –35.036654°



Potential Impact on Science

- L1 is the farthest reflector from the apparent lunar center
- Offers best leverage on libration determination
  - key for C.o.M. motion → gravity
  - also for lunar interior study
- Unlike Apollo reflectors, L1 (and L2) offer *both* latitude and longitude libration sensitivity
- More reflectors probe tidal deformation



Reflector	θ from center	libration sensitiv.	longitude sensitiv.	latitude sensitiv.
A11	23.5°	0.40	0.40	0.01
A14	17.9°	0.31	0.30	0.06
A15	26.4°	0.44	0.06	0.44
L1	50.0°	0.77	0.45	0.51
L2	39.5°	0.63	0.46	0.37

Summary: Good News for LLR

- Lunokhod 1 is found, and good coordinates established
- The reflector is in very good condition
- A fifth reflector provides better probe of tidal deformation
- L1 is particularly well-placed for libration determination
  - best lever arm
  - latitude *and* longitude sensitivity
  - key for translating reflector measurements into center-of-mass measurements (thus tests of gravity)
  - key for elucidating lunar interior

- P.S. Lunar reflectors have degraded with time; see me if interested