VLBI Experiments with Moon Exploration Spacecraft

Presentation at 9th ILEWG International Conference on Exploration and Utilization of the Moon (ICEUM9/ILC2007)

22-26 October, 2007, Sorrento, Italy

S.V. Pogrebenko[1], L.I.Gurvits[2]

prepared 2007.10.16, revision 8.2

(1) – Joint Institute for VLBI in Europe, Dwingeloo, The Netherlands, pogrebenko@jive.nl

(2) – Joint Institute for VLBI in Europe, Dwingeloo, The Netherlands, lgurvits@jive.nl

Abstract:

We analyze different possible applications of VLBI to future Moon Exploration Missions. Several scientific and engineering case studies are discussed.

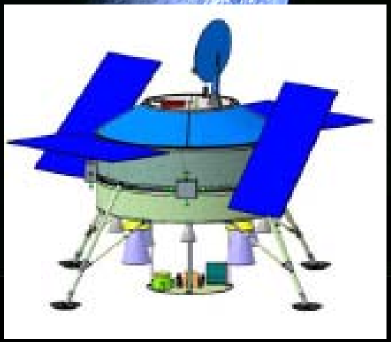
The Moon is getting to be quite a busy place

JAXA, Selene

CNSA, Chang ’E

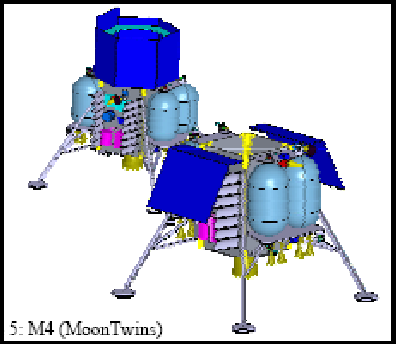
NASA, LRO

ISRO

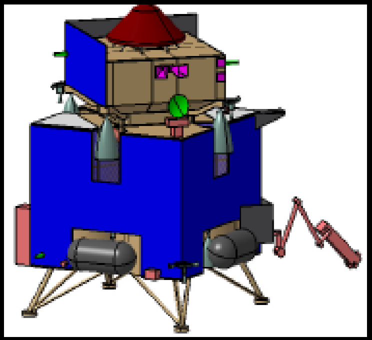


ESA M2 Lander

ESA M3 Lander and Orbiter



ESA M4 Moon Twins



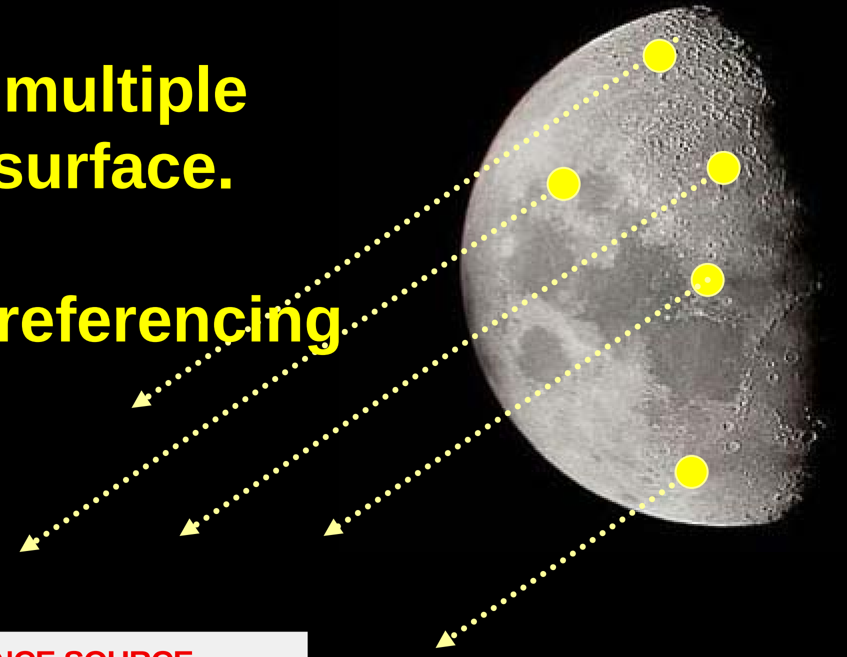
ESA LSR Lunar Sample Return

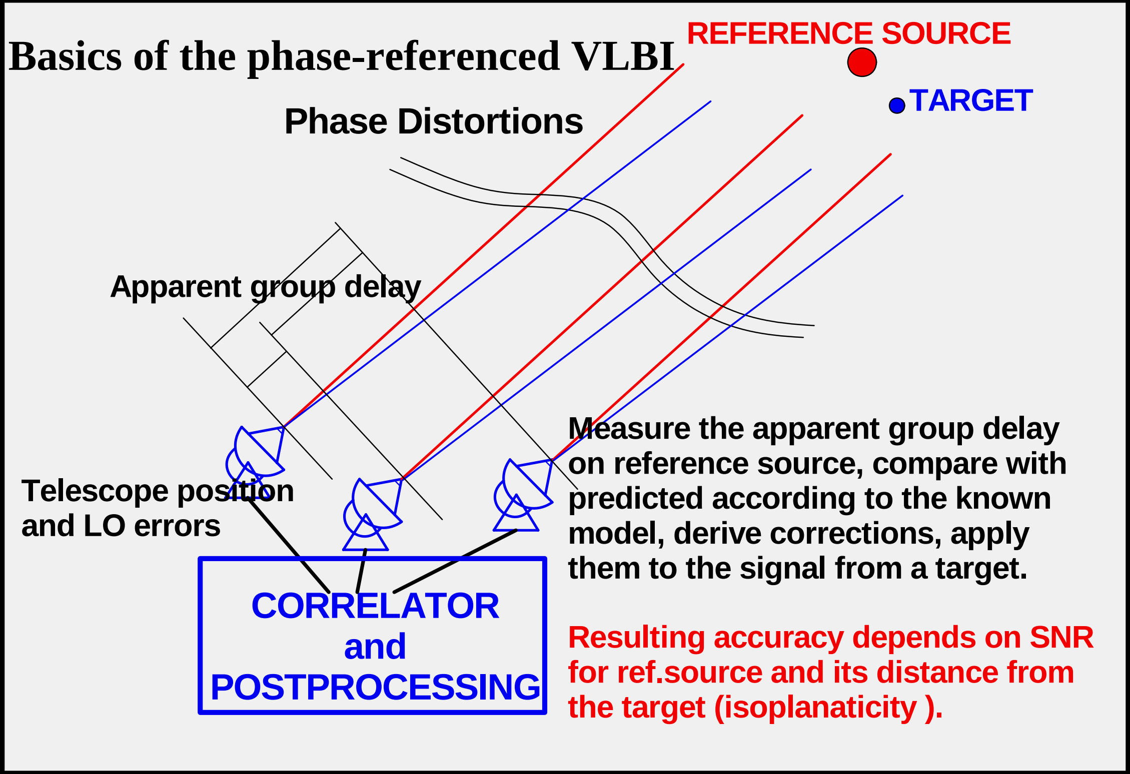
Ref: ESA /PB-HME(2007)47

Will be crowded soon !

Will be crowded soon with multiple transmitters on the Lunar surface.

