Continued Use of the Mean Earth (ME) Coordinate System for the Moon

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Executive Summary
To accurately communicate the location of features on the Moon, a coordinate system is required. The Mean Earth (ME) reference system has been accepted internationally as the standard system for the Moon, fixing observable lunar features with an accuracy of about 1 meter. This system has been used for centuries, and several petabytes of data from dozens of international lunar missions have been placed in the current ME frame. Products derived from these data, e.g., maps, mosaics, databases, and publications, have used the ME system. Various organizations wish to instead use the Principal Axis (PA) reference system for lunar mapping. The PA system is important for dynamical purposes while the ME system was meant for cartographic purposes. The PA system and frames are not more accurate or simpler to use than the ME system and frames. In our estimation, a change to the PA system would introduce a highly likely risk of confusion in the planetary science and exploration communities regarding the location of features on the Moon with the potential for major consequences for future lunar missions. Updating and reprocessing all lunar data and creating new maps in the PA system would require substantial resources and time and are not necessary. ***We recommend that the ME system continue to be used for lunar mapping.***

Introduction: The NASA Planetary Science Division requested that the Lunar Exploration Analysis Group (LEAG) produce a concise white paper on the merits of continuing with the ME coordinate system for the Moon. The authors are members of the planetary science community selected by the LEAG Executive Committee.

Lunar exploration requires positional knowledge of features on the surface of the Moon that is as accurate and precise as practically possible. For example, landing humans near the lunar south pole and supporting surface operations for Artemis III will require the combination of multiple lunar datasets from recent orbital missions. This is only possible if these data use a common reference coordinate system and frame. A lunar coordinate system allows the spatial relationships between lunar features on, below, and above the surface to be rigorously defined.

Two different systems have long been in use for the Moon. These are the Mean Earth/polar axis, or often just Mean Earth (ME) and the Principal Axis systems. 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 rotation pole, and it is the current standard for mapping and defining surface coordinates. PA is defined by the axes of the principal moments of inertia of the Moon [1–3], and it has been mostly used for modeling of geophysical parameters, such as the lunar gravity field.

The ME system has been employed for lunar mapping purposes for centuries, and there are many reasons to continue its use as the standard lunar coordinate system. The PA system is not more accurate and has no clear advantage over the ME system for mapping purposes. Below we summarize our rationale and findings for the continued use of the ME system for lunar mapping.

Background and Rationale for Findings: The terms "coordinate system" and "coordinate frame" have specific meanings. A coordinate *system* is an overall concept of an idealized coordinate model. A coordinate *frame* is a specific realization of a system, e.g., a solution that uses data to define coordinates or locations in a dataset.

The ME system has been used for lunar mapping, starting in the 18^{th} century [4]. The International Astronomical Union's (IAU) Working Group on Cartographic Coordinates and Rotational Elements (WGCCRE) has recommended the ME system for cartography since its initial report in 1980 [1]. In 2008, the Lunar Reconnaissance Orbiter (LRO) mission and the Lunar Geodesy and Cartography Working Group (LGCWG) [5] recommended use of the Jet Propulsion Laboratory's (JPL) DE 421 ephemeris, to be rotated into the ME system, as the ME reference frame for mapping. The WGCCRE made the same recommendation in 2011 [2] and 2018 [3]. To our knowledge, all space agencies worldwide have followed this recommendation. It is understood that for both the PA and ME systems, the coordinate frame and the ephemeris can and should be updated as additional knowledge of the Moon and its orbit is gained.

The maximum difference between the ME and PA systems/frames is 875 meters with components in both longitude and latitude. The amount varies depending on location but is usually at least several hundred meters. Mislocation on this scale could lead to serious problems during landing, surface, and rendezvous operations if the wrong system is used. Points on the lunar surface with the same ME and PA coordinates are often not visible from the other. Figure 1 shows the offset difference in location at the Apollo 14 landing site.

Finding 1: The difference in the ME and PA coordinates of a point on the lunar surface is at least several hundred meters. Lunar surface operations could be considerably affected if the coordinate system is misunderstood.

