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Moon to Mars
Architecture

white paper

Lunar Reference Frames

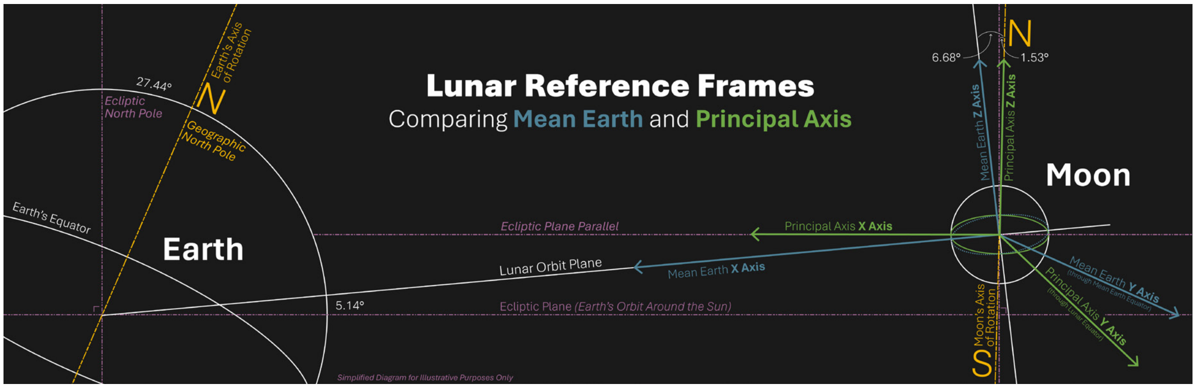
Introduction

As NASA returns to the Moon to establish a long-term presence there, navigation capabilities will be critical to all aspects of science and exploration. **Accurate and precise lunar navigation data improves safety, enhances planning, and enables crewed and robotic missions to achieve agency goals.**

NASA's Moon to Mars Objectives[1] — the agency's vision for crewed, deep space exploration — include a lunar infrastructure goal to "Develop a lunar position, navigation and timing architecture capable of scaling to support long term science, exploration, and industrial needs." Additionally, the National Cislunar Science and Technology Strategy[2] — a 2022 White House Office of Science and Technology Policy product — calls for NASA to lead the development of standards around "a Lunar reference frame tied to the celestial and terrestrial reference frames."

NASA's Moon to Mars Architecture[3] — the agency's roadmap for achieving the Moon to Mars Objectives — includes the Communications and Position, Navigation, and Timing (C&PNT) sub-architecture. NASA documents the architecture, including its C&PNT components, in the agency's Architecture Definition Document,[4] which is updated annually.

To empower sustained exploration of the Moon, NASA must thoughtfully consider the navigation standard it incorporates into the Moon to Mars Architecture. **This white paper identifies key considerations for the selection and implementation of or lunar reference frames for NASA's Artemis campaign.**



Figures 1: *Simplified diagram highlighting differences between lunar reference frames. (NASA)*

What is a Reference Frame?

The International Astronomical Union defines a reference system as the "theoretical concept of a system of coordinates, including time and standards necessary to specify the bases used to define the position and motion of objects in time and space" and a reference frame as "practical realization of a reference system."[5] Simply put, reference frames help mission planners understand where things are in space relative to one another.

Reference frames enable cartography, navigation, and operations on planetary bodies. They also create a shared navigation vernacular for mission planners, empowering cooperation and coordination that transcend boundaries of language or nation.

At the Moon, NASA has historically used two different body-fixed reference frames, each with different applications: **Mean Earth** and **Principal Axis**.

Mean Earth

Mean Earth has been used since the 18th century to observe and map the lunar surface and is still commonly used today. For this frame, the mean direction of Earth defines zero longitude (the x axis) and the mean direction of the Moon's rotation determines latitude (the z axis). The Moon's center of mass is the origin (center) of the Mean Earth coordinate system.[6,7]

The lunar surface science community commonly uses the Mean Earth reference frame for spatial data, to generate terrain and elevation models, and to reference surface features. Even as humanity's knowledge of the Moon improves, updates to the Mean Earth frame remain consistent with previous frames, minimizing changes to the coordinate frame in which surface feature locations are recorded (e.g., Apollo sample locations noted in the Mean Earth coordinate frame remain relatively consistent over time.)

