Lunar surface control network with retro-reflectors and radio trans-ponders in Chang'E lunar missions

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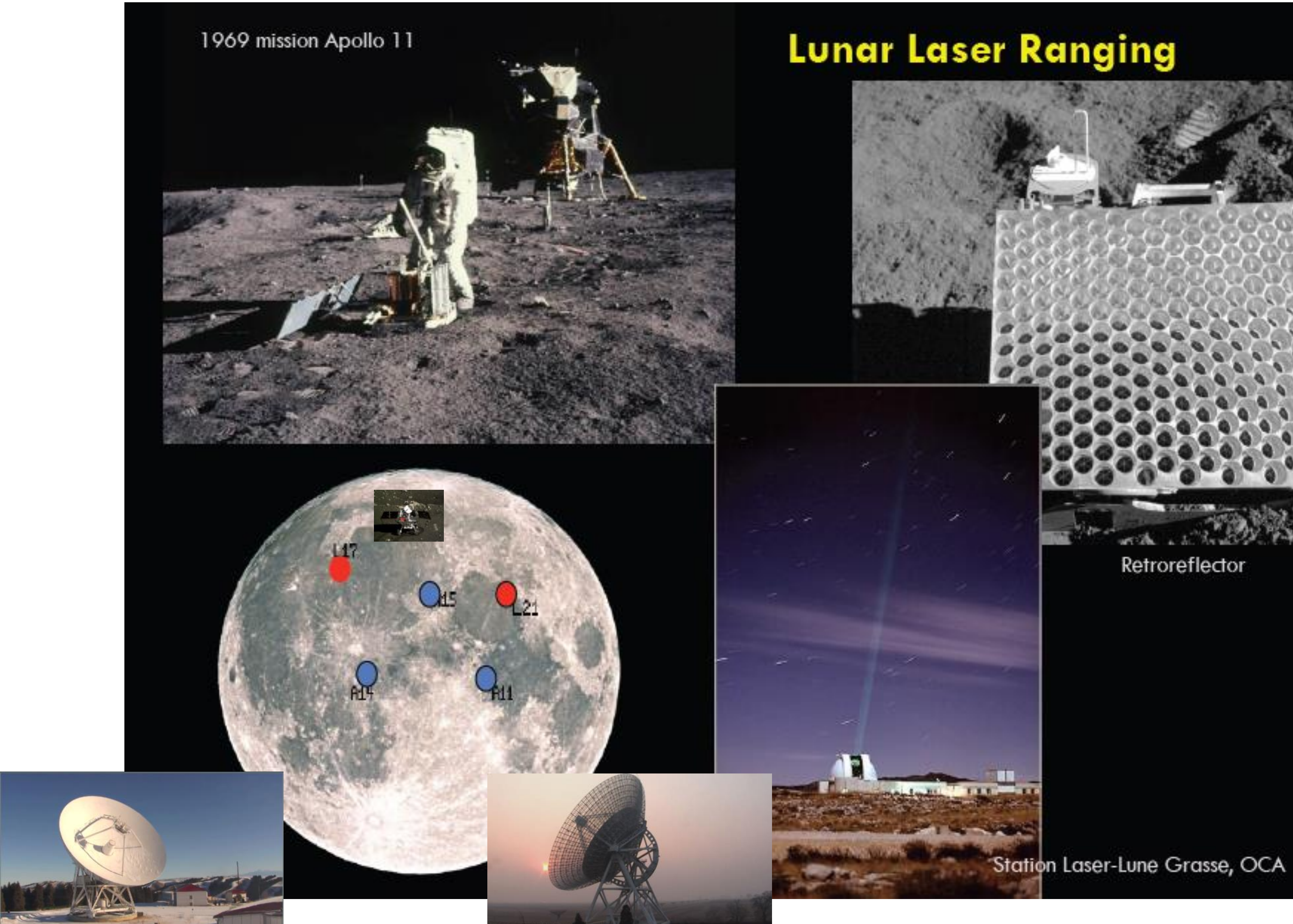
2019: LLR (50 yr) + LRR (6 yr)



Our Motivations

- To study the lunar internal structure and dynamical rotation (Physical Libration).
- To meet the requirements from Lunar landing missions (of China).
- To measure the UT1 independently.
- To transfer time and frequency in the Earth-Moon space with high accuracy and precisions.

Why Optical + Radio

- Radio CW gives local weather free R&RR measuring chance;
- One uplink coherent site with PLL on lunar surface + multi downlink sites can measure phase and Doppler together, with best geometric configuration;
- Laser can calibrate the initial ambiguity for CW phase ranging, and transfer the time with high accuracy in Earth-Moon space;
- UT1 can be measured by radio lunar ranging and Doppler with high frequency, except for VLBI method;
- Co-located retro-reflector and radio transponder can be used to link the celestial reference frames;
- Lunar physical libration and general relativities can be studies more efficiently in Earth-Moon space.
- Can be down by co-located LLR and radio antenna together