A perfect situation for phase-referencing VLBI





Power Budget and Geometrical Accuracy Estimates:

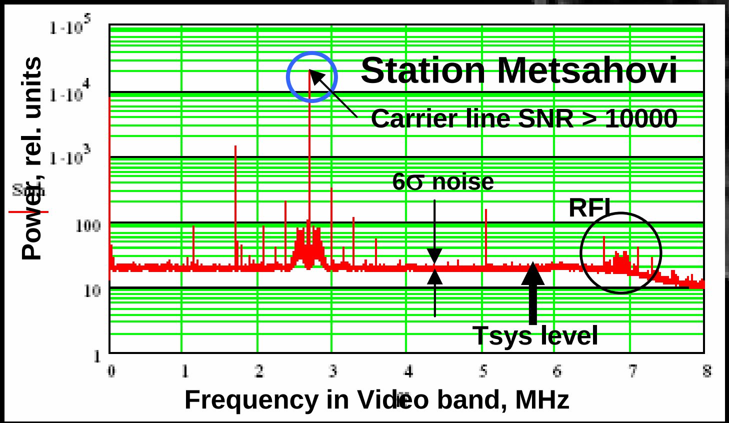
A single Earth-based 10-m antenna with “an empty sky” (Tsys=40-70K)

and with “the full Moon in-beam” (Tsys=300–500K)

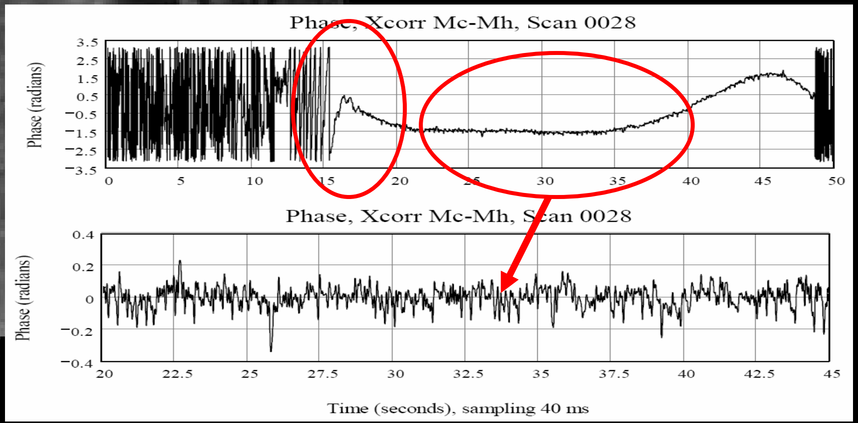
can detect a 1 mW single-tone transmitter at the Moon’s distance with

SNR = 3 in just several seconds.

SMART-1 VLBI test run results



Singe dish spectrum
(125 Hz resolution, 10 s integration)
of SMART-1 signal over an 8 MHz video band



Cross – correlation phase
on the baseline Metsahovi (FI) – Medicina (IT);
Stochastic phase noise 4.6 ps rms at 40 ms sampling

Metsahovi 14m antenna (Helsinki University of Technology, FI)

Power Budget and Geometrical Accuracy Estimates:

Mobile phone-class transmitters on the Moon will be detectable with an SNR of several hundreds in one second, yielding ~1 ps stochastic delay error on Earth-sized baselines.

A 1 ps delay error on a baseline of 3000-4000 km will correspond to a ~3 cm error in measurements of the distance between two transmitters on the Moon, within 1 second .

When observed with an array of several antennas the solution accuracy improves by a factor proportional to the number of antennas in the array.

Errors due to propagation effects will be suppressed, because all the transmitters are in-beam and within the isoplanatic patch of < 30 arc minutes. Although the isoplanaticity issues are the major concern and should be addressed as a special study.

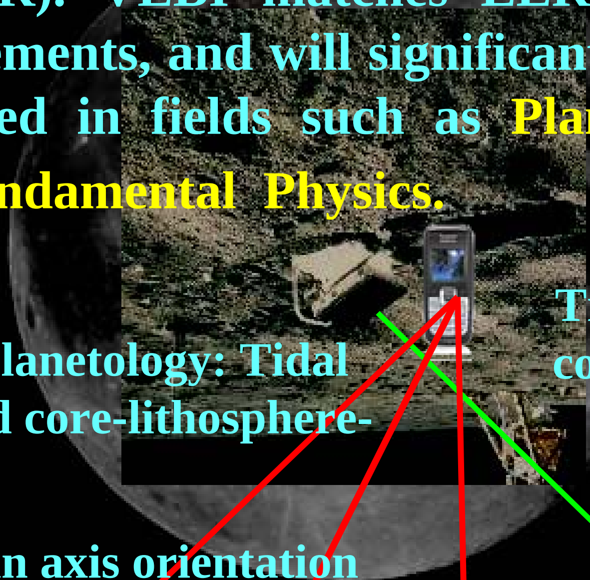
Another order of magnitude in precision, giving residual errors at sub-mm level, can be achieved after several hours by applying Kalman filtering and a model of the Moon's motion and tidal deformation.