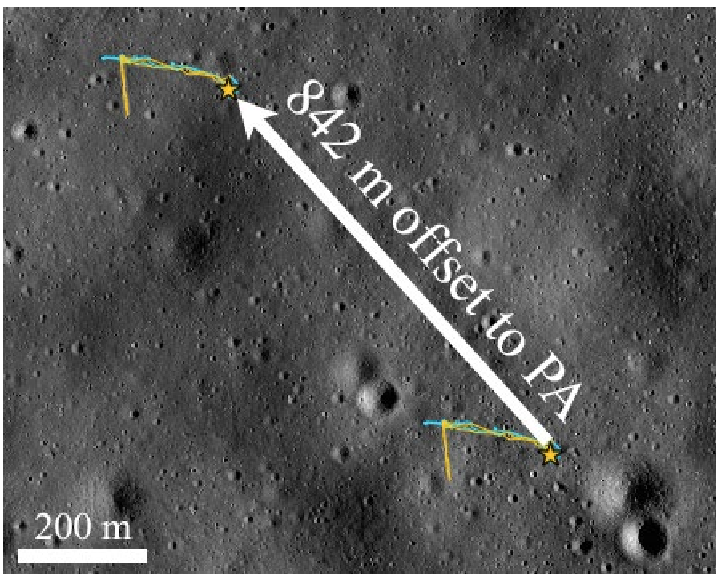

Figure 1: Illustration of the entire Extra-Vehicular Activities (EVA) 1. Paths for Apollo 14 shown as offset if PA coordinates were used for them by mistake. The offset distance is 842 meters. The yellow star shows the Apollo 14 landing site, with the lower right location being the location in this image (using ME coordinates). An interactive view has been made available in Quickmap: https://bit.ly/3sqqNwr. Image is modified from original by the LROC Team: https://www.lroc.asu.edu/featured_sites/view_site/62. The underlying narrow-angle camera image has a resolution of 0.75 m/pixel.

The primary difference between ME and PA frames is that the global orientation of the PA frame can drift as the models for the lunar interior and orbit change, but the ME frame is held fixed with respect to surface features [6]. PA frames are therefore not generally appropriate for defining cartographic coordinates, except to assist in the initial definition of a cartographic frame.

There have been updates recently to the ME frame and associated ephemeris. While the JPL DE 421 lunar laser ranging solution and ephemeris in the ME frame are the current internationally recommended cartographic frame for the Moon, the cartographic lunar orientation model could now be specified by using the JPL DE 440 ephemeris in the ME frame [6]. Differences from the previous ME frame solution are less than 1 meter during the period 1900–2050. This update would help to prepare for the best future accuracy by reducing one source of error. Such an update has been recommended by the Artemis III Science Definition Team [7] and the Lunar Critical Data Products Specific Action Team (LCDP SAT) [8]. We agree that an update should be made, because it would involve a change at the meter level, and reprocessing of data may be needed only for the highest resolution datasets and the highest possible accuracy applications [9].

Finding 2: An ME frame is as accurate as the corresponding PA frame, but ME frames are held fixed with respect to surface features. The ME frame is most appropriate for use in lunar mapping.

All scientific papers, published geologic maps, and lunar databases citing the locations of features on the Moon based on the ME system would have out-of-date coordinates and would be rendered inaccurate by a change to PA coordinate systems.

Changing from the ME to PA system would also necessitate converting all lunar geo-referenced data and related documentation. At least several petabytes of data from lunar missions, including archived products from NASA and international missions, would need to be considered. The steps needed to change frames would have to be determined, planned for, properly funded, carried out, and the converted products archived with changes documented.

In the NASA Planetary Data System (PDS), LRO data are 65% of the holdings (including millions of images and billions of lidar measurements) [10] and more than 3 petabytes in size. The LRO Camera (LROC) alone has provided approximately 3.5 million images and 1.5 petabytes of data (as of 2023 April 24). However, this does not include the many other U.S. lunar missions since the 1960s, which would require complicated and new legacy data processing methods to convert.