… …

Beacons and Retro-reflectors

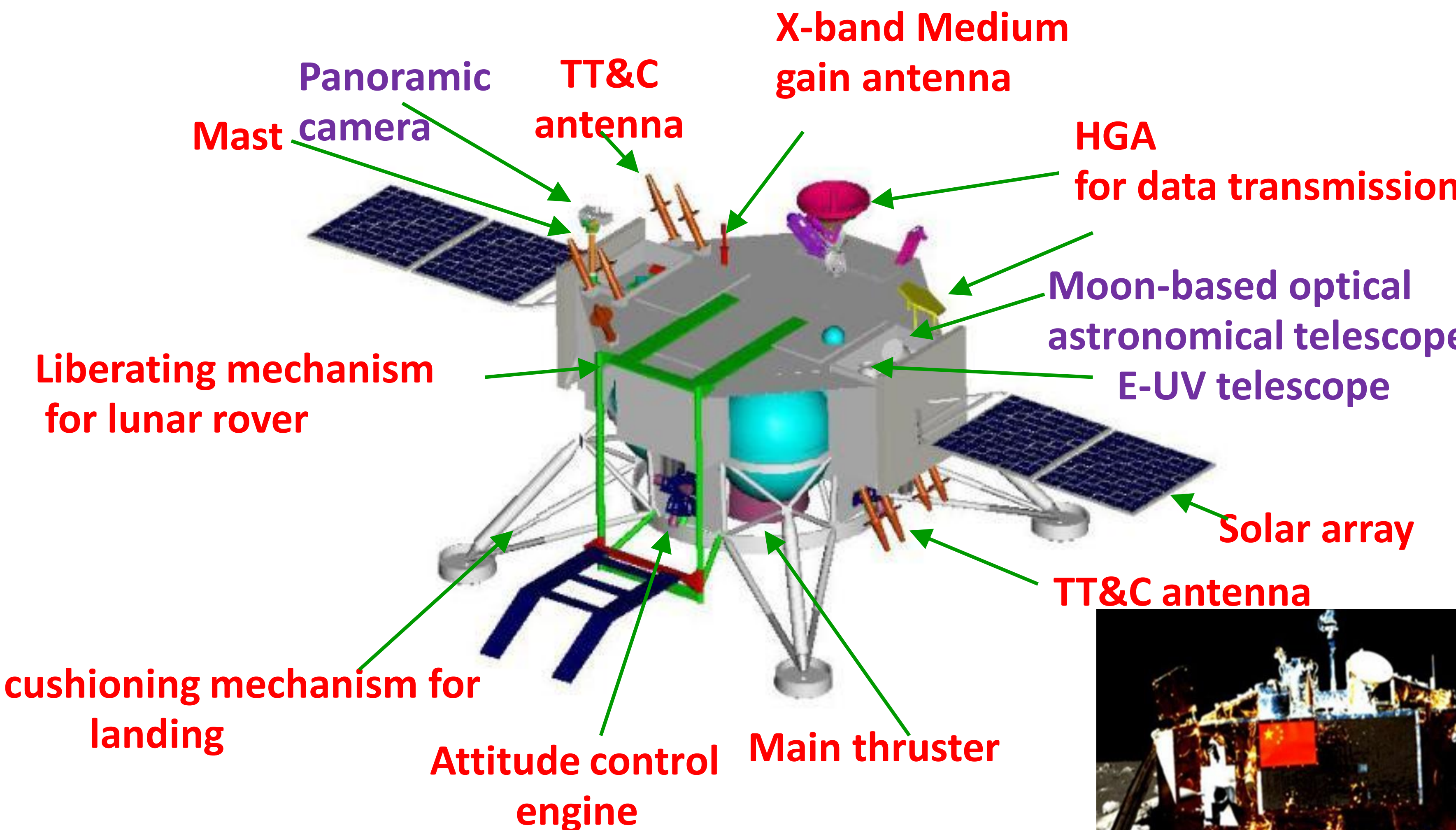
- Setting places: rim, high latitude or pole area
- Setting method: international collaboration
- Beacons: may cover S/C/X/Ku/Ka bands,

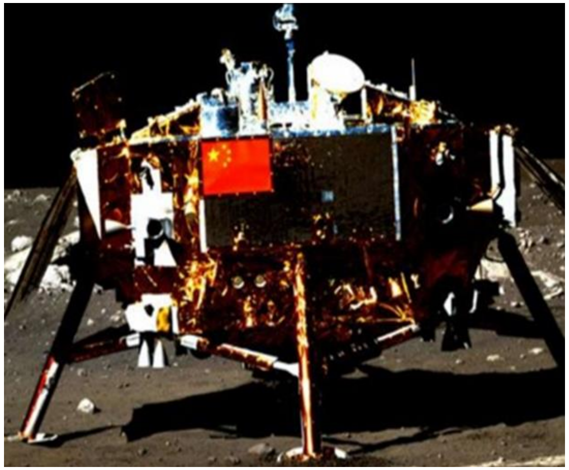
  with carrier waves, DOR sub-carriers, PN modulated signal
- Retro-reflectors: larger mirror, unified designed and made. For example, Italia…

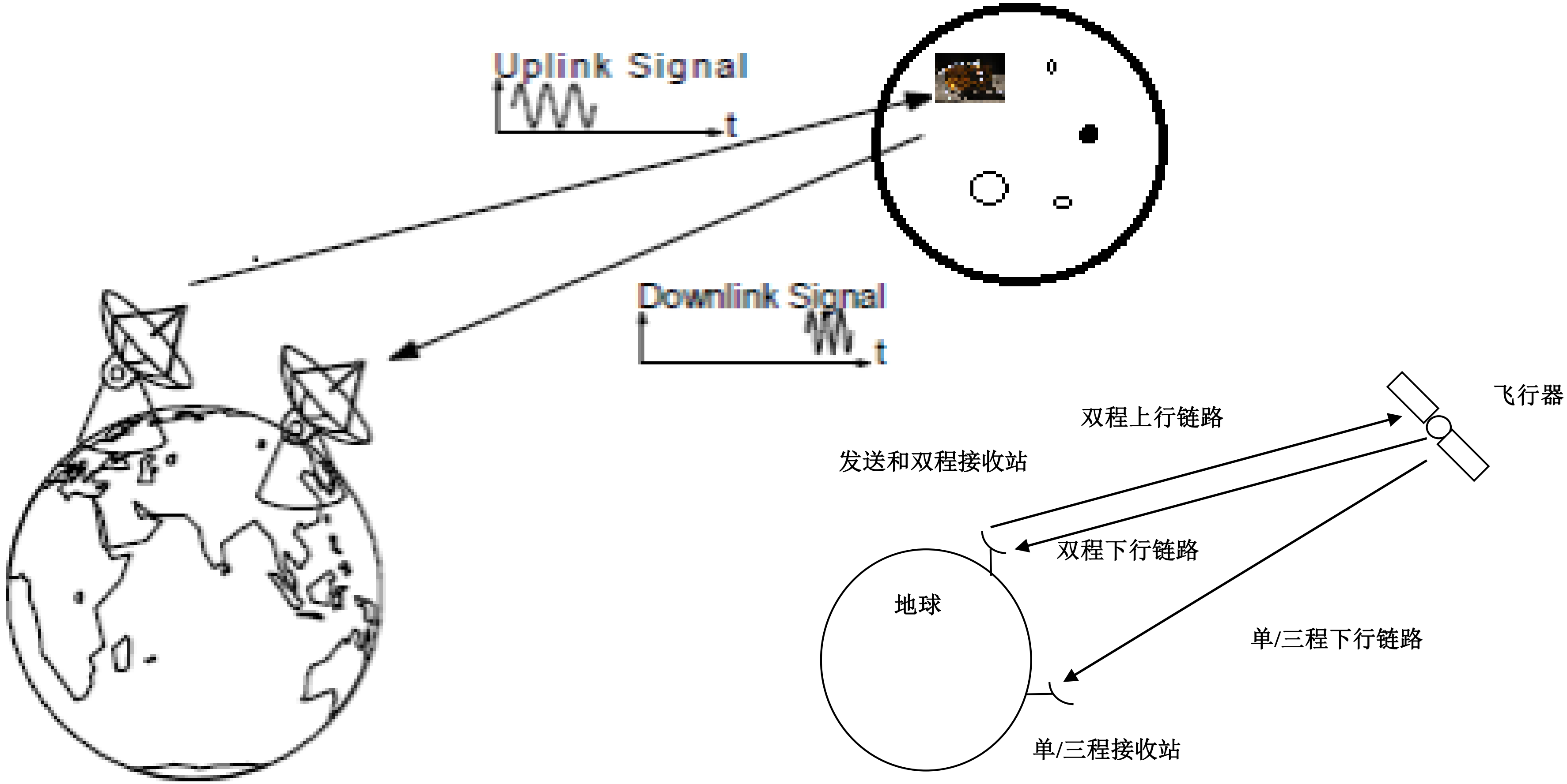
Radio science experiments have been involved in all of the CE-1/2/3/4/5 lunar missions by our team. In Chang'E-3 mission, 2 & 3-way Lunar Radio-phase Ranging (LRR) was developed and tested at X-band.

