Lunar Reference Frame – Status and Possible Updates

Brent Archinal[1] and the IAU Working Group on Cartographic Coordinates and Rotational Elements
(1) Astrogeology Science Center, U. S. Geological Survey, 2255 N. Gemini Drive, Flagstaff, AZ 86004; barchinal@usgs.gov; +1-928-556-7083

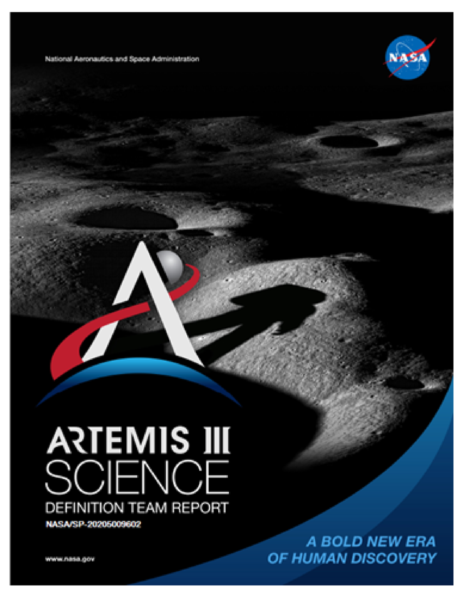
I. Introduction: Interest in Improving the Lunar Reference Frame

The IAU Working Group on Cartographic Coordinates and Rotational Elements (WG) has made past recommendations regarding the lunar reference frame [Archinal et al. 2018], and now there is increased interest in improving that frame.

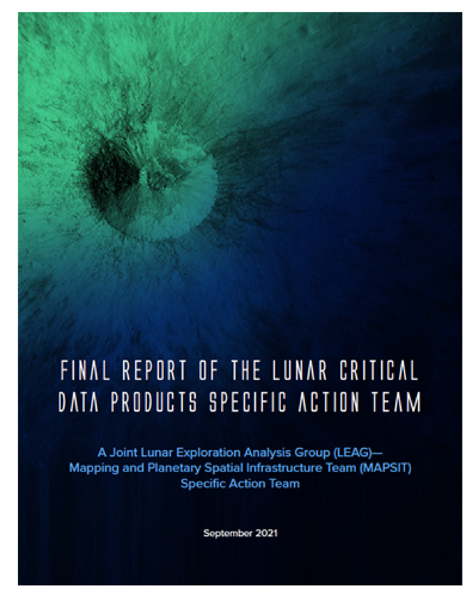
- Over the last 2 years, both the Artemis III SDT report [NASA, 2020] and the LEAG-MAPSIT LCDP SAT report [Joint LEAG and MAPSIT, 2022] have included recommendations for an updated lunar reference frame.
- Ryan et al. [2021] have published new Solar System ephemeris results that include a new lunar laser ranging (LLR) solution and lunar orientation ephemerides. The latter includes the DE440 ephemeris in the ME frame (defined below), which is compatible with their earlier DE421 ME frame recommended for use by the WG.
- Besides NASA's interest in improving the lunar frame, the USA National Geospatial-Intelligence Agency is considering the creation of a Lunar Reference System [Garner, 2022].

Given the expected huge increase in lunar missions, including Artemis and CLPS missions from the U.S., this may be a good time for the WG to consider updating the recommendations on a lunar reference frame.

Our goal here is to solicit input on such recommendations.



Artemis III SDT Report [NASA, 2020]



Joint LEAG-MAPSIT LCDP SAT Report [2022]

II. Systems and Frames, Background

Two common lunar reference systems

- mean Earth/polar axis (ME)
- principle axis (PA) or axis of figure
- spherical coordinates

ME

- Mean direction of Earth defines 0° longitude, mean rotation pole defines latitude
- In use in some form since 1775 (used by Tobias Mayer; see Davies and Colvin, 2000) at least, for almost all cartographic products
- **Adopted by the IAU (WGCCRE)**
- **In use by LRO and all international missions**

PA

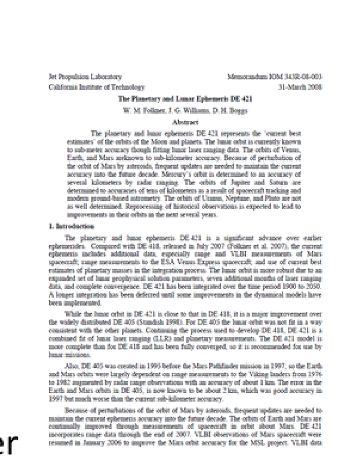
- 3 maximum moments of inertia define axes
- Important for dynamical (LLR) and gravity field studies (C21, S21 and S22 are all zero)

ME to PA difference

- 860 m total (560 m in longitude)
- Due to asymmetry in lunar gravity field
- "small" but obviously significant

Current IAU/WGCCRE Frame Orientation Definition

- Orientation model (frame) in PA system given directly via JPL DE 421 ephemeris [Folkner et al. 2008]
- Accompanied by specific 3 angle rotation to obtain orientation (frame) in ME system
- M = Rx(–0."30) Ry(–78."56) Rz(–67."92) P
- ME to PA difference derived from LLR solutions (no global rotation of retroreflectors allowed in ME coordinates)
- *However, no longitude defining features specified*



