Lunar Observatories — Demand and Opportunities for Geological Studies and Geophysical Network Sciences

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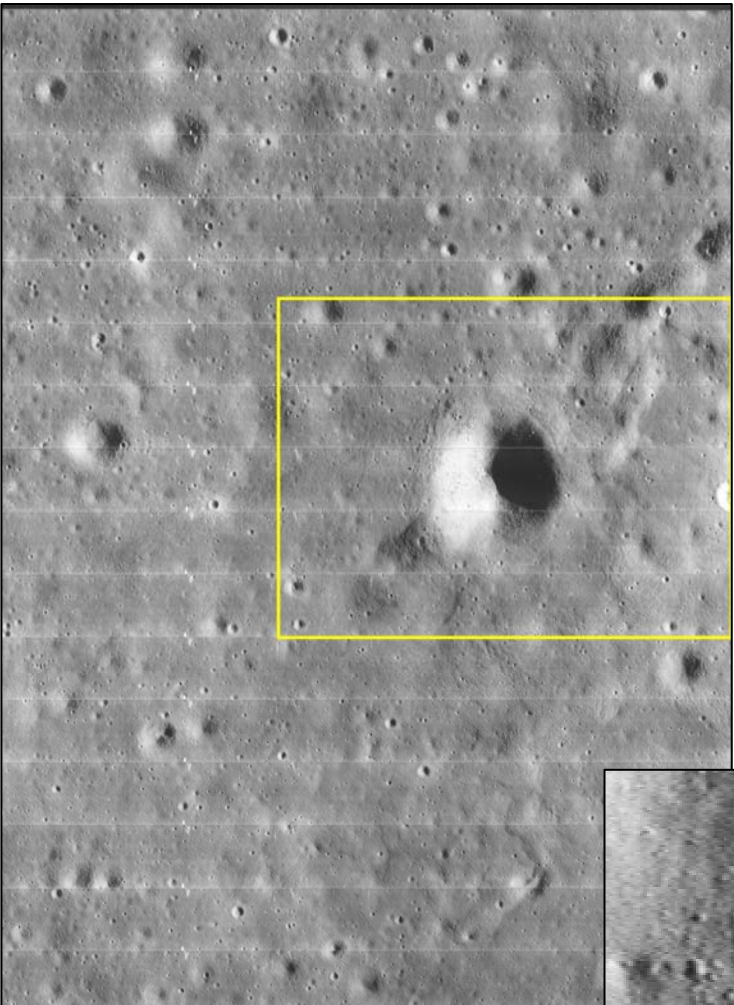
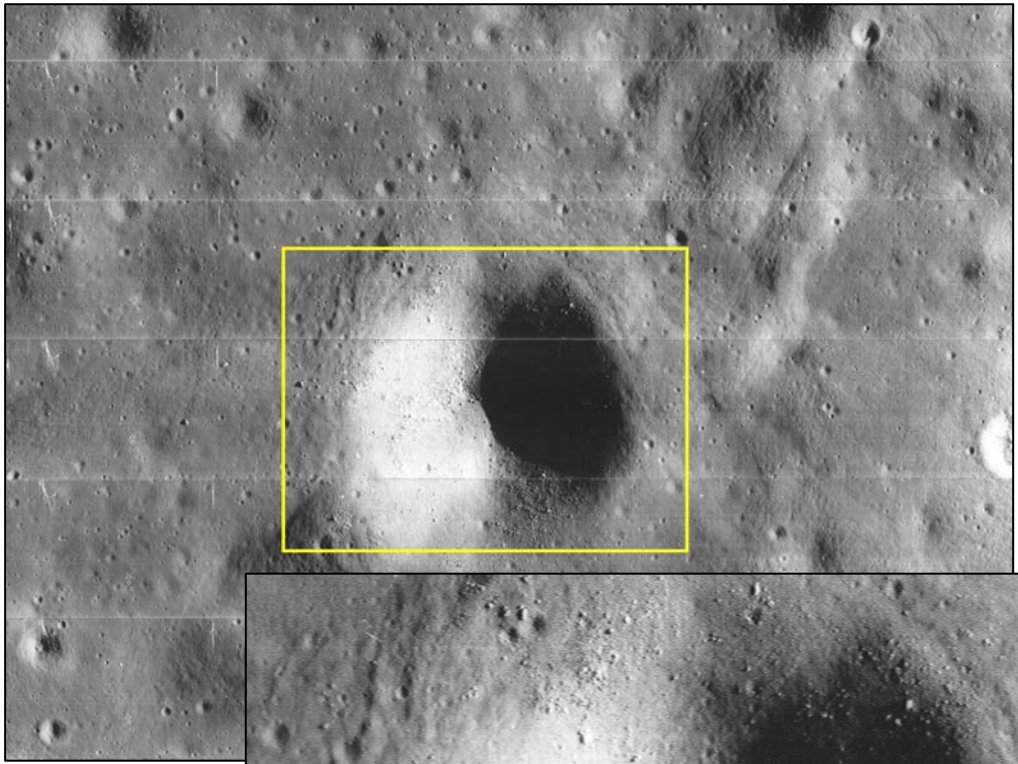
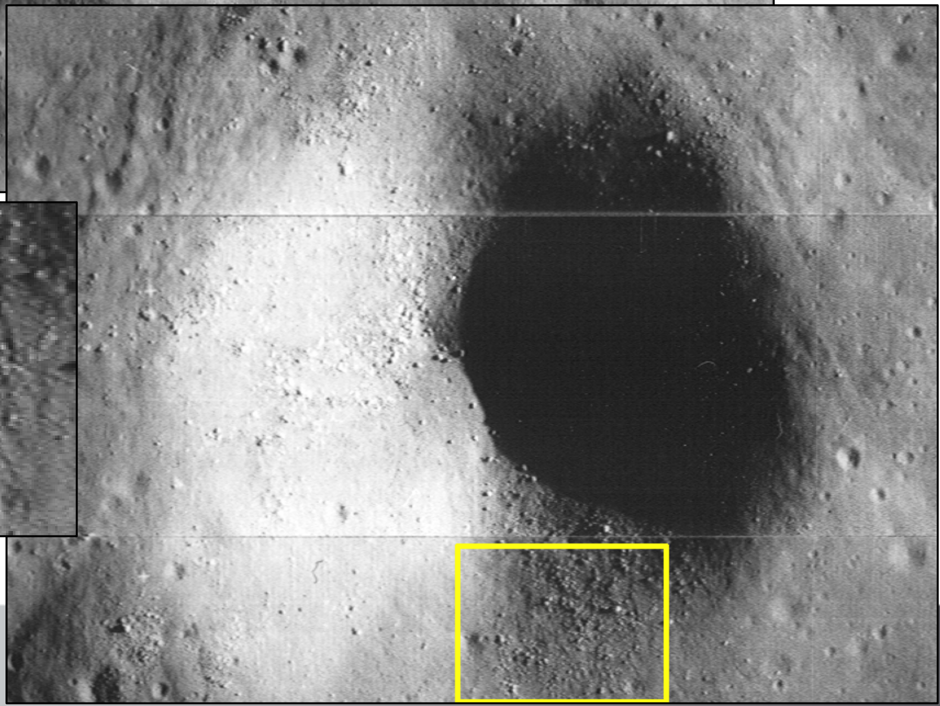
Lunar Observatories — What Is Needed