This LRR method can become a new space geodetic technique to study the geodynamics, lunar dynamics, and to test the theory of relativity, as LLR did.

Scientific Instruments on CE-3/4 Lunar Lander







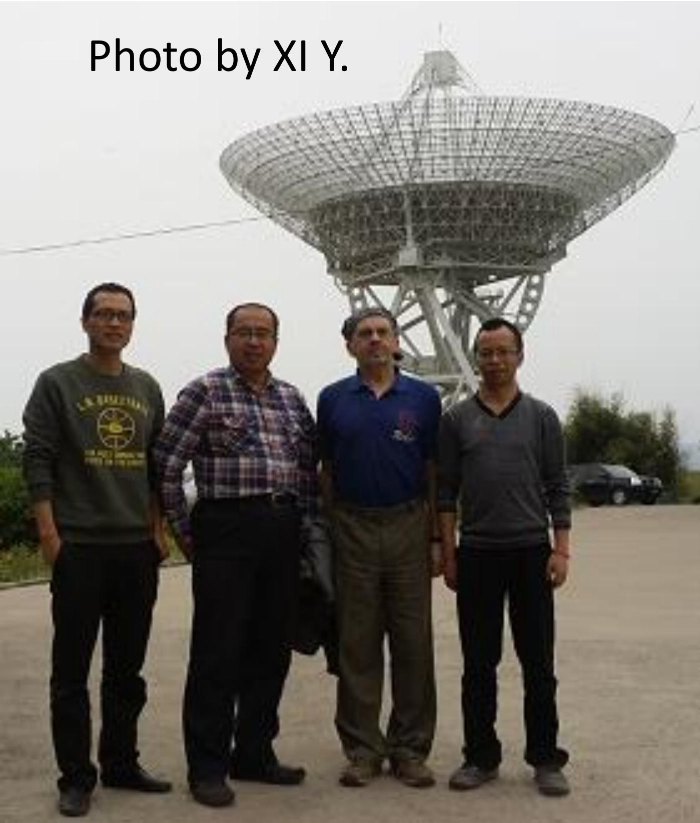
Open loop radio Doppler and phase range tracking with:

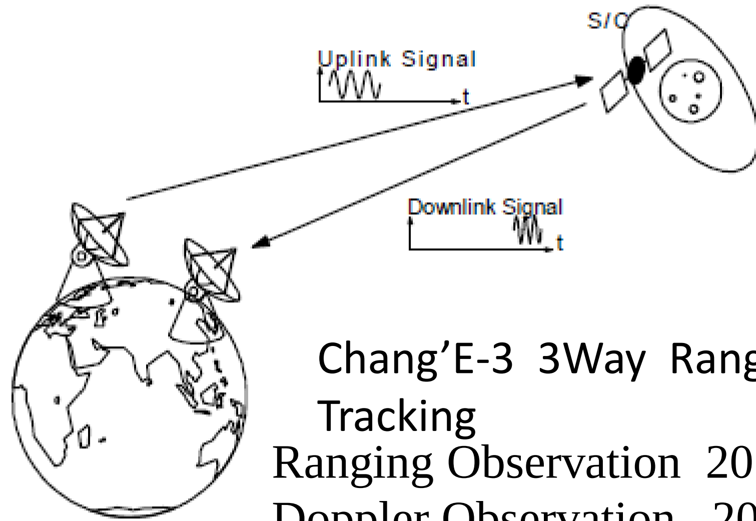
(1) H-Clock at each ground station, table and precise;

(2) X-band PLL transponder & transmitter on board;

