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Working Towards Improved Lunar/Planetary Reference Frames

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Abstract

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 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 firmly tie the LRO orbit into the Lunar-fixed reference frame. We demonstrate for the Apollo 15 site that images and Laser altimeter data taken by the LRO can be firmly tied to our Lunar reference frame using Lunar Laser Reflector stations as control points.

1. Introduction

The Lunar Reconnaissance Orbiter (LRO) launched in 2009 by the National Aeronautics and Space Administration (NASA) is orbiting the Moon in a ∼200 x 30 km elliptical polar orbit with the periselene over the lunar south pole. Its main objective is the detailed exploration of the Moon's surface by means of the Lunar Orbiter Laser Altimeter (LOLA) and three high resolution cameras bundled in the Lunar Reconnaissance Orbiter Camera (LROC) unit. Referring these observations to a Moon-fixed reference frame requires the computation of highly accurate and consistent orbits. For this task Earth-based observations are available, primarily radiometric tracking data from stations in the United States, Australia and Europe. In addition, LRO is prepared for one-way laser measurements from specially adapted sites. Currently, 10 laser stations participate more or less regularly in this experiment.

The outstanding quality of the optical observations collected by LRO has allowed for discovering details hidden to any previous lunar mission. The LRO Narrow Angle Camera (NAC), for instance, images the surface with a resolution of 0.5-2 m/pixel. In these images surface features at the Apollo landing sites such as the Lunar Ranging Retro Reflectors (LRRR) left by Apollo 11, 14 and 15 astronauts are resolved but also vehicles of unmanned Soviet missions can be identified. The NAC images of LRRR thus provide a link to the technique of Lunar Laser Ranging.In the framework of a German Research Foundation (DFG) research unit, processing facilities for both LRO and LLR data are currently established or revised at various institutions in Germany. This work presents individual results as well as the outcome of a joint effort which aimed at producing a consistent data set around LRO images of the LRRR left by Apollo 15. Data processing steps were as follows : a) Centered around the image acquisition times, ephemerides arcs and rotational parameters of the Moon were computed from LLR data. b) Using these lunar ephemerides, LRO orbit arcs were estimated from Earth-based observations. c) 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. At the present stage of the software development, these coordinates are primarily intended to be used as indicators for the accuracy of the LRO orbit.

2. Method

The presented work is based on recent developments on software packages run at the institutions involved:
The Lunar Laser Ranging software package "LUNAR" developed at the Institut für Erdmessung (IfE) provides, among others, precise coordinates of the reflector arrays on the Moon and an accurate lunar ephemeris. The latter is computed by simultaneous numerical orbit integration of the major solar system bodies along with the rotation of the Moon. For a de-

tailed description of the LUNAR LLR ephemeris and analysis package see [1].
The LRO orbit computations are performed by an extension of the Bonn software GROOPS which improves orbit and force parameters in an iterative way. The orbits are based both on Doppler data and laser ranges. 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 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.

3. Results

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. 1. We map-projected these particular NAC images using three different orbit solutions for LRO. First, we used most recent LRO orbits released by NASA based on a GRAIL gravity field and the DE421 lunar ephemeris [2]. We then map-projected the same image using two trajectories of LRO derived from Doppler and laser ranging measurements derived from the University of Bonn. One trajectory, referred to as IfE, is based on lunar ephemerides calculated at the University of Hannover. The other trajectory, referred to as DE, is based on the DE421 ephemeris from JPL. In each of the resulting ortho-images we measured the position of LRRR in the Moon Mean Earth/Rotation axis frame (ME) and compared it to the coordinates given in the literature [3], see Table 1. As expected, the current NASA orbits exceed the accuracy of our own orbits at each of the two considered time periods. However, the results are encouraging and we intend to further improve our models and software tools.

4. Summary and Conclusions

Future work will incorporate the use of crossovers in the LRO orbit determination, refinements in algorithms etc.. Within the DFG research group FOR1503, a refinement of the solar system ephemerides is in preparation. This ephemerides will also contribute to a better referencing of the LROC images.

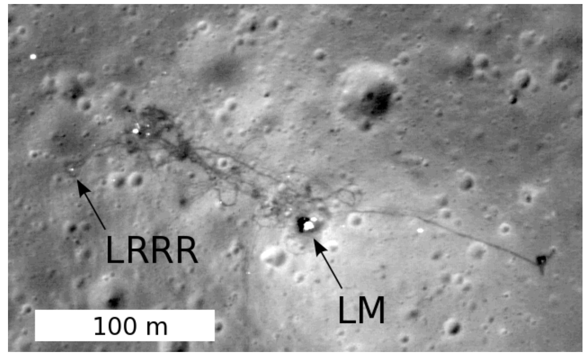

Figure 1: Apollo 15 landing site with Lunar Module and LRRR (NAC image: M111578606L).

Table 1: This table lists the ME-coordinates of the Apollo 15 laser reflector as measured by LLR and in LROC images processed with current GRAIL orbits and the LRO orbits derived in this work.

Frame	Longitude [°]	Latitude [°]	Diff. [m]
LLR	3.628507	26.133395	–
P1 NASA	3.628177	26.133462	9.22
P1 IfE	3.629848	26.133132	37.85
P1 DE	3.629830	26.133132	36.88
P2 NASA	3.628415	26.133280	4.30
P2 IfE	3.633889	26.136982	182.45
P2 DE	3.633889	26.136990	182.60

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