# Working Towards Improved Lunar/Planetary Reference Frames

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DFG Forschergruppe Referenzsysteme

## Introduction

We are engaged in a comprehensive analysis of lunar/planetary dynamics to provide updated reference frames for deep space navigation and lunar exploration. On the basis of Lunar Laser Ranging (LLR) data, we have updated the Earth-Moon ephemeris as well as the lunar rotation model and reference frame. We use ranging and radio tracking data to the LRO spacecraft as well as numerical integrations in the GRAIL-derived lunar gravity field to consistently link the LRO orbit into the lunar-fixed reference frame. We demonstrate for the Apollo 15 site that images and laser altimeter data taken by LRO can be firmly tied to our lunar reference frame using Lunar Ranging Retro Reflectors (LRRR) as control points.


**Fig. 1:** Artist's view on LRO in orbit.

In order to determine the coordinates of the Apollo 15 laser reflector we combined LLR and LRO data in the following processing steps:

1. Centered around the image acquisition times, ephemerides arcs and rotational parameters of the Moon were computed from LLR data.
2. Using these lunar ephemerides, LRO orbit arcs were estimated from radio and laser observations.
3. The computed LRO arcs were finally used to reference the LRO images in a Moon-fixed frame. The final output of this processing chain is a set of coordinates of the Apollo 15 array which only depends on LLR and LRO data.

## Lunar Ephemeris and Reflector Coordinates

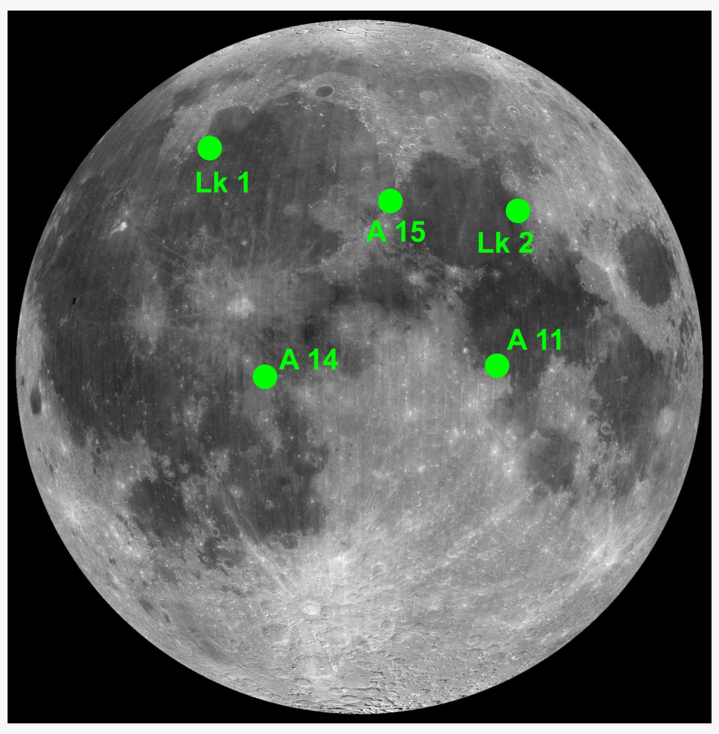


**Fig. 2:** Position of the 5 LRRR on the Moon.

The lunar ephemeris (position, velocity, orientation) is obtained by numerical integration of the Einstein-Infeld-Hoffmann equation of motion for the solar system bodies in combination with the simultaneous integration of the lunar rotation. In this first step, the model for the solar system includes all major bodies (Sun, Planets, Moon) as well as Ceres, Vesta and Pallas. The initial values for the solar system bodies (position and velocities) are taken from the JPL DE421 ephemeris. Initial values for lunar orbit, lunar rotation and some values for Earth's orbit are determined by the analysis of more than 44 years of LLR data [1].

The reflector coordinates are determined in the lunar principal axis (PA) reference frame which is used within the ephemeris computation. The rotation angles for the transformation to the lunar Mean Earth/Rotation axis (ME) frame, which is mainly used for cartographic purposes, are derived from a long-time ephemeris integration.

## LRO orbit computation

For LRO orbit determination, an independent processing chain was set up at University of Bonn based on the Bonn in-house software GROOPS. It applies the classical variational equation approach where orbit and force parameters are iteratively improved. Unlike the official NASA orbits, our solutions are based both on Doppler and laser observations. The Doppler data are by default converted to ranges which facilitates the combination of the data types. Force modeling includes gravitational attraction from the latest GRAIL model, direct and solid body tides and surface forces using a LRO macro model. Special attention is paid to the proper determination of the various measurement biases. At the present stage, our solutions differ from NASA orbits by a few tens of meters, with single outliers (see Fig. 3).