(3) Many antennas, VLBI & DSN of China TT&C

(4) Open loop multi channel RSR with frequency resolution of 10^-16



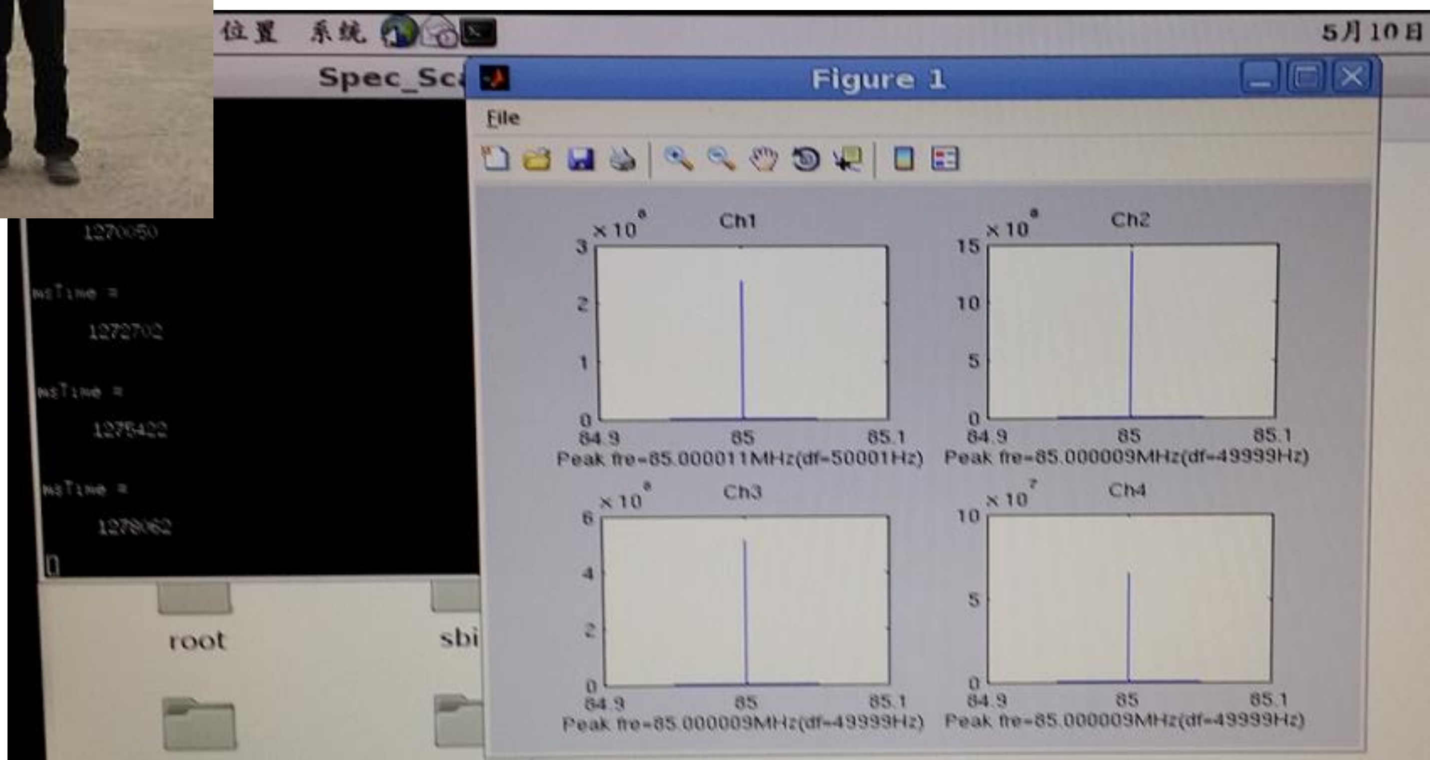


Chang'E-3 3Way Ranging/Doppler Tracking

Ranging Observation 2014.11 – 2016.07

Doppler Observation 2013.12 – 2016.07

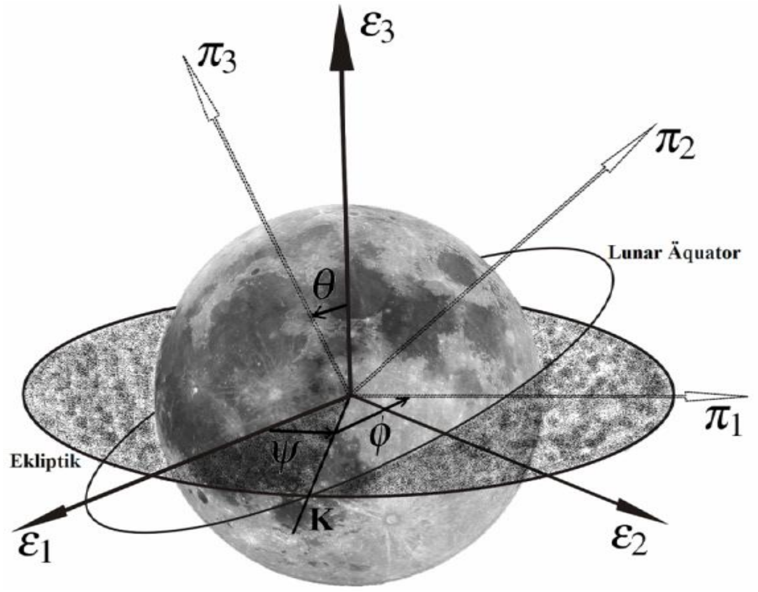
1st Miyun/Beijing Observation

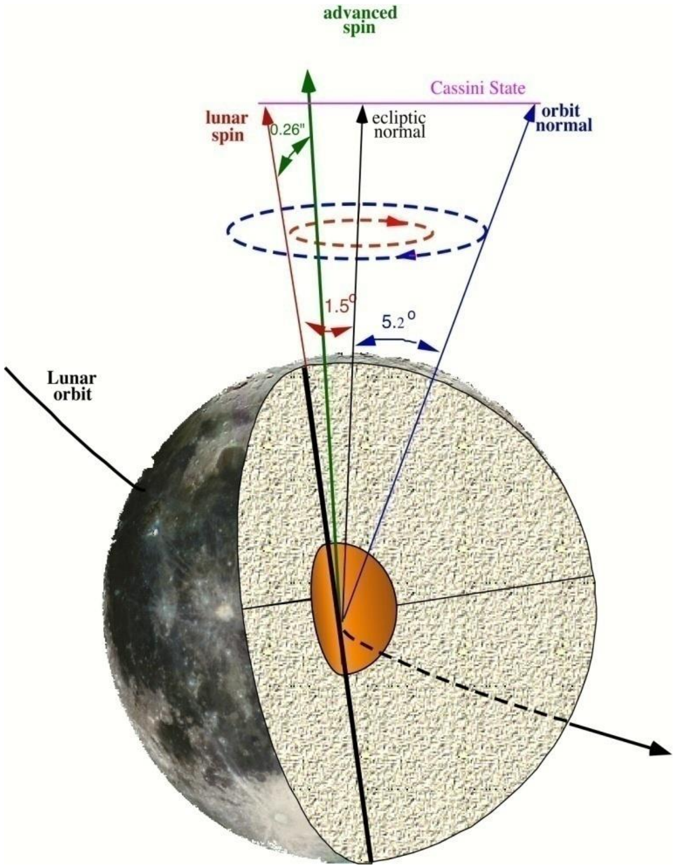


Why Lunar Radio-phase Ranging (LRR)?