Simultaneous in-beam observations of an orbiting S/C and Lunar surface beacons will provide the position of the S/C with sub-meter accuracy in the frame determined by the beacons.

Each 8-12 hours the Moon will be close enough to the VLBI calibrator radio source, which will allow to lock the state vectors of the beacons to the ICRS with sub-nanoradian accuracy.

Picture credit: Andrew Co.

VLBI on multiple transmitters on the Moon's surface is complementary to Lunar Laser Ranging (LLR). VLBI matches LLR's radial accuracy in (differential) lateral measurements, and will significantly improve the overall accuracy of the data applied in fields such as **Planetology, Selenodesy, Celestial Mechanics and Fundamental Physics.**



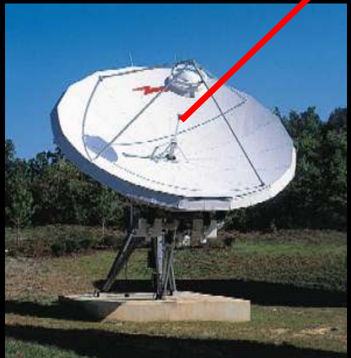
Input will be provided to

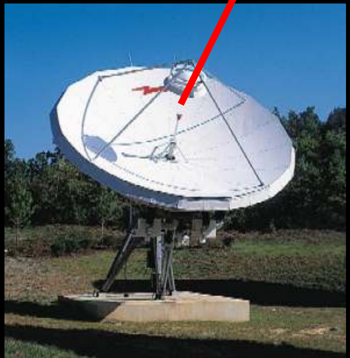
1. Selenodesy and Comparative Planetology: Tidal modes - Moon's liquid core and core-lithosphere-crust interaction;

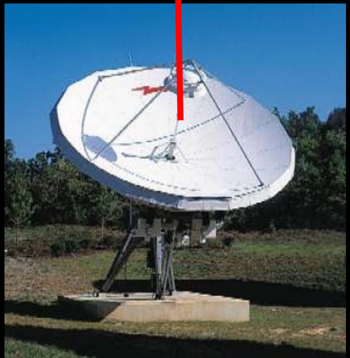
2. Celestial Mechanics: Lunar spin axis orientation parameters (LOPs), their correlation with EOPs;

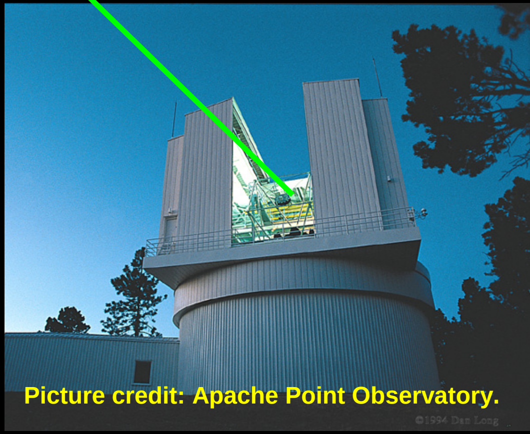
3. Fundamental Physics: Consistency of the Moon's observed motion with General Relativity.