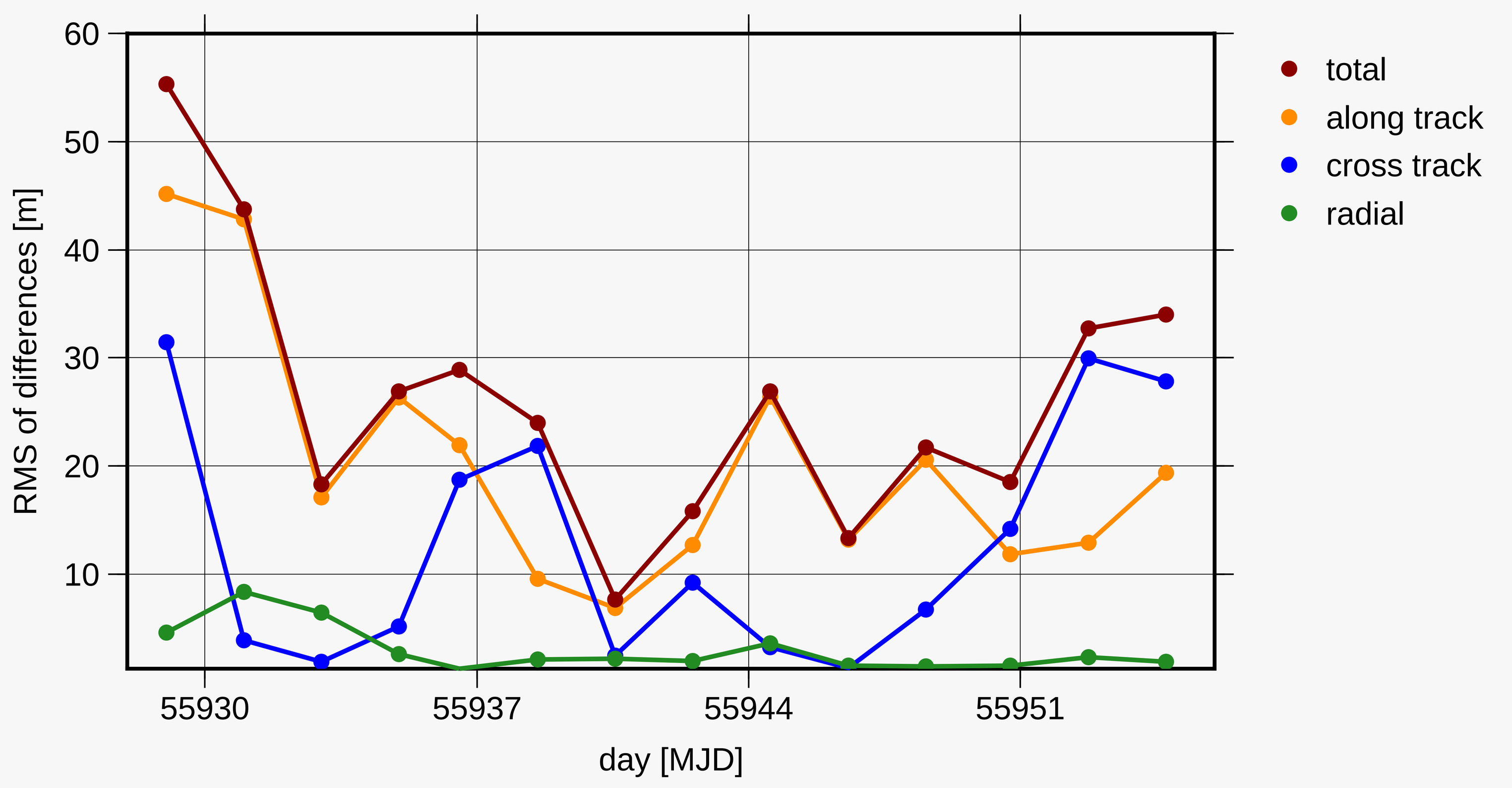


**Fig. 3:** Differences of 14 orbit arcs from laser and Doppler data to NASA orbits (January 2012, arc length 2.5 days).

## Localizing the Apollo 15 laser reflector

At the Institute of Planetary Geodesy at the Technical University of Berlin, the LRO orbits are used to map-project NAC images. Knowing the position and attitude of the LRO spacecraft, exterior orientation parameters for the NAC camera can be derived. Along with the knowledge of the lunar orbit, images taken by the NAC can be located on the lunar surface and coordinates can be attached.