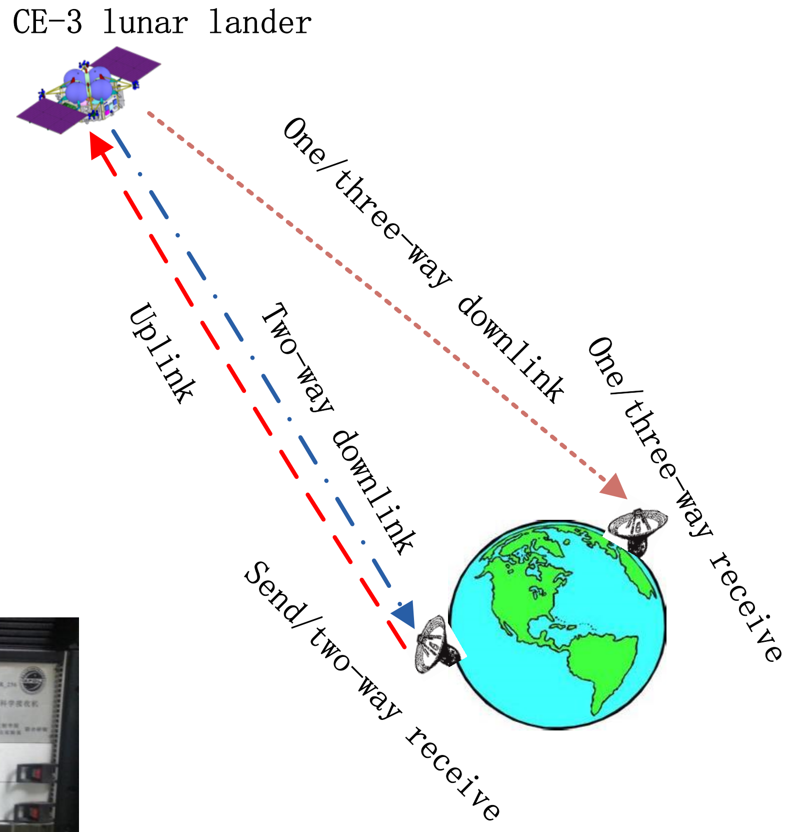
Scientific objectives:

1. To realize radio ranging (<0.5 mm resolution, 2~3cm post-processing ranging error as LLR)
2. To monitor lunar orbit and rotation
3. To measure the LPhL
4. To prepare for Mars ranging
5. To study the general relativity





Tracking and obtaining data



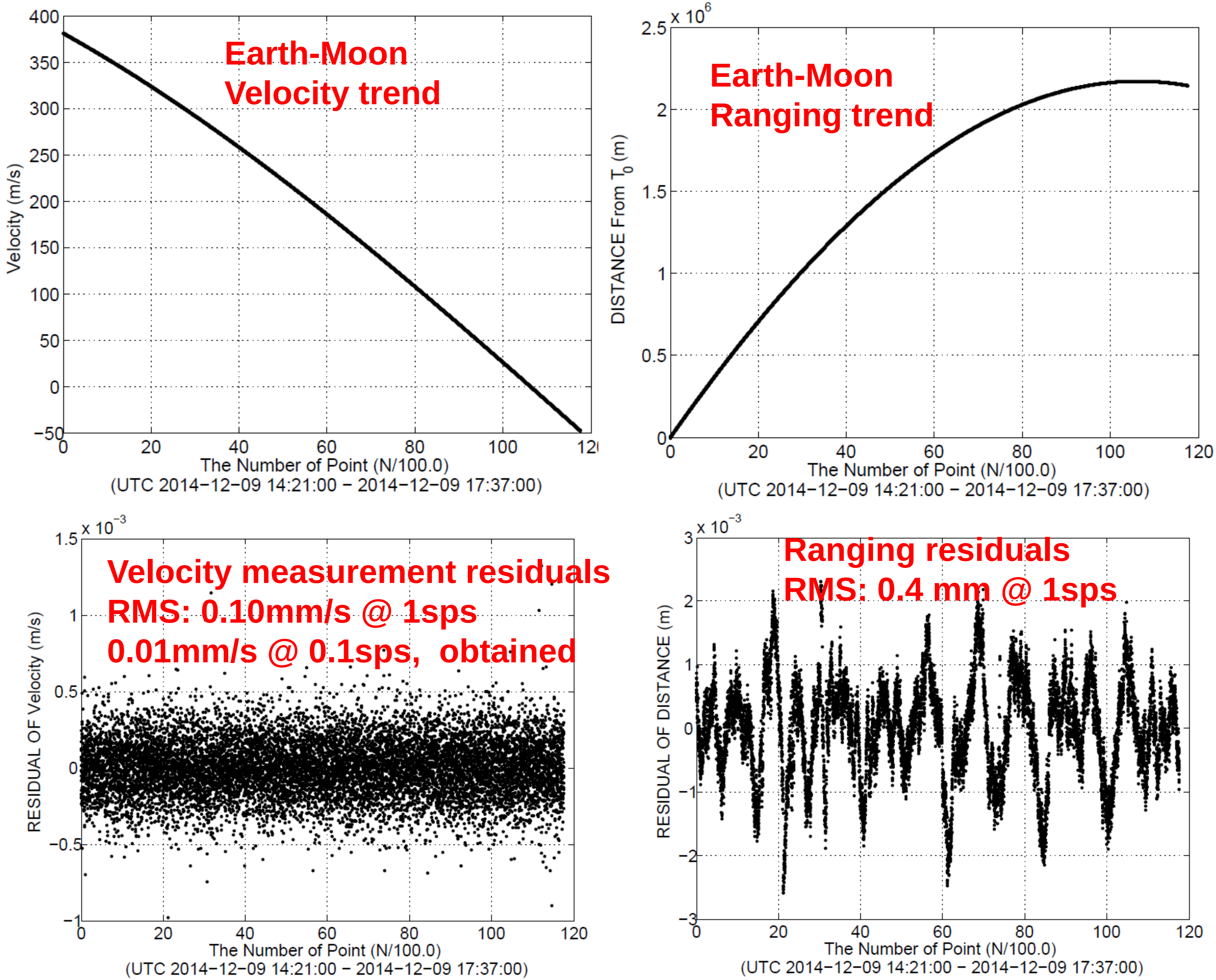
- CE-3 lunar lander

  -> **radio beacon**

  -> **transferring signal**
- Uplink and downlink for 2/3-way ranging
- Uplink station:

