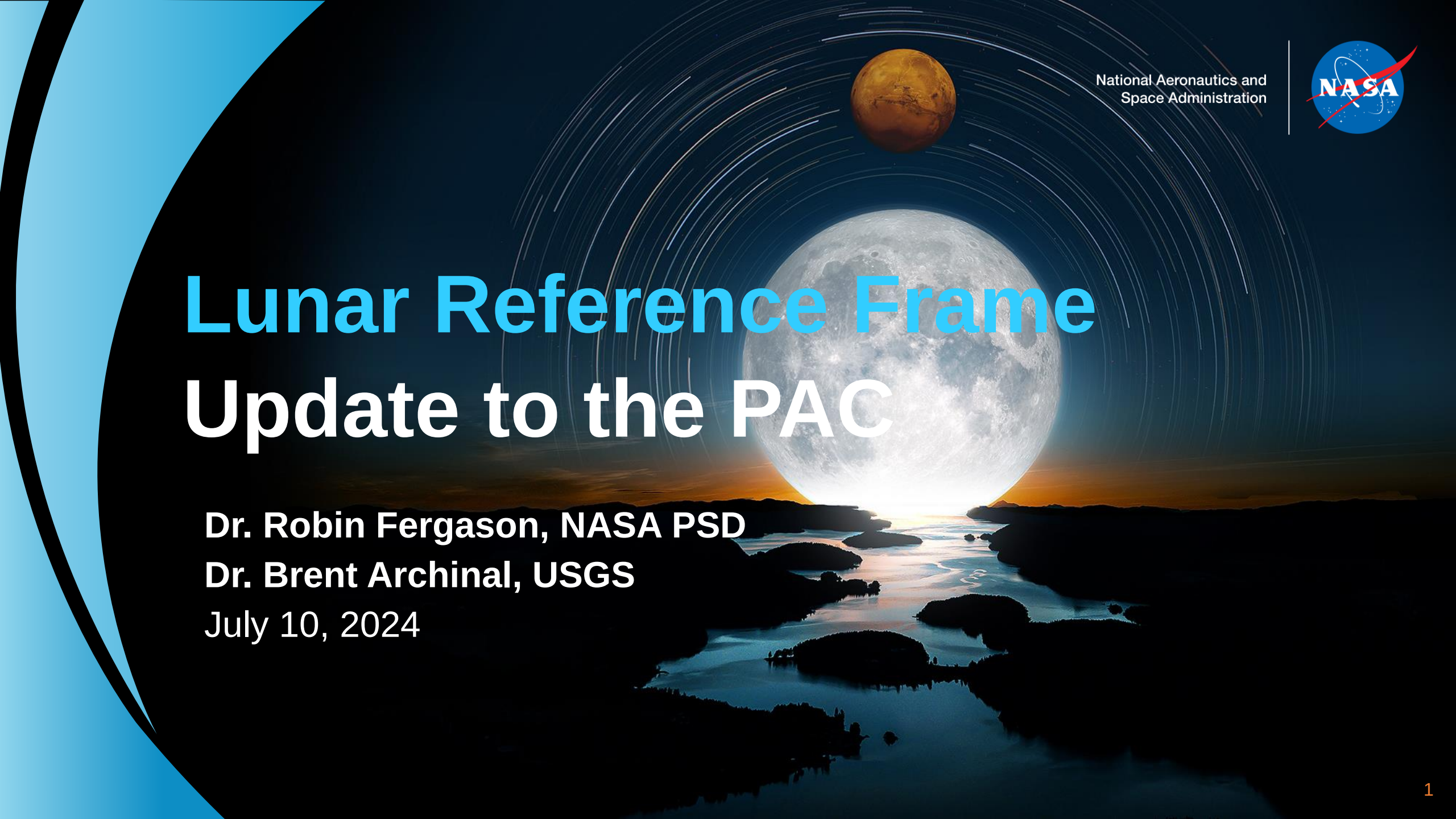
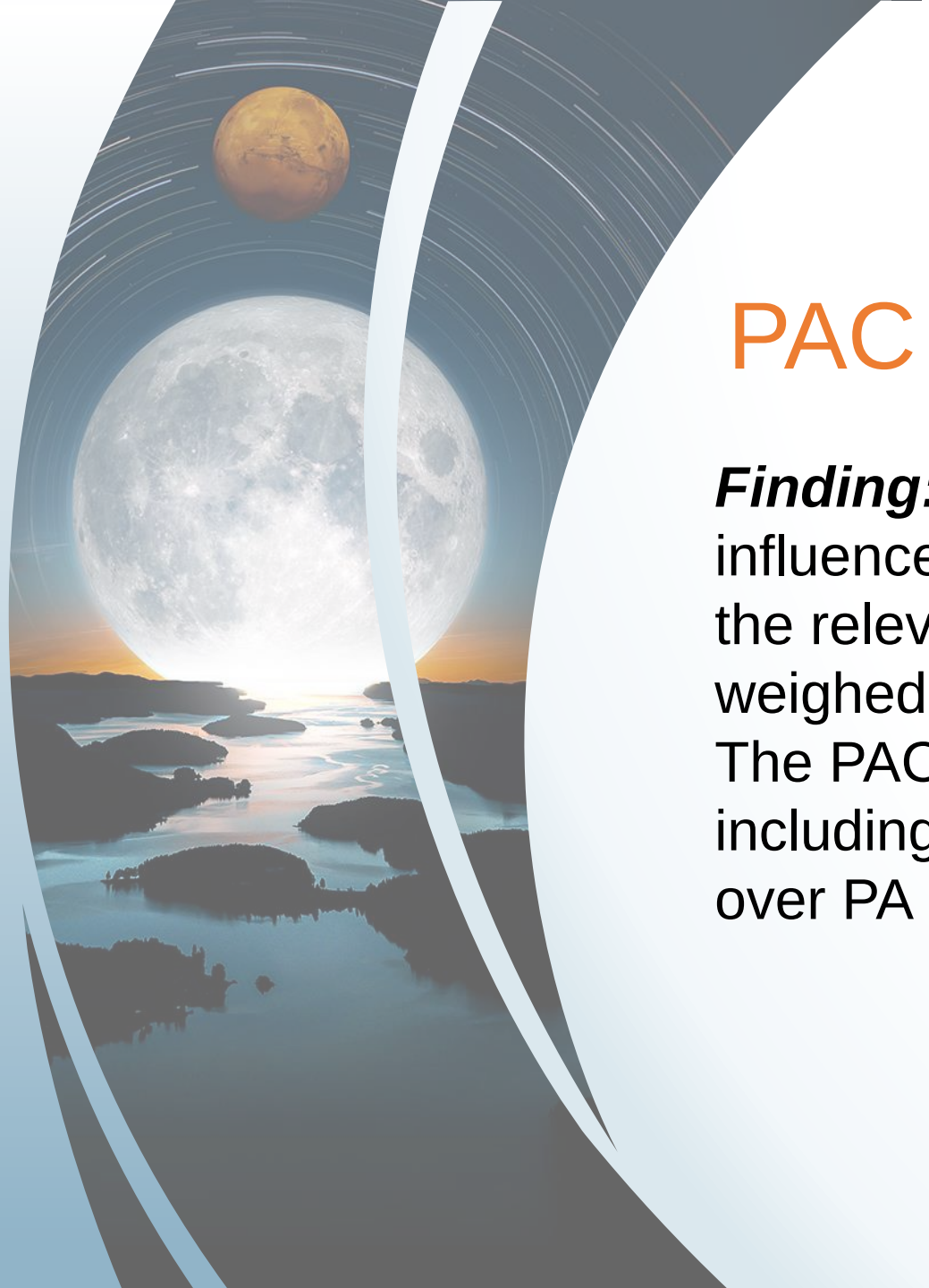