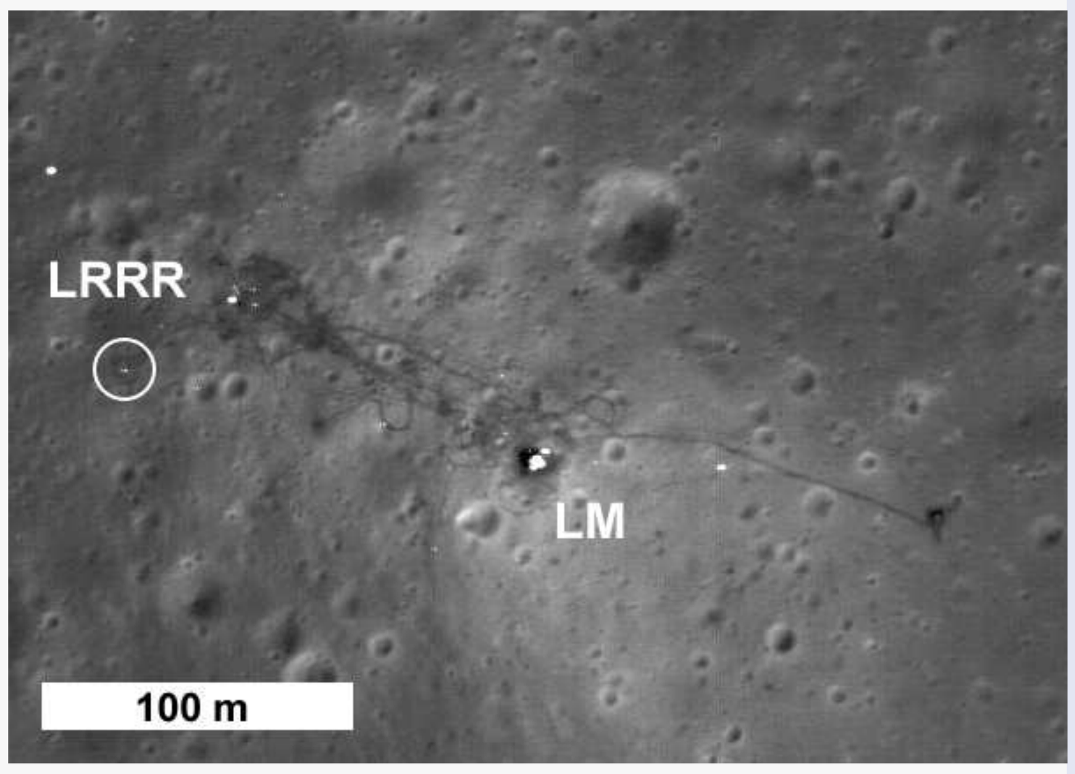


**Fig. 4:** Apollo 15 landing site with Lunar Module (LM) and LRRR (NAC image: M111578606L).

The location of the LRRR could be identified in two NAC images (P1: M111578606L, P2: M175252641R) of the Apollo 15 landing site, as displayed in Fig. 4. We map-projected these particular NAC images using three different orbit solutions for LRO.

1. We used most recent LRO orbits released by NASA based on a GRAIL gravity field and the DE421 lunar ephemeris [2], denoted as "NASA" in Table 1.
2. We used the University of Bonn orbits which are based on the DE421 ephemeris, denoted as "DE" in Table 1.
3. We used the University of Bonn orbits which are now based on the IfE ephemeris, denoted as "IfE" in Table 2.

In each of the resulting ortho-images we measured the position of LRRR in the ME frame and compared it to the ME coordinates given in the literature [3] for DE421 ephemeris (Table 1) and to the IfE ME coordinates (Table 2).

**Tab. 1:** ME coordinates of the Apollo 15 reflector as measured by LLR and in LROC images with underlying DE421 ephemeris.

| | Longitude [°] | Latitude [°] | Difference [m] |
|---|---|---|---|
| A15 (DE421) | 3.628507 | 26.133395 | - |
| P1 NASA | 3.628177 | 26.133462 | 9.22 |
| P1 DE421 | 3.628525 | 26.133626 | 7.02 |
| P2 NASA | 3.628415 | 26.133280 | 4.30 |
| P2 DE421 | 3.628415 | 26.133362 | 2.69 |

**Tab. 2:** ME coordinates of the Apollo 15 reflector as measured by LLR and in LROC images with underlying IfE ephemeris.

| | Longitude [°] | Latitude [°] | Difference [m] |
|---|---|---|---|
| A15 (IfE) | 3.628177 | 26.133063 | - |
| P1 IfE | 3.628507 | 26.133642 | 19.73 |
| P2 IfE | 3.628388 | 26.133370 | 10.94 |

## Summary and Outlook

We presented the first results of lunar coordinate determination from LRO images combined with a lunar ephemeris from a LLR solution and an independent LRO orbit determination. For this purpose we used the Apollo 15 LRRR as control point. When using the original NASA orbits of LRO, coordinate differences up to 9 m appear. After computing the LRO orbit, based on DE421 ephemeris, we could show an improvement of about 2 m. Using the independent IfE ephemeris, the differences are up to 20 m, however, the results are encouraging and we intend to further improve our models and software tools.

Future work will incorporate the use of crossovers in the LRO orbit determination, general refinements in algorithms, etc. Within the DFG research group FOR1503, a refinement of the solar system ephemerides is in preparation and will be added in the next step of the lunar ephemeris computation. This ephemeris shall also contribute to a better referencing of the LROC images as Moon-wide realisation of the lunar reference system.

### References

**[1] Müller et al. (2014).** Lunar Laser Ranging and Relativity. In: *Frontiers of Relativistic Celestial Mechanics*, vol. 2, p. 103-156, ed. S. Kopeikin, DeGruyter.
**[2] Mazarico et al. (2013).** Improved Orbit Determination of Lunar Orbiters with Lunar Gravity Fields Obtained by the GRAIL Mission. *LPSC*, 44, p. 2414.
**[3] Williams et al. (2008).** DE421 Lunar Orbit, Physical Librations and Surface Coordinates. JPL-IOM 335-JW,DB,WF

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