JPL DE 421 paper

Lunar Laser Ranging Retroreflector (LRRR) network

III. Items To Consider

Longitude Definition

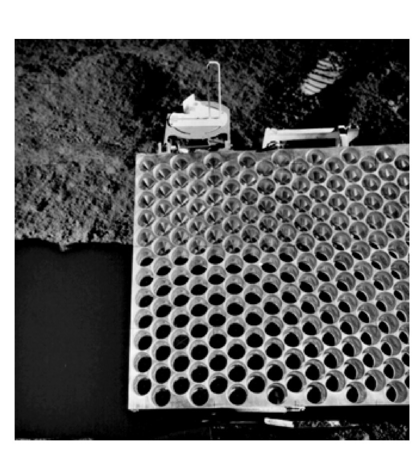
- The Moon is one of a few Solar System bodies without a longitude defining feature.
- It may finally be time to use an LLR solution of LRRR targets (see image) to define lunar reference frame, following long-standing IAU and WG recommendations.
- The DE421 ephemeris in the ME system frame could be used. I.e., a no-net rotation from the LLR solution used to define the DE421 ME frame.

New Lunar Ephemeris Available

- New JPL DE440 ME frame ephemeris available (see image)
- Using new LLR data (since 2008) and improved models and LLR solution (see table)

Changes Not Large

- Differences shown in next panel. Differences in ephemeris on order of a meter, for the LLR solution up to ~1.5 m.
- Not so significant as to be noticeable except at highest current levels of accuracy.
- May help to prepare for even better accuracy in the future, removes minor source of error.
- Currently would need to use JPL products, as they include the most recent LLR solution and ephemeris results.
- In the future, for further updates or alternate versions of frame and ephemeris will want to consider LLR solutions and ephemerides from other sources, e.g., possibly in some sort of combined solutions.



The Apollo 15 retroreflector array – the largest of the LRRR

Ryan et al. [2020] JPL DE440 and DE441 paper

Table 1. Lunar laser retroreflector array coordinates for DE440 using a frame based on mean Earth/mean rotation axes and center of mass.

Array	*X*	*Y*	*Z*	*R*	E Longitude	Latitude
	meters	meters	meters	meters	degrees	degrees
Apollo 11	1591747.866	691221.719	20397.513	1735472.498	23.4730537	0.6734295
Apollo 14	1652818.597	-520455.449	-110358.373	1736335.843	-17.4786746	-3.6440726
Apollo 15	1554936.909	98606.467	764413.816	1735477.026	3.6285583	26.1334407
Lunokhod 1	1114957.719	-780931.538	1075635.760	1734928.549	-35.0079211	38.3152952
Lunokhod 2	1339387.864	802312.157	755848.281	1734638.657	30.9222014	25.8322743

LRRR ME Coordinates in LLR Solution used for DE440

IV. Differences Between DE440 and DE421 ME Frames

Summary of Differences

- Maximum difference during LRO mission so far: ~40 cm
- Largest in Z rotation
- Maximum difference during Artemis period: ~45 cm
- Similar magnitude for all 3 axes in 2030s
- Maximum difference (years 1900–2150): 1 meter

- Maximum LLR coordinate difference: 143 cm

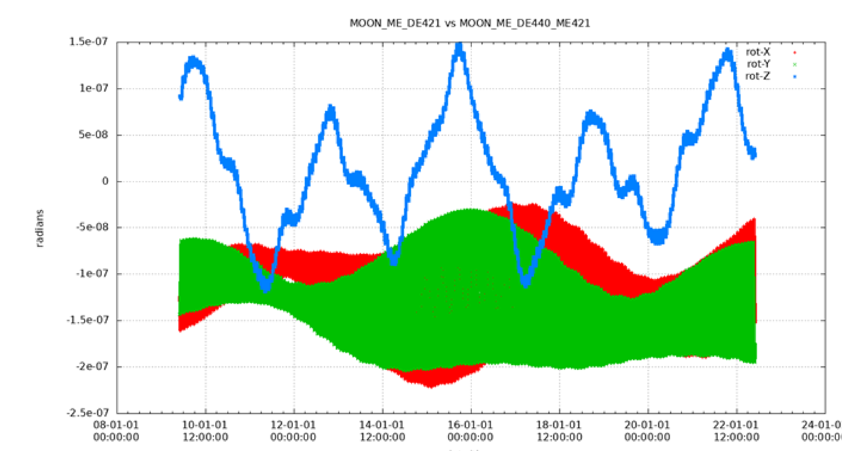
Compare to:

- Nominal mission LROC NAC ground sample distance: 50 cm
- Smallest LROC NAC ground sample distance: ~25–30 cm
- Nominal LOLA spot size: 5 m
- Smallest LOLA spot size: 2.5–3 m