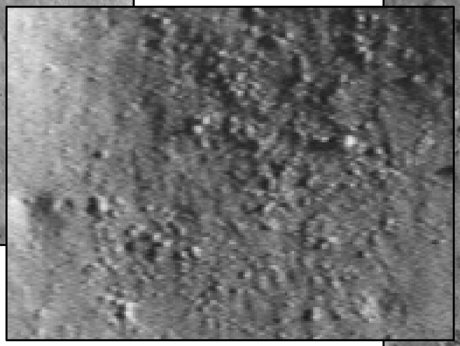
- Good knowledge of landing site area prior to landing, e.g. morphology, topography, obstacles, …
- Improved knowledge on regolith properties
- Precise location and tie to celestial reference frame
- Detection and monitoring of crustal „shaking“ and deformation
- Imaging instruments on lander and rovers for navigation, operations and surveillance ➔ tools available for local geological studies

Lunar Orbiter-2, 1966-11-22









LO2 110h2 (North of Ptolemaeus)
Spatial resolution: 0.6 m/pix

Lunar Exploration

	SMART-1 [ESA]	**SELENE [JAXA]**	C**hang'E** [CNSA]	C**handrayaan**1 **[ISRO]**	**LRO [NASA]**
Launch	2003	2007	2007/8	2008	2008
Orbit	400 x 4000 km polar	100 km polar circular	200 km polar circular	100 km polar circular	50 km polar circular
Objectives	Technology demonstration; investigate poles; Sept 2006 impact ending	Study lunar origin and evolution; develop technology for future lunar exploration	Surface structure, topography, composition; particle environment	Simultaneous composition and terrain mapping; demonstrate impact probe	Improve geodetic net; evaluate polar areas; study radiation environment
Payload	AMIE, CIXS, SIR, plasma experiments	TC, MI, SP, relay satellites, X-ray, g-ray; laser altimeter; radar sounder, magnetometer, plasma imager	4-band micro-wave, IIM, X-ray, gamma-ray, WA stereo, energetic ions, laser altimeter	TMC, HySI, LLRI, HEX, Impact probe + *C1XS, SARA, SIR2, miniSAR, M3, RADOM*	LOLA, LROC, LAMP, *LEND*, CRaTER, Radiometer **LCROSS**

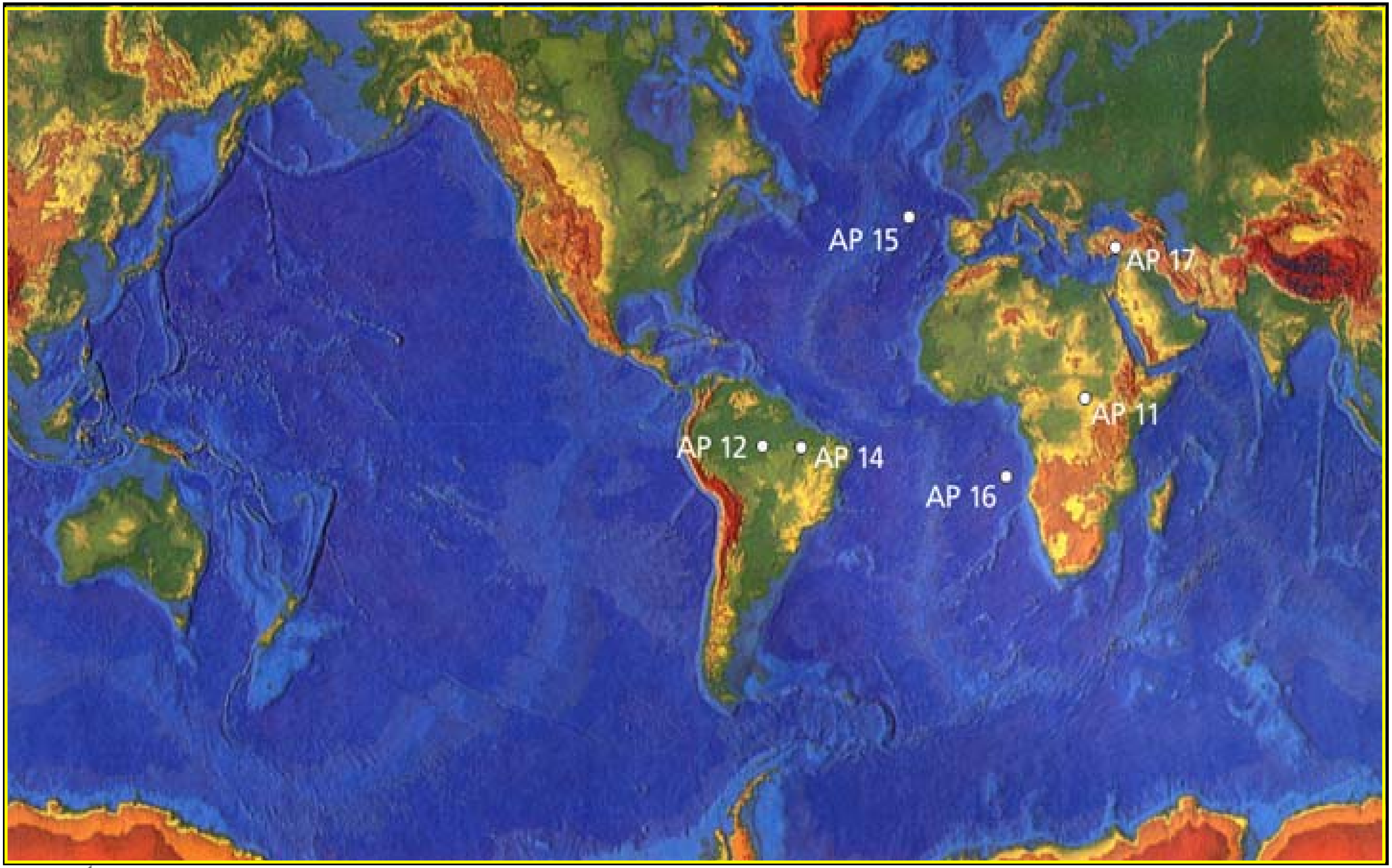
Lunar Missions: Cameras and Spectrometers

	Imaging resolution	Imaging coverage	Digital terrain model	Spectr. (Vis/NIR) spatial resolution	Spectrometer coverage
Scientifically requested	*1m*	*100 %*	*Stereo (3d imaging) 5 m grid, 1 m height global*	*<50m*	*100%*
Missions up to now Lunar Orbiter to Smart1 (not including Apollo)	**2m ~50m**	**few % at 2m 99% at 50m**	**97% at ~8km, no poles >100m range few %**	**300m**	**10%**
Selene, Japan	**10m**	**undefined (probably global)**	**Laser altimeter ? m grid, 5m height coverage undefined**	**500m**	**undefined**
Chang'e-1, China	**> 100m**	**undefined**	**Laser altimeter performance unknown**	**performance unknown**	**undefined**
Chandrayaan, India	**5m**	**undefined (probably 10%level)**	**Laser altimeter ? m grid, 10m height coverage undefined**	**80-130m**	**< 50% at 80m 130m global**
LRO, USA	**~1m 100m**	**10% at 1m landing sites 100% at 100m**	**Laser altimeter 50m grid, 1m height global**	**N/A**	**N/A**