  Jiamusi, Kashi
- Downlink station:

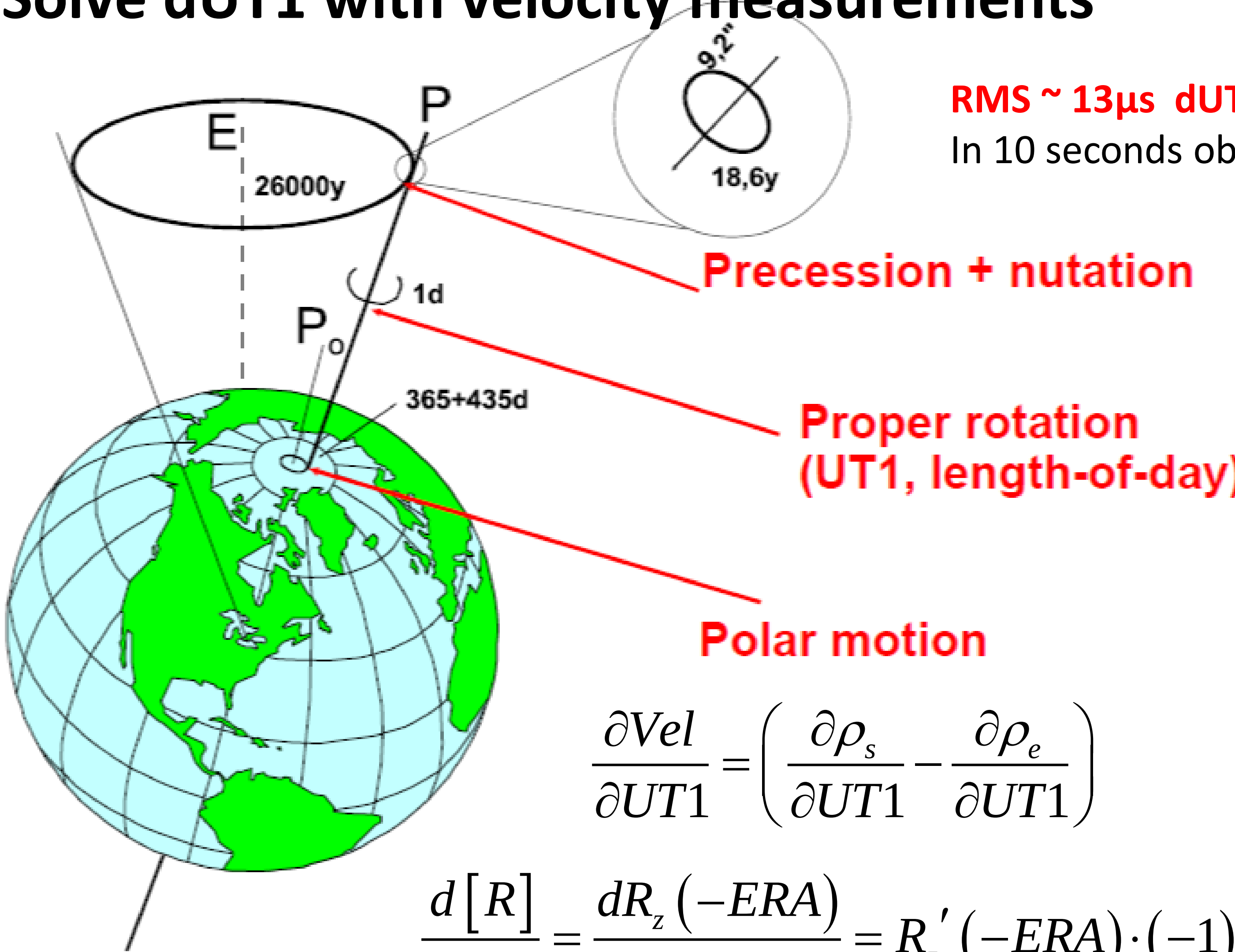
  Jiamusi, Miyun, Kunming, Sheshan25, Tianma65, Urimuqi


Earth-Moon
Velocity trend
Velocity (m/s)
The Number of Point (N/100.0)
(UTC 2014−12−09 14:21:00 − 2014−12−09 17:37:00)
Earth-Moon
Ranging trend
DISTANCE From T0 (m)
x 10^6
The Number of Point (N/100.0)
(UTC 2014−12−09 14:21:00 − 2014−12−09 17:37:00)
Velocity measurement residuals
RMS: 0.10mm/s @ 1sps
0.01mm/s @ 0.1sps, obtained
RESIDUAL OF Velocity (m/s)
x 10^−3
The Number of Point (N/100.0)
(UTC 2014−12−09 14:21:00 − 2014−12−09 17:37:00)
Ranging residuals
RMS: 0.4 mm @ 1sps
RESIDUAL OF DISTANCE (m)
x 10^−3
The Number of Point (N/100.0)
(UTC 2014−12−09 14:21:00 − 2014−12−09 17:37:00)

Comparing Space Geodetic Tools

	Geo -center	ICRF	Lunar center	EOP UT1 fast	Precession Nutation	Single site work	Ephemeris Earth & Moon
VLBI	no	yes	no	Yes yes	Yes	no	no
GNSS	no	yes	no	No no	no	no	no
SLR	yes	no	no	No no	no	yes	no
LLR	yes	yes	yes	Yes no	yes	yes	yes
DORIS	yes	no	no	No no	no	yes	no
LRR	yes	yes	yes	Yes yes	yes	yes	yes

Solve dUT1 with velocity measurements



RMS ~ 13μs dUT1 obtained

In 10 seconds observation

$$\frac{\partial Vel}{\partial UT1} = \left(\frac{\partial \rho_s}{\partial UT1} - \frac{\partial \rho_e}{\partial UT1} \right)$$

$$\frac{d\left[R\right]}{dUT1} = \frac{dR_z\left(-ERA\right)}{dUT1} = R_z'\left(-ERA\right)\cdot\left(-1\right)\cdot\frac{dERA}{dUT1}$$

$$\frac{dERA}{dUT1} = 2\pi \cdot 0.002737811911354448 \quad rad/s$$

CE-6, 7 & 8

CNSA is calling for collaboration on lunar exploration for CE-6/7/8 lunar exploration projects, which may be launched in 2023~27 one after another.