Mapping products cannot simply be converted by shifting pixels but would have to be reprojected and resampled. Such an effort would require reprocessing any map projected data and map products, which comprise roughly half of the existing few petabytes of lunar data. Specialized personnel will be required to produce converted map products. Our own experience indicates that such knowledgeable individuals are few in number and already overcommitted. This likely includes personnel currently operating the LRO mission and planning for the upcoming Commercial Lunar Payload Services missions, and personnel who are making maps for the upcoming Artemis missions. Without further analysis, we cannot provide quantitative estimates of the work that would be required to convert map products; however, given that at least half the data currently archived would be affected, the cost and personnel necessary to convert these LRO data products would be similar to at least half the costs the LRO instrument teams incur to do their routine data processing and archiving. Products such as digital terrain models, used for landing site mapping, would lose some level of accuracy and precision during resampling and would either need to be recreated or have versions kept in both frames to allow for analysis at full resolution.

The amounts above do not include data distributed to and used by other (e.g., non-NASA) sources. The total downloads to users directly from LROC are roughly 650 million files and approaching 5 petabytes of data (N. Estes, LROC, 2023 May 30). These totals do not include other public and commercial lunar data providers, such as Applied Coherent Technology's Lunar QuickMap, with over 1.5 petabytes of data, or other services such as Arizona State University's Lunaserv or JMARS for the Moon, or JPL's Moon Trek, etc. The amounts also do not include any of the massive data sets from the extensive international missions of recent years, from China, Japan, India, and Korea; all of these data products were processed using the internationally recommended ME frame.

Given the amount of data involved, it should also be noted that operational costs of moving data within, to, and from cloud faculties, and keeping in many cases for some indefinite time, two copies of the data and data products (in the two frames) could also be tremendous. Such costs would fall on current and future NASA missions, other data providers, and international space agencies.

Finding 3: The resources that would be required by the international lunar science and engineering community to change the large volume of existing lunar data and information from the current ME to the PA system would be substantial.

An additional problem would be the confusion over which system/frame a cartographic product is in. There are few datasets or cartographic products in the PA frame. As recommended by the LCDP SAT report [8], which system and frame is in use for any lunar mapping product should be documented. To our knowledge, currently users confidently assume that their data have been placed in an ME system-based frame. Should such products start to be placed in a PA frame, it will be vital that users carefully check which frame their data are in, to avoid the potentially large offsets shown in Figure 1.

We have heard the suggestion that it may be desirable to use only one system for spacecraft operations and that using only a PA frame satisfies the needs of both mapping and navigation. However, any desired gravity field model easily can be converted to the current ME-based frame and used for orbital calculations and navigation. Changing one or a few gravity field models would likely require far less effort and cause far less confusion.

Finally, there is the overall issue of whether any "new" standard will be accepted by others. The WGCCRE reports recommend that as reference frames are updated the change should be as small as needed to minimize disruption [3]. A switch from using the ME to the PA frame for cartography would not meet that recommendation. Individual space agencies might not wish to change. So once started, the use of both systems for cartography could continue indefinitely.

In our estimation it is significantly easier, more cost-effective, and less confusing to continue to use the ME frame to determine surface coordinates, rather than converting petabytes and decades of scientific data to a new reference frame unnecessarily. The PA system-based frame can continue to be used for dynamical uses as needed.

Finding 4: The confusion introduced in use of many existing datasets, data products, databases, and publications by changing from the ME coordinate system to the PA system would be substantial.

Conclusion: Countless lunar scientists and explorers have worked for decades to ensure that their datasets, products, and scientific results are in the same standard reference frame and can be easily compared and used. Switching to the use of the PA frame for lunar mapping needlessly invalidates this work, incurs potentially immense cost, introduces confusion among users, and makes the data more difficult to use.

We strongly believe that an ME system-based reference frame and coordinate system should be maintained for lunar cartographic products and purposes. PA system-based frames can continue to be used for dynamical purposes, and the relationships between these frames should continue to be derived or defined.

Acknowledgments: Some of the text here has previously appeared in [11]. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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