True 3D solution when using co-located radio transmitters and laser retro-reflectors







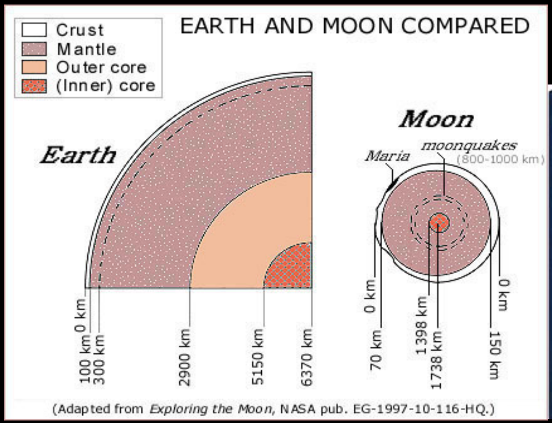


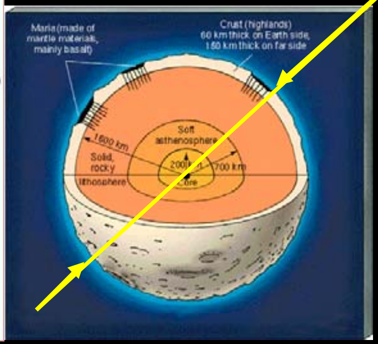
Picture credit: Apache Point Observatory.

Accurate measurements will be provided to several research areas

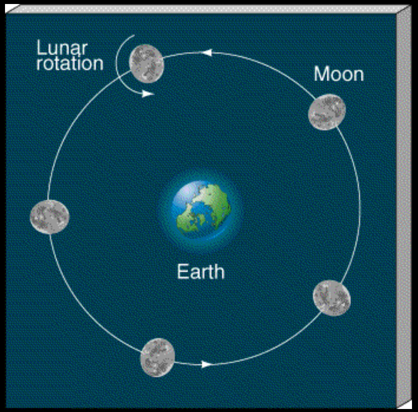
Selenodesy and Comparative Planetology: Tidal modes - Moon's liquid core and core-lithosphere interaction

Moon's crust tidal wave with an amplitude of 10 cm and period of 27 days can be measured with sub-mm accuracy



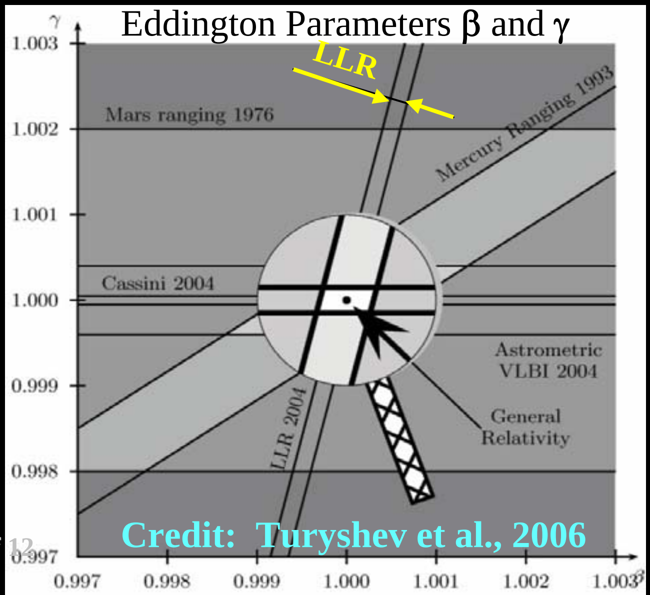


Celestial Mechanics: Lunar spin axis orientation parameters (LOPs), their correlation with EOPs, Improvement of the Earth-Moon barycenter motion model; LOPs can be measured with an accuracy matching that of EOPs.



Picture Credit: http: //physics.fortlewis.edu/Astronomy/astronomy%20today/CHAISSON/AT308/HTML/AT30803.HTM

Fundamental Physics: precise measurements of the Moon's motion checked for compliance with General Relativity, tightening the constraints in Eddington diagram



Credit: Turyshev et al., 2006

Q: Why LOPs and not MOPs?