Key landing area will be the lunar south pole area, near-side of the Moon.

On CE-7 & 8, radio beacons of transmitter and transponder of multi-frequency will be used. We are promoting to use atomic clock for beacon.

We are collaborating with Italia INFN colleague on promoting a joint LLR by means of using their reflector(s) on our mission(s).

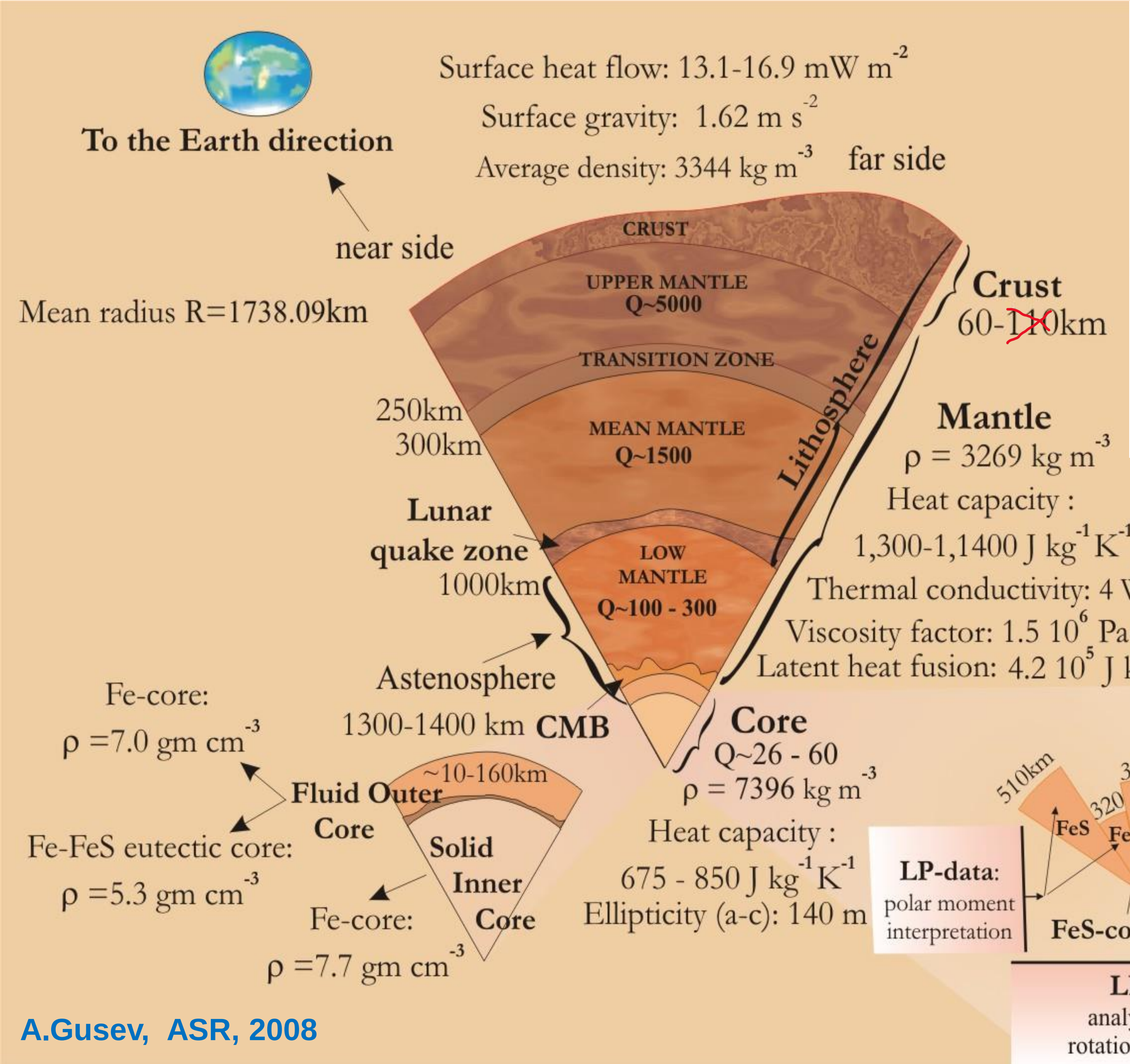
All can use MoonLIGHT Retro-reflectors so as to reduce the error

- INFN-Frascati, U. Maryland, INFN/Univ. Padua and Naples
- Lunar stations: ASI-MLRO (Italy), APOLLO (US), OCR (France)

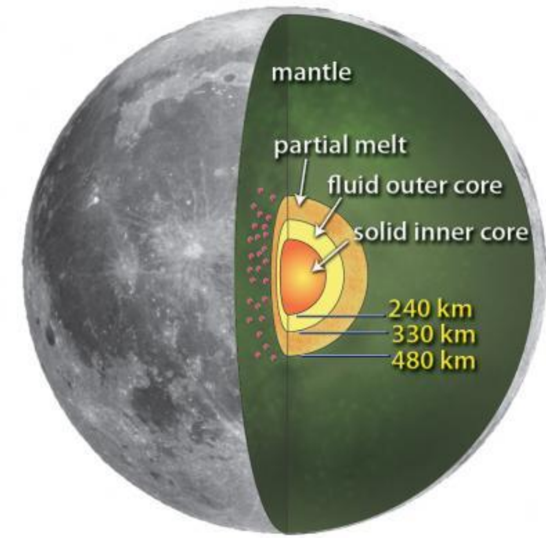
MoonLIGHT: 100 mm **GNSS: 33 mm (Apollo: 38 mm)**

MoonLIGHT readied for test

Multi-layer lunar core



A.Gusev, ASR, 2008



Excellent match !