Lunar Reference Frame
Update to the PAC

Dr. Robin Fergason, NASA PSD
Dr. Brent Archinal, USGS
July 10, 2024



PAC Finding – November 2023

Finding: The PAC recognizes NASA's potential influence over planetary mapping standards and that the relevant planetary science communities have weighed in on the question of lunar reference frames. The PAC endorses the MAPSIT/LEAG white paper, including their reasoning and findings (i.e., use of ME over PA lunar reference frame for mapping).

Lunar System and Frame Background

A reference ***coordinate system*** is an overall concept, including theory and conventions to form an idealized coordinate model
A reference ***coordinate frame*** is a specific realization of a system, e.g., a solution that, using data, defines point coordinates

- **Two common lunar reference systems**
  - Mean Earth/polar axis (ME), or Mean Earth/Rotation (MER)
  - Principal axis (PA) or axis of figure
- **ME System**
  - The mean direction of Earth defines 0° longitude, the mean direction of the Moon's polar axis defines latitude
  - In use in some form since before 1775 (by Tobias Mayer; see Davies and Colvin, 2000), for essentially all cartographic products (mapping)
- **PA System**
  - 3 maximum moments of inertia define longitude and latitude
  - Important for dynamical (LLR) and gravity field studies (C21, S21, and S22 are all zero), spacecraft force modeling, and topographic studies
- **ME to PA difference**
  - Varies, usually several hundred meters; up to 875 m (572 m in longitude)
  - Due to asymmetry in the lunar gravity field, discovered in the 1960's
  - Obviously significant for most purposes

Lunar System and Frame Background

Current frames are derived from lunar laser ranging (LLR) solutions

- Observations of the 5 available retroreflectors **===>**
- Solutions from JPL (DE, see Park et al., 2021), IMCCE-Observatoire de Paris (INPOP)

PA frames

- Solutions done in PA system, providing positions for LRRR
- Successive solutions will change internally and in overall orientation, due to more data, stations, improved modeling, gravity field changes, lunar orbit changes, and eventually the addition of new techniques (VLBI and radio navigation)
- Will have shifts in overall lunar orientation due to these changes
- *So NOT suitable as a highest accuracy cartographic (mapping) reference frame*