Principal Axis

The Principal Axis frame adopts the principal axes and rotation of the Moon (i.e., the coordinate frame orientation is determined by the Moon's shape and mass distribution and rotates with the Moon). Like Mean Earth, the Moon's center of mass is the origin (center) of the Principal Axis coordinate system. Due to the nature of the Earth-Moon system, the Mean Earth and Principal Axis rotation axes do not coincide (see Figure 1).

Mission operators often use a Principal Axis frame for flight dynamics and navigation for cislunar spacecraft because lunar gravity is commonly computed in this frame, and thus gravitational forces on a spacecraft can be easily derived in that frame. It's also used for studies and modeling concerned with lunar gravity, topography, geodesy, and internal modeling.

Key Considerations

Accuracy and Safety

Equivalent coordinates on the lunar surface for Mean Earth and Principal Axis frames can differ by as much as 875 meters (i.e., a little over half a mile). This discrepancy can pose risks during mission-critical activities (e.g., lunar landings) or introduce errors in scientific investigations.

For the Artemis campaign, NASA has stringent surface location accuracy requirements to ensure the safety of lunar astronauts. Both the Mean Earth and Principal Axis frames are accurate to about the meter level, which is about 10% of the navigation accuracy budget for Artemis missions.

Collaboration and Consensus

Because the Mean Earth and Principal Axis frames are better suited to different applications, their adoption also varies. No single reference frame is ideal for all stakeholders — reference frames are chosen according to intended use case.

Establishing a consensus approach to lunar reference frames requires NASA to consider the needs of individual Artemis exploration assets. These assets will, by necessity of mission and vehicle design optimization, use different reference frames based on mission objectives and destinations. The reference frames used may also vary based on the implementing commercial organization or international partner.

NASA should establish standards, roles, and responsibilities to ensure proper configuration management of reference frame definitions and transformations. Additionally, the agency should ensure dissemination of these products to industry, academic, and international partners.

Backwards Compatibility

As reference frames evolve over time, it will become necessary to document transformations that maintain backwards compatibility with previously used frames in addition to transformations between frames. These calculations will be critical to preserving backwards compatibility with heritage data and systems.

Architectural Flexibility

Receivers of navigation signals should be designed to perform transformations to the reference frame best suited to their mission. This is not an unusual consideration for terrestrial applications, as receivers designed for the Global Navigation Satellite System[8] perform transformations between the reference frames of its component navigation systems (e.g., between the U.S. GPS, which uses the World Geodetic System 1984[9] maintained by the U.S. National Geospatial-Intelligence Agency,[10] and European Galileo,[11] which uses an independent version of the international terrestrial reference frame).[12]

Considering current spectrum allocations and constraints for radio navigation satellite systems — as defined by the Space Frequency Coordination Group[13] and International Telecommunications Union[14] — lunar navigation will likely secure relatively low bandwidth. This will limit satellite systems to broadcasting in a single reference frame (and data to support transformations by users).

Artemis Continuity

Both Mean Earth and Principal Axis user communities have already created science and navigation data within their respective frames. If NASA were to require use of a single reference frame, users would need to spend time and budget reprocessing their data, adding unnecessary processing risk, resource reprioritization from other tasks, and additional workload with little return value.

For the Artemis campaign, NASA is utilizing a Mean Earth frame for site selection and surface analyses. Transitioning to Principal Axis would disrupt progress, shifting focus from time-sensitive Artemis planning activities.

Recommendations

The Artemis campaign will comprise many systems in lunar orbit and on the Moon's surface. To realize a capable and extensible C&PNT sub-architecture, space vehicles and exploration assets must communicate navigation data between one another. To support these complex interactions, NASA must develop standards for reference frames and transformations. This guidance will enable consistency, simplify early mission and systems development, and reduce risk in surface operations.

