**UPDATING THE CARTOGRAPHIC LUNAR REFERENCE FRAME.** Brent Archinal¹ and the IAU Working Group on Cartographic Coordinates and Rotational Elements, ¹U. S. Geological Survey, Astrogeology Science Center (2255 N. Gemini Drive, Flagstaff, AZ 86004, USA; barchinal@usgs.gov).

**Introduction:** The IAU Working Group on Cartographic Coordinates and Rotational Elements (WGCCRE) has made past recommendations regarding the cartographic lunar reference frame (LRF; [1, 2, 3]). This includes recommending the use of an ME system-based frame (defined below) to define the orientation and therefore the cartographic frame for the Moon. We are currently considering what recommendations to make for our next main report (e.g., updating [3]).

Both the Artemis III SDT report [4] and the LEAG-MAPSIT LCDP report [5] have included recommendations for an updated lunar LRF. A white paper from the NASA Lunar Exploration Analysis Group (LEAG) [6] has also recommended the continued use of an ME system-based frame.

In 2023, as we have described previously [7, 8], personnel from the U. S. National Geospatial-Intelligence Agency (NGA) and NASA [9] have said they and possibly other groups are (or may be) planning to use a principal axis (PA) system-based reference frame (again, defined below) for the Moon as part of their work to develop a lunar reference system. Unfortunately, there have been no published proposals about such plans. It is unclear what the benefits of such a change might be, and when and how it would be implemented. Laurenti et al. [10] peripherally address this issue. They demonstrate that orbit propagation needs to be done consistently in the same frame. However, this is well known and to our knowledge has always been done for the Moon and other bodies. They also note that positions in an ME frame will be needed for use with cartographic products.

Using a PA system-based frame for cartography would be of great concern, as essentially all lunar cartographic data and products are currently in an ME frame (e.g., millions vs. dozens or fewer of files and products). Switching between systems might necessitate converting all lunar data and related documentation. Here we briefly describe the two different systems, the relevant frames in those systems, and touch on some of the many issues that would arise if there were a need to use and/or convert data and products from an ME to a PA frame.

Until and unless strong arguments are published that a change to using a PA system-based frame for cartography and other purposes (such as navigation and positioning), we plan to continue to recommend the use of the ME system for mapping, as we have since the WGCCRE began making recommendations in 1980 [1]. We therefore are continuing (as described in previous abstracts and presentations [11, 7, 8]) to consider recommending a (comparatively minor) improvement to the ME system-based reference frame.

**Background:** A coordinate system is an overall concept, including theory and conventions to form an idealized coordinate model. A coordinate frame is a specific realization of a system, e.g., a solution that, using data, defines point coordinates. Two different systems have long been in use for the Moon. These are the Mean Earth/polar axis (ME, sometimes MER for Mean Earth/Rotation) and the Principal Axis (PA) systems. In brief, ME is defined by having 0° longitude in the mean direction of the Earth and an equator defined by the mean direction of the lunar pole, whereas PA is defined by the axes of the principal moments of inertia of the Moon (e.g., see [3]).

The ME system has always been used for lunar mapping, dating to the 18th century. The WGCCRE has recommended the use of the ME system for cartography since its initial report [1]. The LRO mission and LGCWG [11] recommended the use of the JPL DE 421 ephemeris, rotated into the ME system and therefore an ME frame, as the basis for mapping. The LGCWG included representatives from NASA, ESA, China, India, Japan, and the UK. The WGCCRE accepted their input and made the same recommendation [2, 3].

The difference between the two systems/frames has a maximum of 875 meters with components in both longitude and latitude. The difference varies depending on location but is usually several hundred meters.

**Issues With Changing the Cartographic System:** The use of a PA rather than an ME system-based frame for cartography would result in having mapping products in two different incompatible systems, or necessitate making significant changes to all existing lunar mapping data and mapping products and introduce confusion in their use. Space does not permit covering these issues in detail. However, we and others have already highlighted many of the possible issues raised by others (e.g., personnel from the National Geospatial-Intelligence Agency and the NASA Goddard Space Flight Center) in earlier publications [6, 7, 8] that can be consulted for additional information. We will only briefly say that all lunar missions, lunar data sources, and many terabytes of data would need to be considered, including the steps that would be needed to change frames. Confusion would also result when data and products exist for some time, if not indefinitely, in two different frames, and there would be increased difficulty in processing or using lunar data.
As noted in the earlier publications, one issue raised is that a PA frame would be more accurate for cartography, but current methods of updating ME frames show this not to be the case (see the next section for a comparison of the LLR frames). Also as noted in the earlier publications, there have also been claims that using two systems (and their frames) may be confusing for navigation (e.g., orbit propagation) near the Moon. We are unaware of any cases of such confusion and have pointed out that an ME frame could be used for all orbital calculations just as well as any PA frame.

Given these issues, we would argue that an ME system-based frame should continue to be used for cartographic and navigational purposes relative to the lunar surface to which it is fixed. If desired, PA system-based frames could continue to be used for dynamical purposes and the relationships between these frames continue to be derived and specified.

**Improving the Existing ME-Based Frame:** As we have described previously [11, 7, 8] JPL personnel [13] have created an updated lunar laser ranging solution and used it to define an improved PA frame and derived from that an improved ME frame. They have also created new lunar ephemeris (DE440) models tied to these frames. The new JPL solutions use substantially more data, and improved modeling compared to the previous (2008) DE421 solution. While the PA frame has no orientation constraint compared to the previous frame, the new ME frame is derived from a no-net rotation condition from the DE 421 ME frame, thus guaranteeing a DE 440 ME frame and ephemeris that includes the internal improvements of the new LLR solution that yet maintains lunar surface coordinates as accurately as possible. The RMS difference between the DE 421 and DE 440 LLR ME frames is 9 cm (while the old and new PA frames difference is 29 cm).

Differences in the ME frame ephemeris from the previous model are less than 1 meter during the period 1900–2050. See e.g., Fig. 1 in [11]. Differences in the coordinates of the underlying LLR solutions are < 1.5 meters. Such differences are unlikely to be noticeable in the positioning of data products except at the highest current levels of accuracy. This update would nevertheless help to prepare for the best future accuracy, by reducing one source of error.

The current JPL products are the most likely data sources for updating the lunar frame in the near term. Eventually, updates would need to consider LLR solutions and ephemerides from other sources such as the INPOP group (https://www.imcce.fr/inpop), possibly in some sort of combined solutions.

**Request for input:** The WGCCRE would like to proceed with updating our main report by the end of this calendar year. In the near term, “The IAU Commission A3 on Fundamental Standards expects to appoint a working group to discuss best practices for ... emerging [lunar] standards and present recommendations to the IAU” [14]. The WGCCRE is willing to work with the A3 Commission and any new working group, on incorporating our existing or any improved definition of the lunar cartographic (i.e., body-fixed) coordinate system, as part of the broader work to develop a consistent set of lunar-based coordinate systems and terminology. However, in parallel with that work, and perhaps as an interim step to the broader work, we are likely to recommend that the cartographic lunar reference frame be defined as that of the DE 440 LLR solution, rotated to match the DE 421 ME solution, and lunar orientation be defined via the associated DE 440 ephemeris in that frame. If there is felt to be some issue in doing so, it’s important to see published feedback so that the WGCCRE and international lunar community can publicly consider such issues.


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