Necessary remote sensing data will only be available for some areas

Apollo, Surveyor, Luna and Lunokhod Landing Sites

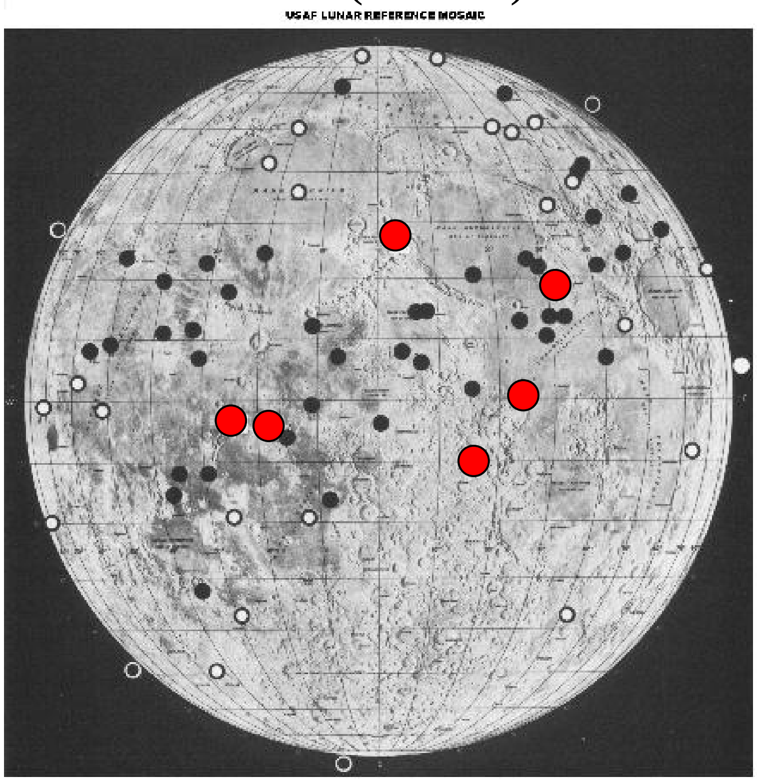
Been There, Done That?

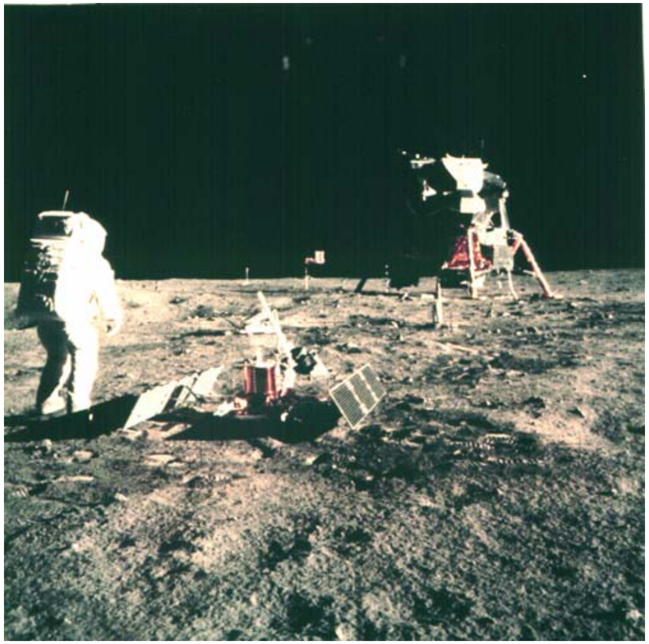


Apollo Surface Stations

Geophysical measurements:

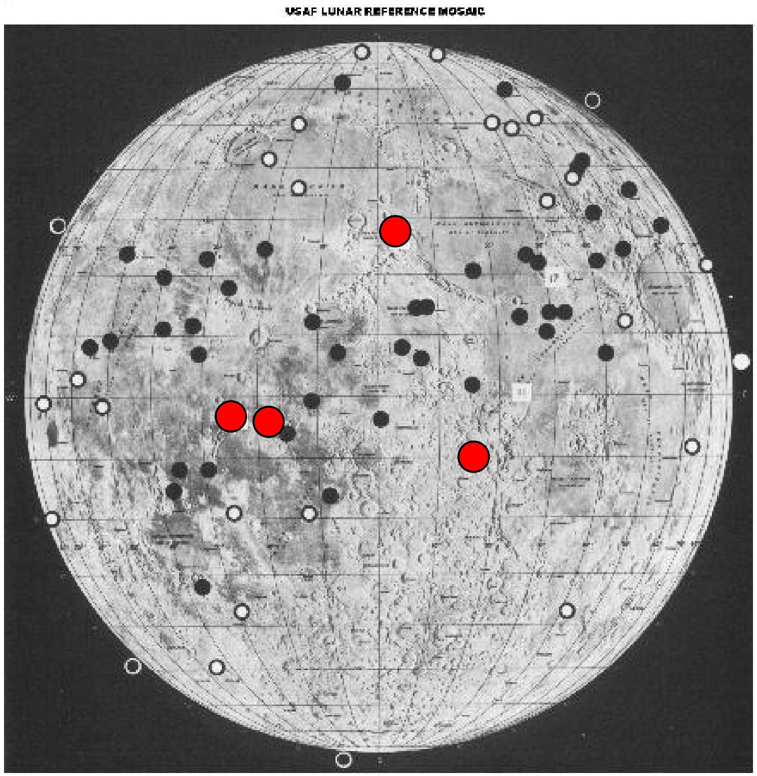
- Seismic stations (12, 14, 15 + 16)
- Magnetometer (12, 15 + 16)
- Thermal flux (15 + 17)





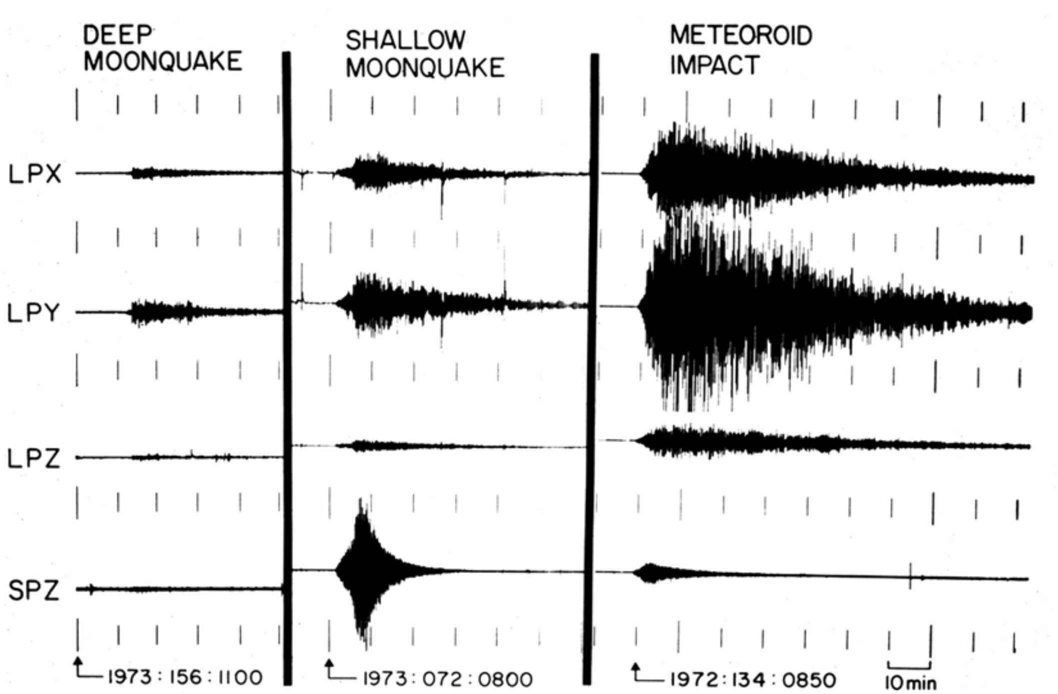
Apollo 11: 16 July 1969
Apollo 12: 14 Nov. 1969
Apollo 14: 31 Jan. 1971
Apollo 15: 26 July 1971
Apollo 16: 16 April 1972
Apollo 17: 07 Dec. 1972