In 2024, NASA established a working group to begin developing an agency approach to lunar reference frames that could meet the needs of the Artemis campaign and future lunar exploration. **Based on the considerations outlined above, the working group recommended that NASA develop a flexible lunar exploration architecture that supports the use of more than one frame.**

The working group also recommended that NASA work with the international community to establish standards for the exchange of surface location data. Defining these interfaces early in the architecture development process will simplify mission engagements.

The working group endorsed the Mean Earth lunar reference frame as the standard for initial surface operations, including planning and user location data exchange. Mean Earth meets identified needs at the lunar surface with minimum impact to current mission planning with minimal need to change heritage data products. **The working group did not endorse a corresponding orbital standard, understanding the need for mission-driven flexibility.**

In the future, NASA plans to use the Architecture Concept Review[15] as a forum to adopt reference frame updates to support agency stakeholder communities. Working with the community, NASA will also establish processes for the reference frame configuration management and the dissemination of reference frame updates.

Key Takeaways

Accurate and precise lunar navigation data improves safety, enhances planning, and empowers science for crewed and robotic missions; lunar reference frames are a critical component of a navigation architecture.

There are two primary lunar reference frames in use: Mean Earth and Principal Axis. Neither frame meets the needs of every stakeholder; each frame is better suited to a different set of specific disciplines and scientific communities. Availability of relevant transformation data allows for conversion between frames.

Establishing a consensus approach to lunar reference frames requires NASA to consider the needs of individual Artemis exploration assets and its industry, academic, and international partners.

It would be impractical and disruptive to establish a single reference frame for all lunar activities. A flexible architecture supporting multiple, complementary reference frames will benefit diverse users.

Adopting a Mean Earth reference frame for initial surface operations, including planning and user location data exchange, will meet current needs identified for missions while on the lunar surface. The working group did not endorse a corresponding orbital standard, understanding the need for mission-driven flexibility.

NASA will use the Architecture Concept Review cycle to evaluate and implement reference frame updates. This evaluation must include all relevant stakeholders and should quantify impacts to all stakeholders.

References

1. **NASA's Moon to Mars Objectives**
https://www.nasa.gov/wp-content/uploads/2022/09/m2m-objectives-exec-summary.pdf
2. **National Cislunar Science & Technology Strategy**
https://www.whitehouse.gov/wp-content/uploads/2022/11/11-2022-NSTC-National-Cislunar-ST-Strategy.pdf
3. **NASA's Moon to Mars Architecture**
https://www.nasa.gov/moontomarsarchitecture/
4. **Architecture Definition Document**
https://www.nasa.gov/moontomarsarchitecture-architecturedefinitiondocuments/
5. **Nomenclature for Fundamental Astronomy**
https://syrte.obspm.fr/iauWGnfa/NFA_Glossary.html
6. **Lunar coordinates in the regions of the Apollo landers**
https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/1999JE001165
7. **A Standardized Lunar Coordinate System for the Lunar Reconnaissance Orbiter**
https://pds-imaging.jpl.nasa.gov/documentation/LRO_Coordinate_System.pdf
8. **United Nations Office for Outer Space Affairs**
https://www.unoosa.org/oosa/de/ourwork/psa/gnss/gnss.html
9. **World Geodetic System 1984**
https://earth-info.nga.mil/index.php?dir=wgs84&action=wgs84
10. **National Geospatial-Intelligence Agency**
https://www.nga.mil/
11. **European Space Agency | What is Galileo?**
https://www.esa.int/Applications/Satellite_navigation/Galileo/What_is_Galileo
12. **Reference Frames in GNSS**
https://gssc.esa.int/navipedia/index.php/Reference_Frames_in_GNSS
13. **Space Frequency Coordination Group**
https://www.sfcgonline.org/home.aspx
14. **International Telecommunications Union**
https://www.itu.int/en/Pages/default.aspx
15. **Architecture Concept Review**
https://www.nasa.gov/moontomarsarchitecture-architectureconceptreview/