Rene Weber, Science, 2011

Retrieve Free Libration from DE430

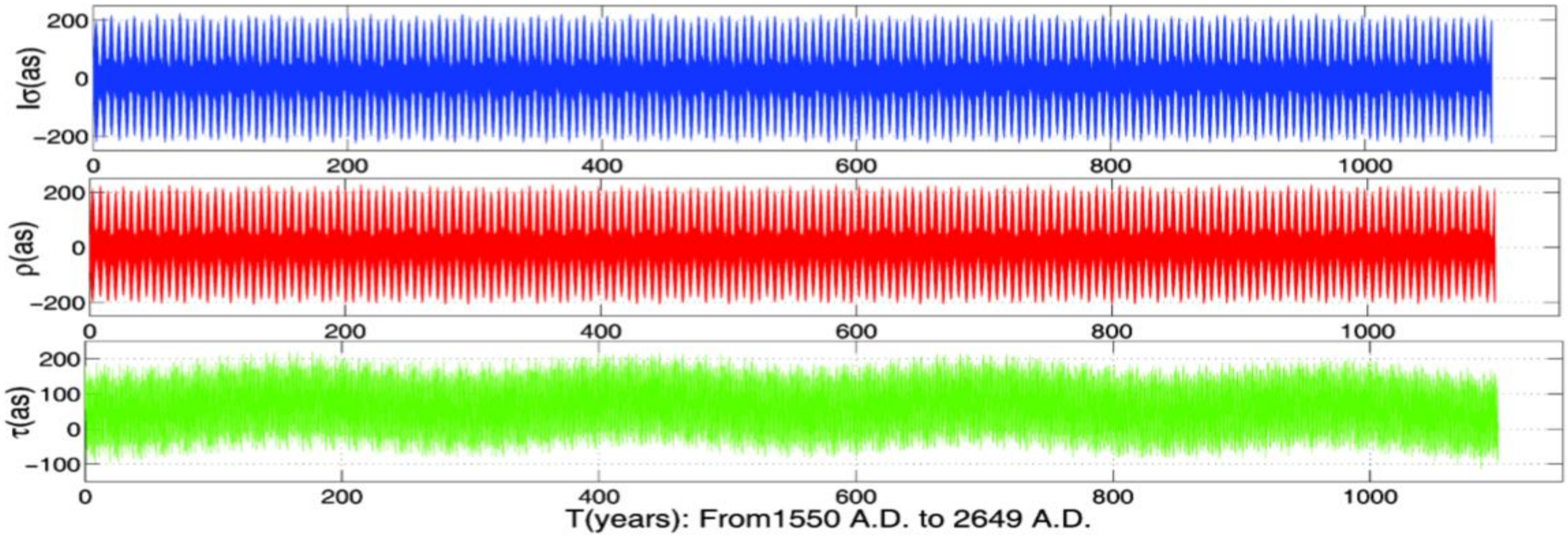


Fig. 2 Temporal evolution of the three librations angles over 1100 yr.

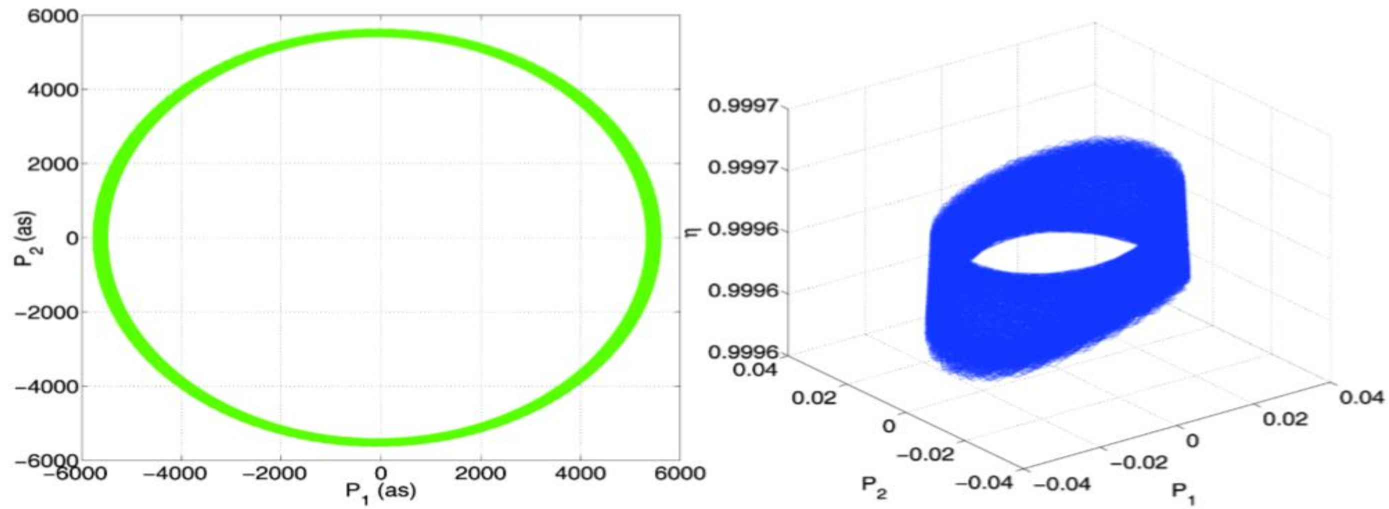


Fig. 3 Ecliptic pole precessional cone over 1100 yr (*left*) and pole oscillation unit vector (P_1, P_2, η) in space (*right*).

Table 2 Free Librations Determined from Ephemeris DE430 and Comparison with the Previous Results

	Longitude blend	Longitude mode	Latitude mode	Wobble mode
Period (d)				
This work	1056.21	1056.16	8806.9	27262.99
Rambaux and Williams (2011)	1056.21	1056.13	8822.88	27257.27
Newhall and Williams (1997)	1056.20	1056.12	8826	27257.27
Chapront et al. (1999)	1056.12	–	8804	27259.29
Amplitude (arc)				
This work	1.8002	1.471	0.025	8.19×3.31
Rambaux and Williams (2011)	1.8080	1.296	0.032	8.183×3.306
Newhall and Williams (1997)	1.8070	1.37	0.022	8.19×3.31
Chapront et al. (1999)	1.8120	–	0.022	8.182
Phase at JD 2451545 (°)				
This work	223.41	210.5	250.67*	161.64
Rambaux and Williams (2011)	223.5	207.0	160.8	161.60
Newhall and Williams (1997)	223.8	208.9	246.4	161.82
Chapront (99)	224.3	–	250.3	161.77

Notes: The difference in phase between this paper and Rambaux & Williams (2011) of the latitude mode is because we used the sine function to fit but they used the cosine function.

We just at the very very beginning on this study.

Hope to make progress step by step with the support from ILRS.

Thank you !