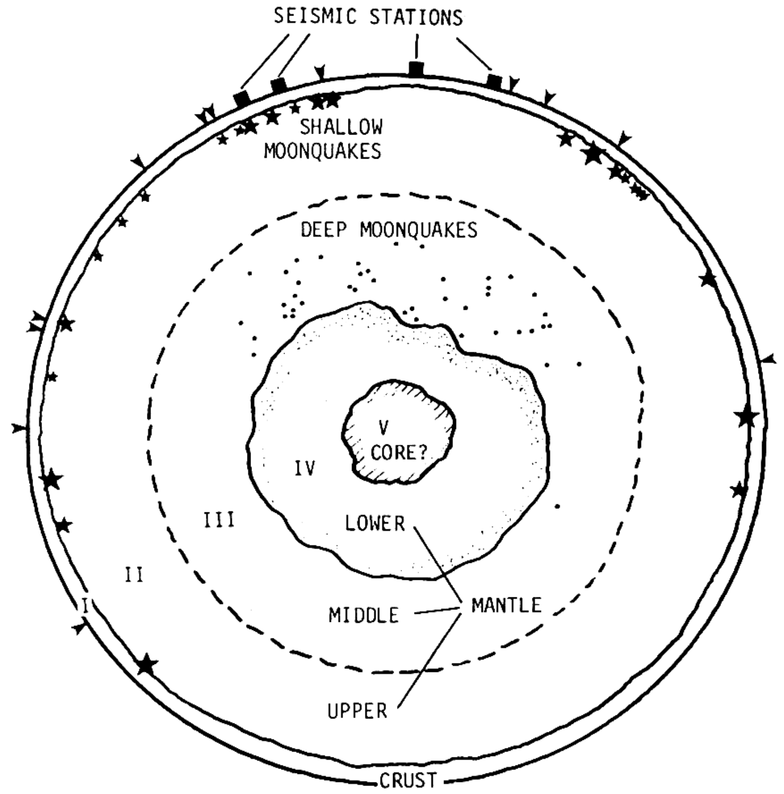
Apollo: Lunar Seismic Stations



- Apollo 12, 14, 15 & 16
- Triangle with ~ 1000 km
- Long-periodic (~ 0.1 Hz) seismometer (3 axis) + short-periodic (~ 1-10 Hz) seismometer (vertical axis)
- November 1969 - September 1977

Seismic Events and Lunar Structure

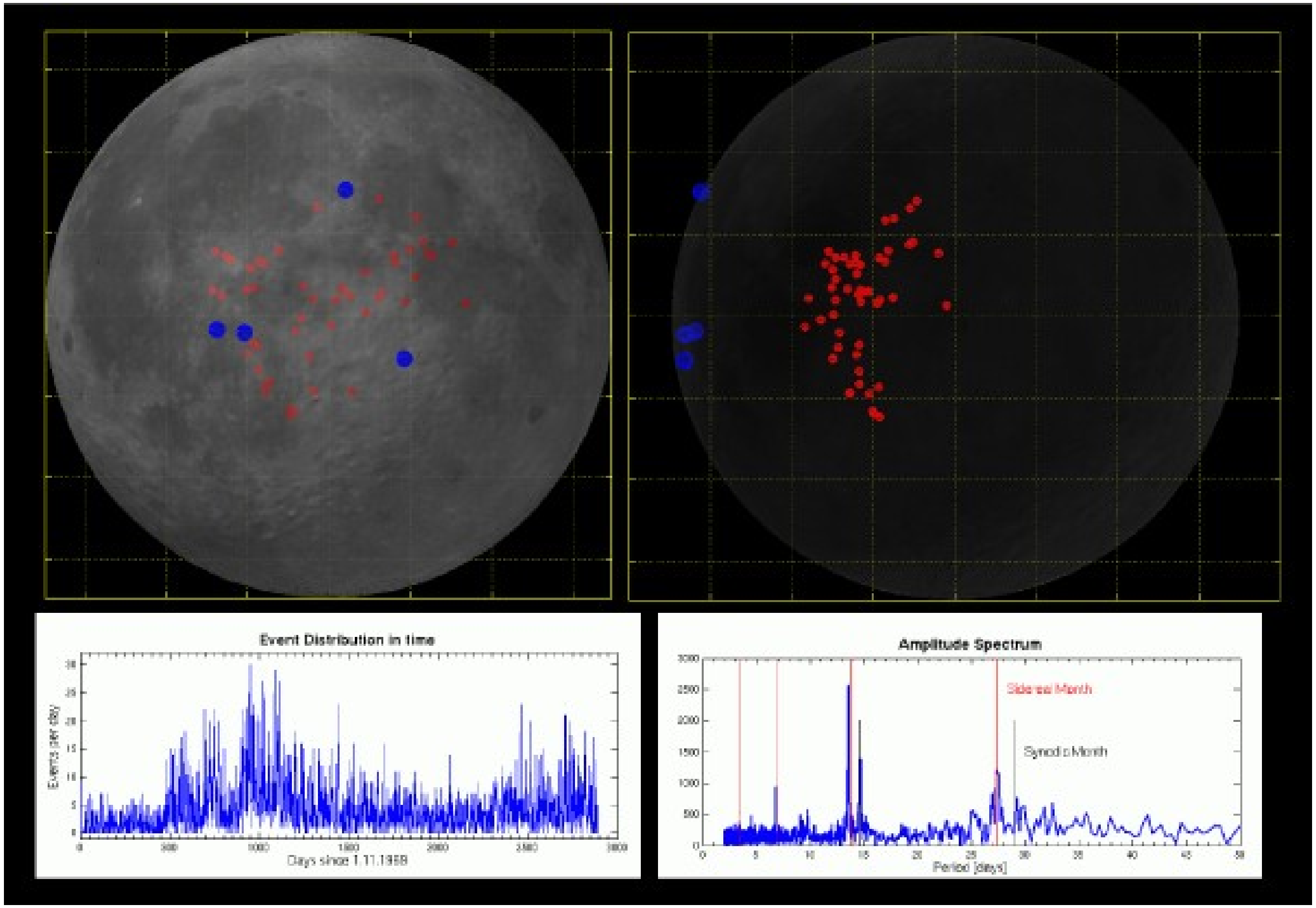




> 13,000 events

Nakamura, 1983

Deep Moonquakes

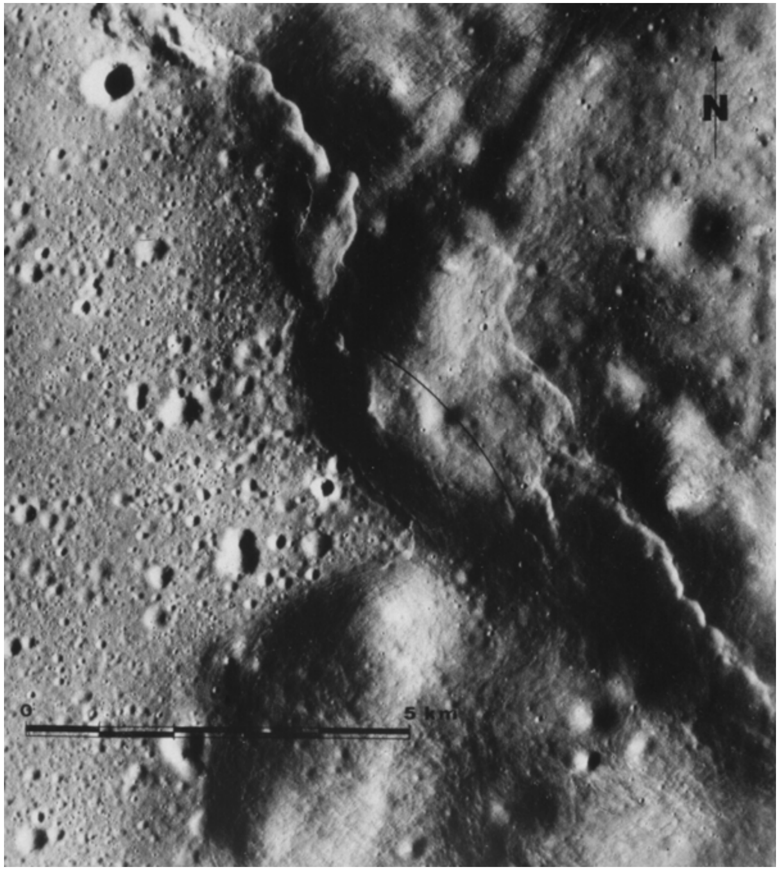


Knappmeyer et al, 2005

- Depths of 700-1200 km
- > 8000 events
- > 300 nests of quakes
- Quakes correlate with tidal cycle
- Nests only on near-side (?) *)