Maximum differences comparable to 0.9 to 1.8 LROC NAC pixels

Maximum differences comparable to 0.1 to 0.2 LOLA spot size

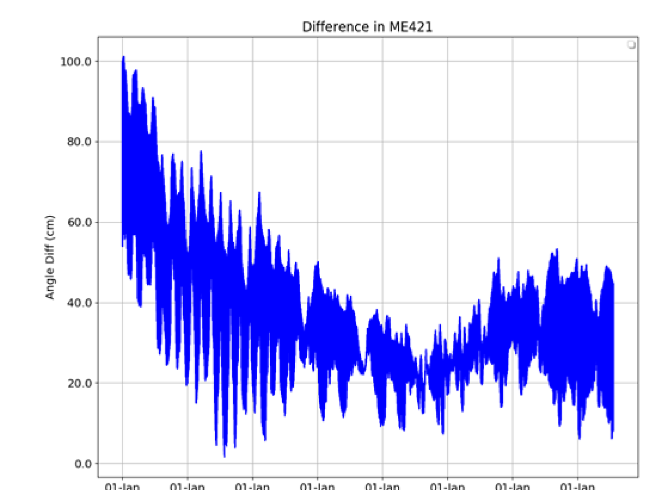
Differences are small – but systematic – compared to 10–13 meters [Wagner et al., 2017] LRO pointing and positioning errors



JPL DE421 ME vs. DE440 ME
LRO Mission period
X, Y, Z rotation differences

Vertical axis covers 4e-07 radians = *70 cm*

Image Credit: Boris Semenov, JPL/NAIF



JPL DE421 ME vs. DE440 ME
Years 1900–2050
total differences (all axes)

Vertical axis covers 100 cm

Image Credit: Ryan Park, JPL; via Boris Semenov, JPL/NAIF

V. Pros and Cons of Changing Frame Definition

PROS

- Finally using fixed surface features (LRRR) to define longitude and latitude (as e.g., for the Earth).
- Frame considered independently of orientation model (ephemeris) for that frame.
- Improvements in the frame based on new LLR data.
- Improvements in orientation model based on new LLR data.
- Changes significant for highest accuracy (meter level) work, but not so large as to affect positioning of most (lower resolution) lunar datasets.
- Increases community awareness of the need to update the frame and orientation model in the future, and of the possible need for a "lunar orientation service" to reach the highest levels of accuracy for navigation and positioning.
- Users would not need to rely on an older ephemeris for lunar orientation and a newer one for other uses (lunar orbit, planetary positions).

CONS

- For the highest accuracy work, modeling/software changes will be needed to implement the new orientation model.
- The changes will need to be published and communicated to the lunar community and education provided on the effects of the changes.
- Some confusion may result if the frame of lunar data products is not clearly labeled (as the LCDP SAT report recommends be done).
- Future updates will continue to be required as more LRRR targets are created, improvements are made in the methods for further LLR and ephemeris solutions, as more data become available, as accuracy requirements increase, and as solution providers increase. But this may happen with or without an update now.

VI. Request for Feedback

The WGCCRE is requesting feedback from the lunar community on the following questions.

1. Is using (the current new JPL) LLR solution to define the lunar reference frame appropriate?
2. Is using the DE440 ephemeris in the DE421 ME frame appropriate as a new lunar orientation model?
3. Are there other LLR and lunar ephemeris solutions that could be considered for use in this process?

Feedback to the lead author is welcome (at e.g., barchinal@usgs.gov), during or soon after the PSIDA meeting. We hope to complete the next version of our main WG report by the end of this year and possibly include an update for a recommended lunar frame definition.

References

Archinal, B. A., et al. (2018). *CMDA* 130:22, DOI: 10.1007/s10569-017-9805-5. http://astrogeology.usgs.gov/Projects/WGCCRE/
Davies, M. E. and Colvin, T. R. (2000). *JGR*, 105, E8, 20,277-20,280, https://doi.org/10.1029/1999JE001165
Folkner, W. M., et al. (2008). *JPL Memorandum* IOM 343R-08-003. ftp://ssd.jpl.nasa.gov/pub/eph/planets/ioms/de421.iom.v1.pdf
Garner, T. (2022). ION Int. Tech. Mtg. https://www.ion.org/itm/virtual-abstract-view.cfm?paperID=10769
Joint LEAG-MAPSIT SAT (2022). https://www.lpi.usra.edu/mapsit/reports/leag_mapsit_report_2022-01-11.pdf
National Aeronautics and Space Administration (2020). Artemis III Science Definition Team report. https://www.nasa.gov/sites/default/files/atoms/files/artemis-iii-science-definition-report-12042020c.pdf
Park, R. S., et al. (2021). *Astron. J.* 161(3), 105, pp. 15, https://doi.org/10.3847/1538-3881/abd414
Wagner, R.V., et al. (2017). *Icarus* 283, 92–103. https://doi.org/10.1016/j.icarus.2016.05.011

Acknowledgements

We thank Ryan Park and Boris Semenov (JPL) for input and figures used here.
Partial funding of this work has been provided by the NASA-USGS Planetary Spatial Data Infrastructure IAA.

Poster #P15