A: Leonid Petrov already reserved MOPs for Mars ☺

Fasten your seat belts - Next stop : Mars.

Scaling the setup for Mars case:

1. **Space segment: 3-4 (or more) of the Huygens-style beacons on Mars surface, X-band carrier line with P=3-5W, transmitting antenna gain 3-6 dBi. Note that all the transmitters will be within <15 arc seconds area and all propagation media effects will be subtracted when the differential positions of the transmitters will be measured.**
2. **Ground segment: a dedicated Small-D VLBI array of 10-15 of 10-12 m dishes with baselines in the range of 100-6000 km and Tsys=40-70K, no Tsys contamination by Mars.**
3. **Stochastic delay noise at sub - picosecond level is achievable with 10 - 20 s integration times.**
4. **1 picosecond delay error on a baseline of 3000 km translates into 15 m position error at 1 AU distance. Expected error of the global solution for 20 s integration time for all baselines will be about an order of magnitude better.**
5. **Expected error of the post-Kalman and basic motion model fitting can be as small as several cm on time scale of several hours.**
6. **Several cm – accurate differential positions of the beacons on the Mars's surface are translated into several milliarcseconds of the MOPs determination accuracy.**
7. **Several cm amplitude of the tidal deformation of Mars can be measured. Mars orbiting S/C can be very accurately positioned in the reference frame determined by the beacons.**

Mars picture credit: NASA/ESA HST

Conclusions:

1. A dedicated VLBI array of ~ 10 to 15 of small (~10-m) fully automated antennas can achieve (sub-)mm-accurate differential positioning of the multiple transmitting beacons on the Lunar surface.

2. Combined with (near-) simultaneous LLR measurements, VLBI data can significantly improve the Moon's orbital and spin motion and tidal deformation models, providing input to Comparative Planetology, Selenodesy, Celestial Mechanics and Fundamental Physics.

3. Simultaneous in-beam observations of an orbiting S/C and surface beacons will provide the position of the S/C with (sub-)1 m accuracy in the frame determined by the beacons.

4. The same technology can be applied to determine Mars tidal deformation with ~cm level accuracy and spin orientation parameters (MOPs) with accuracy comparable of that of EOPs.

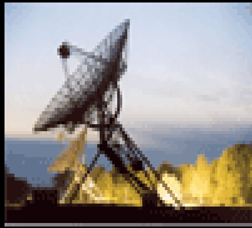
5. Installing the small antennas near the existing large radio astronomical instruments (EVN and SKA-pathfinder sites) and using the existing infrastructure will significantly reduce the costs of construction and operation of the array and improve its calibration. Augmenting the Small-D array with larger antennas at certain occasions will allow to get even more accurate measurements.

ACKNOWLEGEMENTS

SMART-1 observation campaign was conducted in a framework of ESA contract No 18386/04/NL/NR WPCCN-5000 and Agreement between Dutch and Chinese Academies of Sciences. We are thankful to observer's team: G. Maccaferri and S. Montebugnoli (INAF/IRA, IT) A. Mujunen and J. Ritakari (HUT/MRO, FI), T. Foley and I. Avruch (ASTRON/WSRT/LOFAR, NL), and the SMART-1 project science and operation team: B. Foing (ESA/ESTEC, NL), T. Morley and O. Camino (ESA/ESOC, DE), and L. Petrov (NASA/GSFC, US).

Medicina 32m (IT)

Small-D VLBI array



Westerbork 25m (NL)

S.V. Pogrebenko, L.I. Gurvits, JIVE, Dwingeloo, NL

Presentation at 9th ILEWG International Conference on Exploration and Utilization of the Moon (ICEUM9/ILC2007)

22-26 October, 2007, Sorrento, Italy

Commercial spin-offs:

Track the velocity of Lunar automotive vehicles

and issue the speeding tickets;

Assist the Lunar car-accident insurance companies;

Traffic control on Lunar orbits to prevent traffic jams;

Any ideas for Martian spin-offs?

☺

Thank you!

Questions?