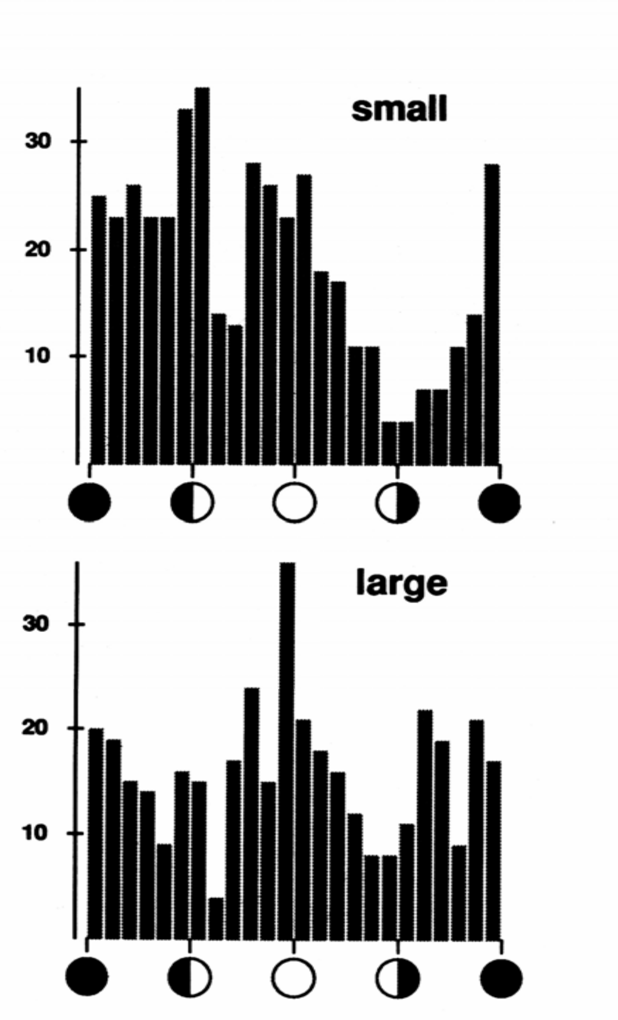
*) except: A033

Shallow Moonquakes



- … occasionally but strong: magnitude up to 5,5
- 28 events
- Sporadic occurrence in crust or upper mantle

Meteoroid Impacts



- 1744 events
- Objects: several grams to 10 tons
- Impact rate of “small” and “large” objects depends on day-time
- Impacts often as swarms

Opportunity for a Lunar Seismic Network

- Implement global broadband seismic netwok by piggy-backing lunar observatory stations
- Objectives
  - Determine seismic velocities below 1000 km depth
  - Detection of surface waves
  - Mapping of crustal thickness (globally)
  - Determine the interior structure (core, partially molten layers, …)
  - Explain the intrinsic mechanism of moonquakes (nests)
  - Monitor meteoroid impacts

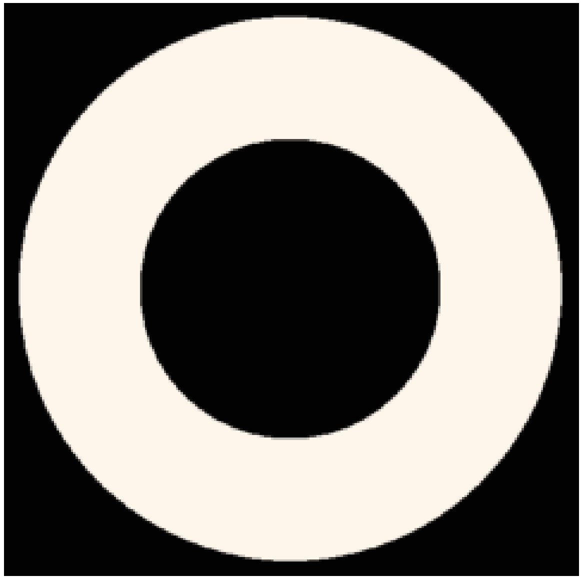
- Normal modes and tidal responses
- Megaregolith structure

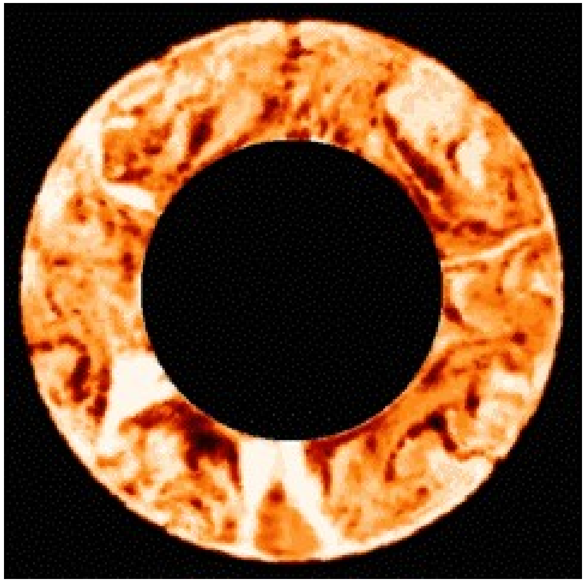
Lunar Magnetic Measurements

- Surface magnetometers on Apollo 12,15 and 16 reveal regional variations in intrinsic magnetic field strength ➔ strong localized magnetic field sources in the crust
- Orbiter (Lunar Prospector, Apollo) and surface measurments during passage of the moon through geomagnetic tail of lunar induced magnetic field indicate
  - Lunar core may have < 450 km radius
  - Temperature may approach melting point at depths between 800 to 1500 km
- Magnetometers proposed as part of geophysical network to
  - Obtain better ground-truth on local magnetic field sources
  - Monitor the residual lunar induced magnetic dipole moment

Lunar Thermal Evolution

- Thermal evolution is a fundamental factor shaping the geologic evolution of a planetary body
- Details are
  - Heat acquired during accumulation
  - Abundance of radioactive isotopes
  - Chemical differentiation
  - Nature of convective processes
- Key parameter for thermal evolution models is the present-day interior heatflux
- Apollo 15 & 17 measured heat flux in KREEP-rich areas which may be mainly determined by crustal radioactive isotopes
- New measurements in areas of different crustal thickness needed to determine average recent heat flow

