Lunar surface control network with retro-reflectors and radio transponders 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

- Panoramic camera
- Solar array
- Cushioning mechanism for landing
- Liberating mechanism for lunar rover
- TT&C antenna
- X-band Medium gain antenna
- HGA for data transmission
- Moon-based optical astronomical telescope
- E-UV telescope
- Mast
- Attitude control engine
- Main thruster
- TT&C antenna
- X-band Medium gain antenna
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

Photo by XI Y.
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
Velocity measurement residuals
RMS: 0.10 mm/s @ 1sps
0.01 mm/s @ 0.1sps, obtained

Earth-Moon Velocity trend

Ranging residuals
RMS: 0.4 mm @ 1sps

Earth-Moon Ranging trend
## Comparing Space Geodetic Tools

<table>
<thead>
<tr>
<th></th>
<th>Geo-center</th>
<th>ICRF center</th>
<th>Lunar center</th>
<th>EOP UT1 fast</th>
<th>Precession Nutation</th>
<th>Single site work</th>
<th>Ephemeris Earth &amp; Moon</th>
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Solve dUT1 with velocity measurements

RMS ~ 13µs  dUT1 obtained
In 10 seconds observation

\[
\partial \text{Vel} \over \partial \text{UT1} = \left( \partial \rho_s \over \partial \text{UT1} - \partial \rho_e \over \partial \text{UT1} \right)
\]

\[
d \left[ R \right] \over d\text{UT1} = dR_z \left( -\text{ERA} \right) \over d\text{UT1} = R_z' \left( -\text{ERA} \right) \cdot (-1) \cdot \frac{d\text{ERA}}{d\text{UT1}}
\]

\[
\frac{d\text{ERA}}{d\text{UT1}} = 2\pi \cdot 0.00273781191135448 \text{ rad/s}
\]
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)
Multi-layer lunar core

To the Earth direction

Mean radius $R = 1738.09\text{ km}$

Surface heat flow: $13.1-16.9\text{ mW m}^{-2}$
Surface gravity: $1.62\text{ m s}^{-2}$
Average density: $3344\text{ kg m}^{-3}$ far side

Core
- $Q \approx 26 - 60$
- $\rho = 7396\text{ kg m}^{-3}$
- Heat capacity: $675 - 850\text{ J kg}^{-1}\text{ K}^{-1}$
- Ellipticity $(a-c)$: $140\text{ m}$
- Fluid Outer Core
- Solid Inner Core
- $\rho = 7.0\text{ gm cm}^{-3}$
- $\rho = 5.3\text{ gm cm}^{-3}$
- $\rho = 7.7\text{ gm cm}^{-3}$

Mantle
- $Q \approx 5000$
- $\rho = 3269\text{ kg m}^{-3}$
- Heat capacity:
  - $1300-1400\text{ J kg}^{-1}\text{ K}^{-1}$
- Thermal conductivity: $4\text{ W m}^{-1}\text{ K}^{-1}$
- Viscosity factor: $1.5 \times 10^6\text{ Pas}$
- Latent heat fusion: $4.2 \times 10^5\text{ J kg}^{-1}$

Lithosphere

Crust
- $60-110\text{ km}$

Near side

Excellent match!
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 ($P_1$, $P_2$, $\eta$) in space (right).
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<th>Wobble mode</th>
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**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!