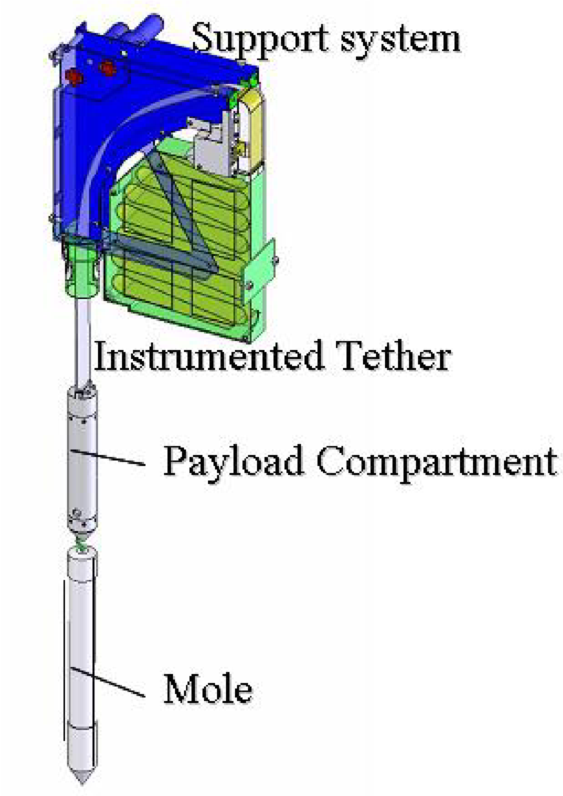


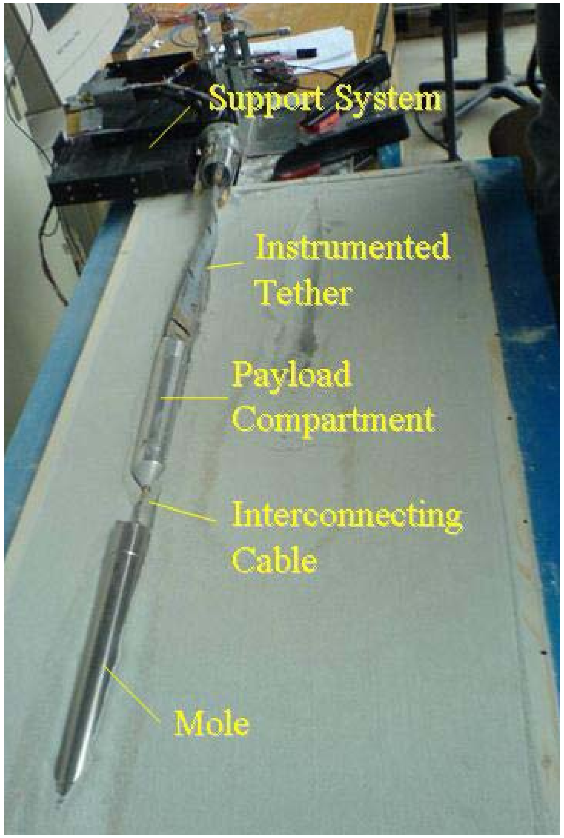


Breuer et al, 2005

Heat Flow and Physical Properies Package (HP^3)

Heat flow & regolith physical properties and structure





Breadboard

Sensors:

- Heat sensors
- Electrical sensors
- Tiltmeter & accelerometer

Measured:

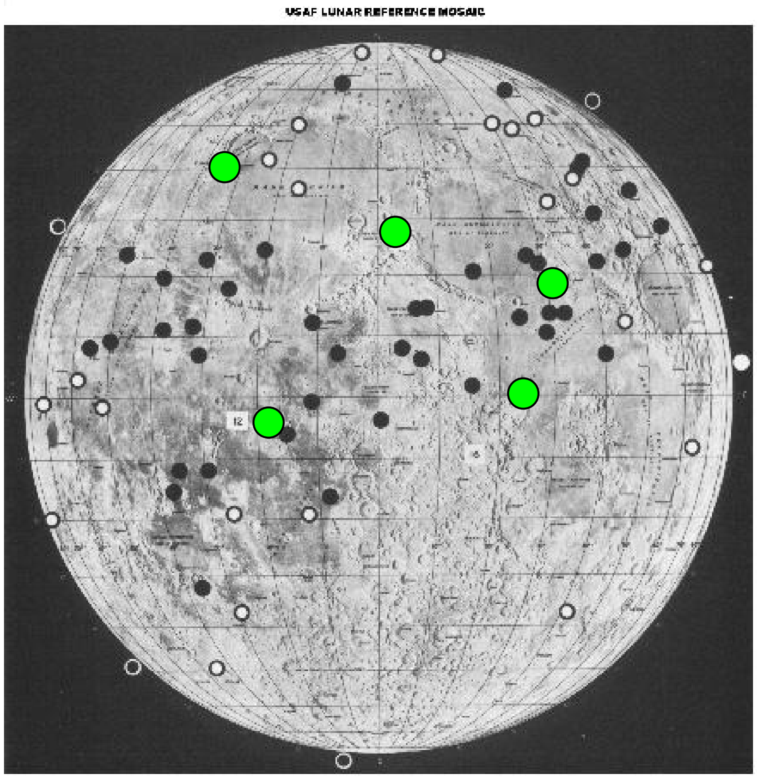
- Temperature
- Thermal conductivity
- Thermal diffusivity
- Electrical conductivity
- Relative permittivity

Derived:

- Surface planetary heat flow
- Porosity
- Grain size
- Compressive & shear strength
- bulkdensity

Laser Retroreflectors on the Moon

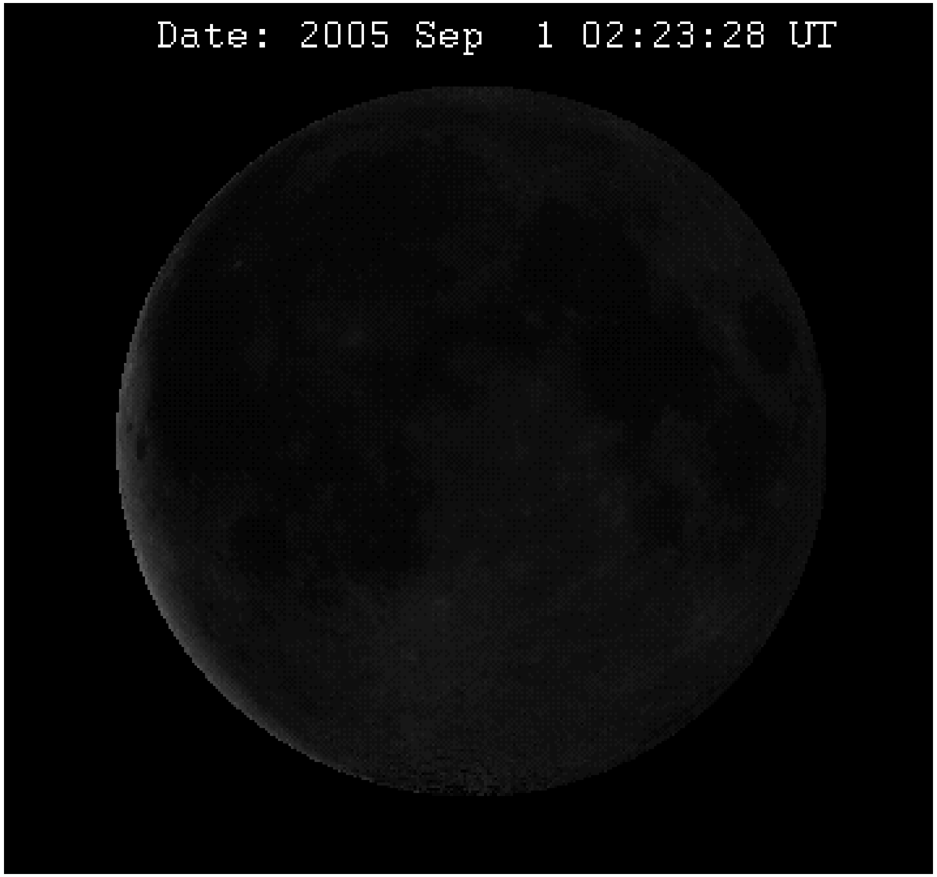
- Apollo 11, 14, 15
- Luna 17, 21 (Luna 17 “lost”)



Wettzell

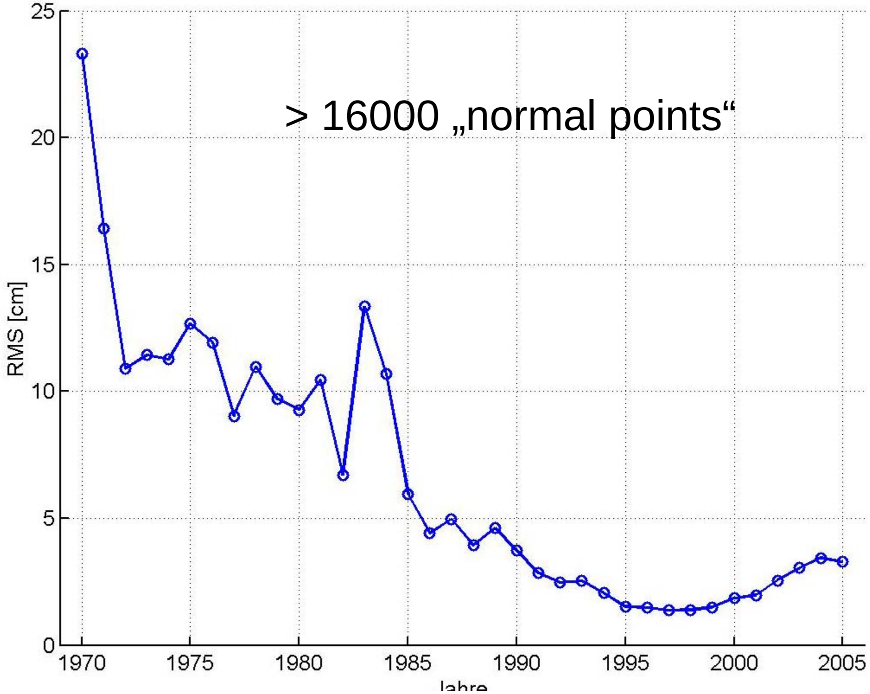
Apollo 15 Retroreflector

Lunar Librations

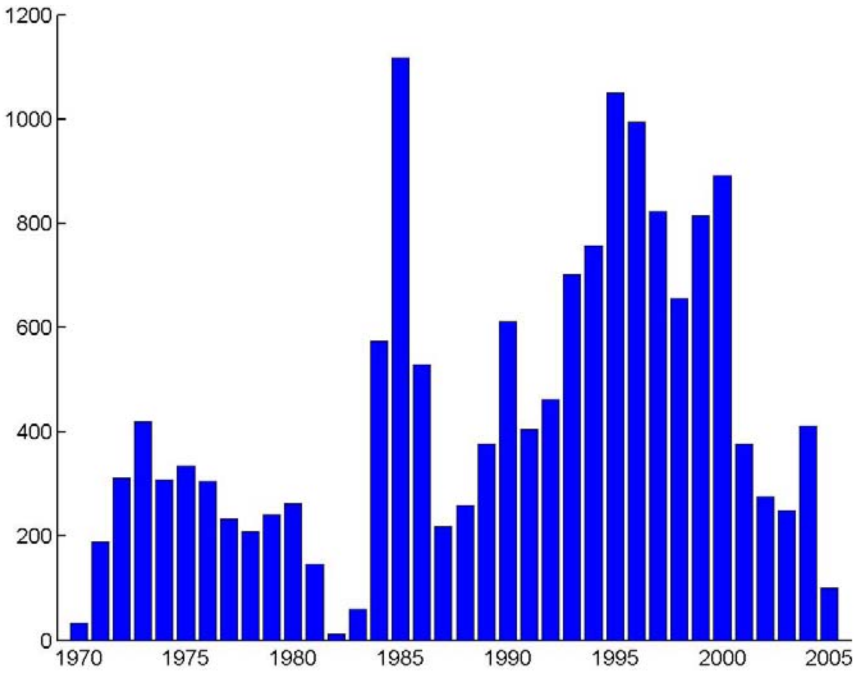


- Optical libration
  - libration in longitude ~ 7.9°
  - libration in latitude ~ 6.7°
  - parallactic (daily) libration ~ 1°
- physical libration (tidal forces) ~ < 0,04°

Laser Ranging Measurements

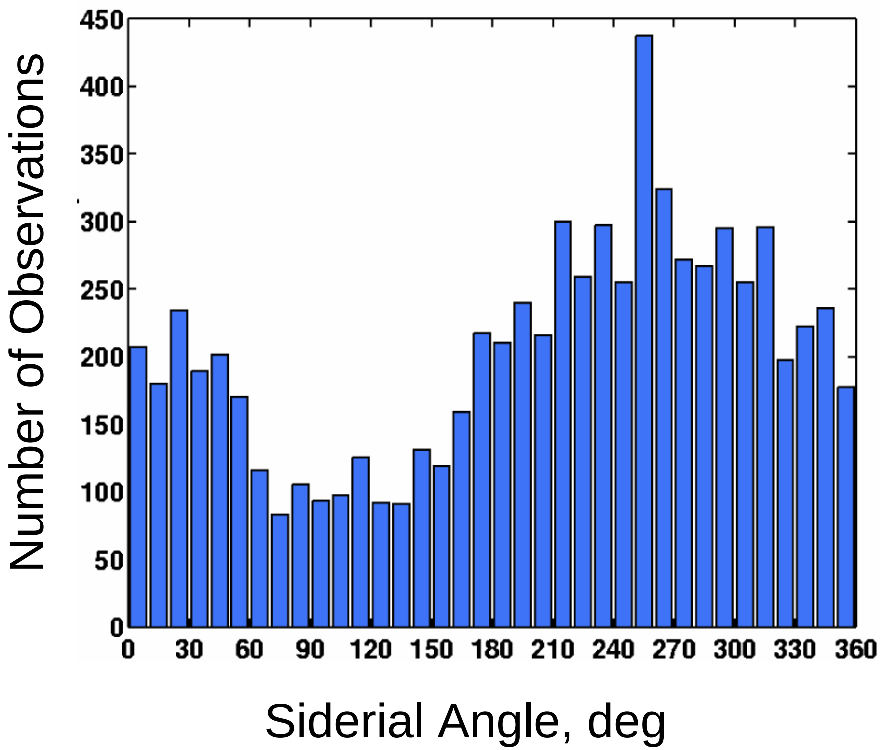


Laser Ranging radial distance residual errors



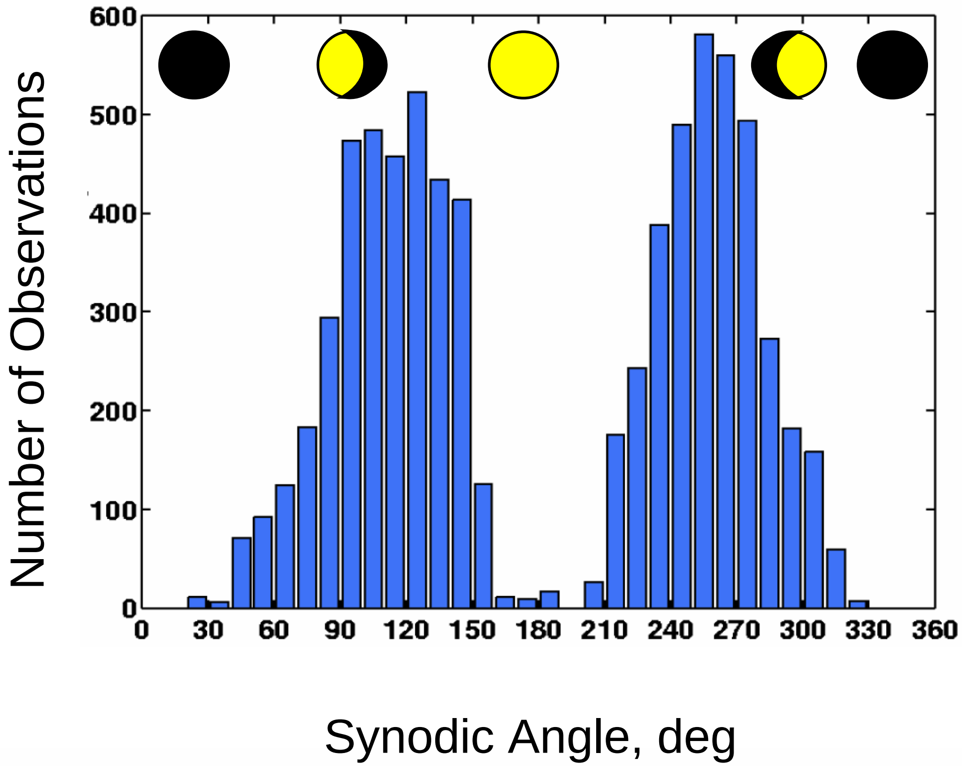
Laser Ranging statistics

Laser Ranging Measurement Bias



Very little observations from southern hemisphere

No observations at full or new moon



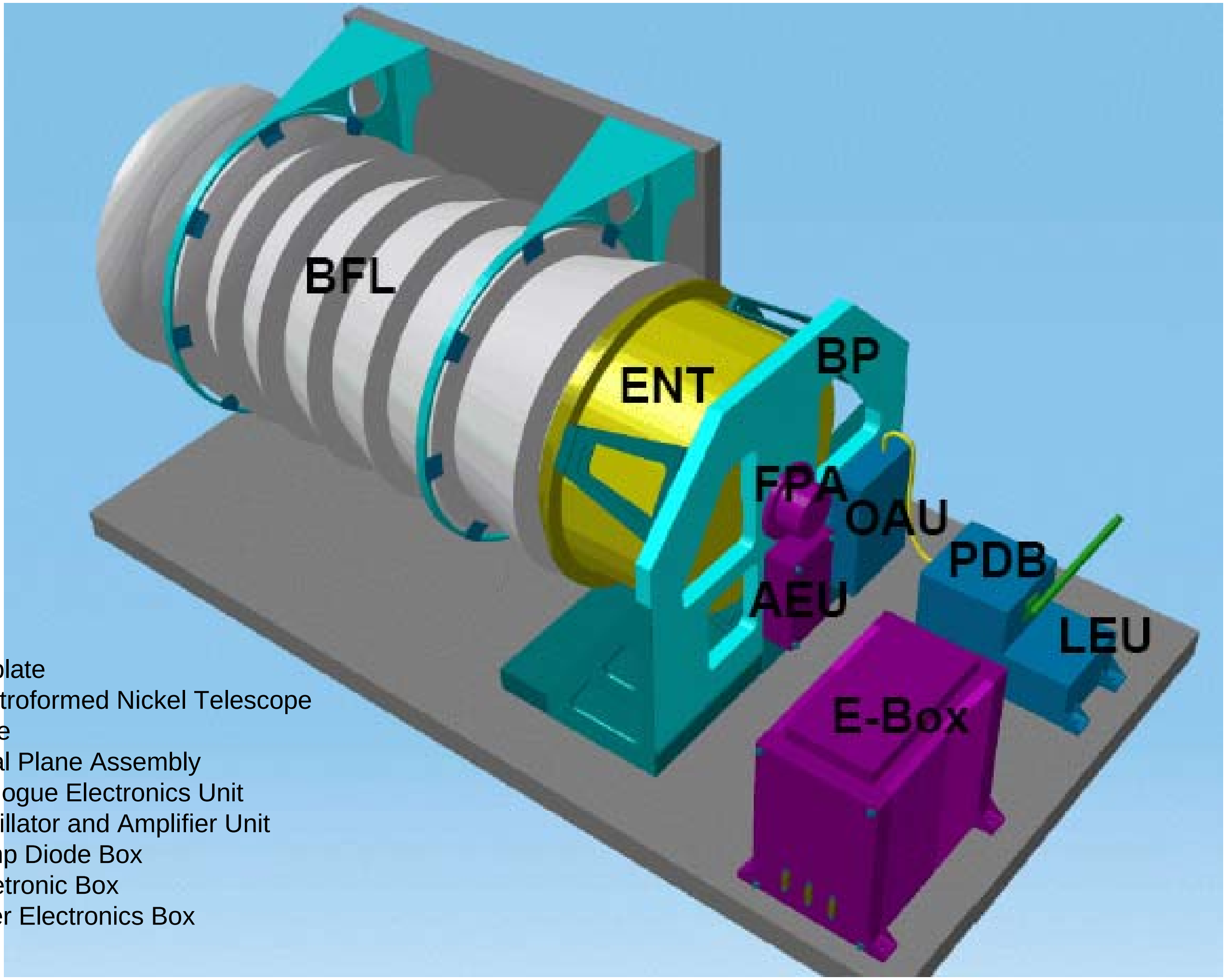
Laser Ranging:
Lunar Observatory Stations as Opportunity

- Laser retroreflectors with some disadvantages:
  - No measurements at full and new moon feasible
  - Only some of > 30 ILRS stations are technically able to perform measurements

- Laser beacons on lunar surface (about 20° FOV)
  - Much stronger signal (e.g. r^4 vs. r^2)
  - Observations at full and new moon (cover all time variations)
  - More stations able to perform measurements (also in southern hemisphere)
  - Higher accuracy (e.g. librations, deformation)

- Use of optical link (but much smaller FOV)

BELA (BepiColombo Laser Altimeter)



qualified laser are available

BP = Baseplate
ENT = Electroformed Nickel Telescope
BFL = Baffle
FPA = Focal Plane Assembly
AEU = Analogue Electronics Unit
OAU = Oscillator and Amplifier Unit
PDB = Pump Diode Box
E-Box = Eletronic Box
LEU = Laser Electronics Box

Lunar Laser Ranging Objectives

- Lunar interior structure, especially size and state of possible core:
  - Improve measurement accuracy of librations amplitudes
  - Define tidal deformation (amplitude and phase)
  - Refine tidal acceleration (3.8 cm/yr)

- Test of relativity, especially
  - Strong equivalence principle (Nordtvedt parameter)
  - Gravitational constant time stability

- Coordinates and reference frames
  - Determine coordinates of surface station
  - Refine selenocentric reference frame (e.g. horizontal error at high latitudes > few km, vertical accuracy > few 100 m)
  - Improve tie to J2000 reference frame

Lunar Geodesy Further Improvements

- Low-power microwave transmitter (pseudo random noise code):
  - Recorded by terrestrial VLBI stations
  - Map the moon with ist complex motion to celestial quasar reference frame (only nearside)

- „GPS"-type cesium clock and p-code transmitter
  - Tie selenocentric reference frame to terrestrial reference frame
  - Transform the moon in a „natural GPS-satellite" without atmospheric drag and solar radiation pressure

Conclusions

- Lunar observatory stations are a plattform to include geophysical stations for network sciences and instrumentation for geologic studies (e.g. imaging)
- Geophysical stations should include seismometer, magnetometer, heat probe and regolith analyzing tools
- On lunar near-side, geodetic experiments are beneficial for both, geosciences and astronomy