ME frames

- New frames based on PA LLR solutions, so ***internally identical***
- DE 421 ME frame orientation was based on mean direction of Earth
- But now, a comparison is made to the previous ME frame and a 3-axis no net rotation added
- Frames thus kept locked to the lunar surface assuring that ***surface feature coordinate changes are minimized***

Why the Reference Frame Matters

- Various PA frames used/defined via LLR, gravity fields, lunar topography
- Specific ME frames used for all mapping, and hence navigation to lunar surface
- Transparent to most users as *ME lunar ephemeris is used to process all lunar datasets and products for mapping*
- For surface coordinates (mapping) ME system and frames use recommended and/or in use by:

  - IAU (& IAG) Working Group on Cartographic Coordinates and Rotational Elements (WGCCRE) 1980-2018
  - LRO Mission and Lunar Geodesy and Cartography Working Group, 2008
  - NASA Planetary Data System, 2008
  - Artemis III Science Definition Team, 2020
  - Lunar Critical Data Products SAT, 2022
  - Artemis Geospatial Data Team
  - LEAG and NASA Planetary Science Advisory Committee, 2023
  - All known missions internationally by all nations for mapping and navigation

An international standards success story

Current Planetary Reference Frame Development and Management

- The PSD funds the development, maintenance, and publishing of celestial body ephemerides and reference frames for all bodies in our solar system (since Apollo):
  - Solar Systems Dynamics group at JPL
    - Maintain and publish ephemerides for all celestial bodies in our solar system
    - Derive and publish both the PA and ME lunar reference frames
  - Planetary Cartography group at the USGS Astrogeology Science Center has provided the following community services for the past 30+ years.
    - Serve on international standards boards (largely the IAU WG on Cartographic Coordinate and Rotation Elements) to help define and maintain reference frame standards (see Archinal et al., 2018).
    - Develop and maintain the ISIS3 photogrammetric software portfolio that the community (missions and researchers) use to project data accurately onto the surface.
    - Maintain the capability to generate gold-standard instrument sensor models and cartographic products and generates these products for community use.

What are the Concerns?

- A PA system-based frame has been proposed for all lunar use, including surface navigation and mapping
- Concerns regarding the continued use of a ME system-based frame
  - Higher accuracy needs in the long term
    - This need is currently unquantified and not tied to a science objective or technical requirement.
    - As additional data is collected and a larger geodetic infrastructure is developed, both the PA and ME frames definition accuracy will improve.
  - The need to use both frames while doing cislunar navigation, causing potential confusion or error
  - A “better” connection to lunar geophysics, via LLR and gravity field solutions
- The authors of LEAG White Paper have considered various possible issues and believe an ME frame should continue to be used for mapping and PA frames can continue to be used for dynamical purposes
  - Both the LEAG and the Planetary Science Advisory Committee have endorsed the paper’s conclusions

Lunar Reference Frame Summary

- The lunar (science and exploration) community needs to be aware of these two systems and frames and their uses.
- If a PA system-based frame begins to be used for mapping and navigation, all users will have to take much more care about which system data and products are in.
- The NASA Federated Board has created a working group to make recommendations regarding the use of lunar reference frames.
- No matter the outcome, better international cooperation on lunar standards for mapping and navigation would be useful
  - Perhaps with an expansion to an international Lunar Spatial Data Infrastructure
  - Perhaps as a possible *International Lunar Year* project

Working Group Approach

- November 2023 – Presented perceived needs to the Federated Board for discussion and feedback.
- January 2024 - Federated Board stood up a NASA Working Group to engage stakeholders and technical experts.
  - Establish a recommended technical approach for consideration by NASA Leadership.
  - Document in a white paper and presentation to the Federated Board ahead of Architecture Concept Review (ACR24).
- Working group is divided into two teams: Leadership and Technical
  - Leadership: Identify driving use cases and consider interagency and international aspects of standardization and implementation.
  - Technical: Analyze driving use cases and deliver technical findings to Leadership team.
- Leadership and Technical teams work closely and collaboratively

Working Group Representation

- Cross-directorate participation to help ensure all NASA stakeholders are represented.
  - Exploration Systems Development Mission Directorate (ESDMD)
  - Science Mission Directorate (SMD)
    - Exploration Science Strategy and Integration Office (ESSIO)
    - Planetary Science Division (PSD)
    - Jet Propulsion Laboratory (JPL)
  - Space Operations Mission Directorate (SOMD)
    - Space Communications and Navigation (SCaN) Program

- Stakeholders outside of NASA were consulted (*not official WG members*)
  - Department of Commerce
  - DOD US Naval Observatory (USNO)
  - DOI US Geological Survey (USGS)
  - National Geospatial-Intelligence Agency (NGA)
  - National Science Foundation (NSF)

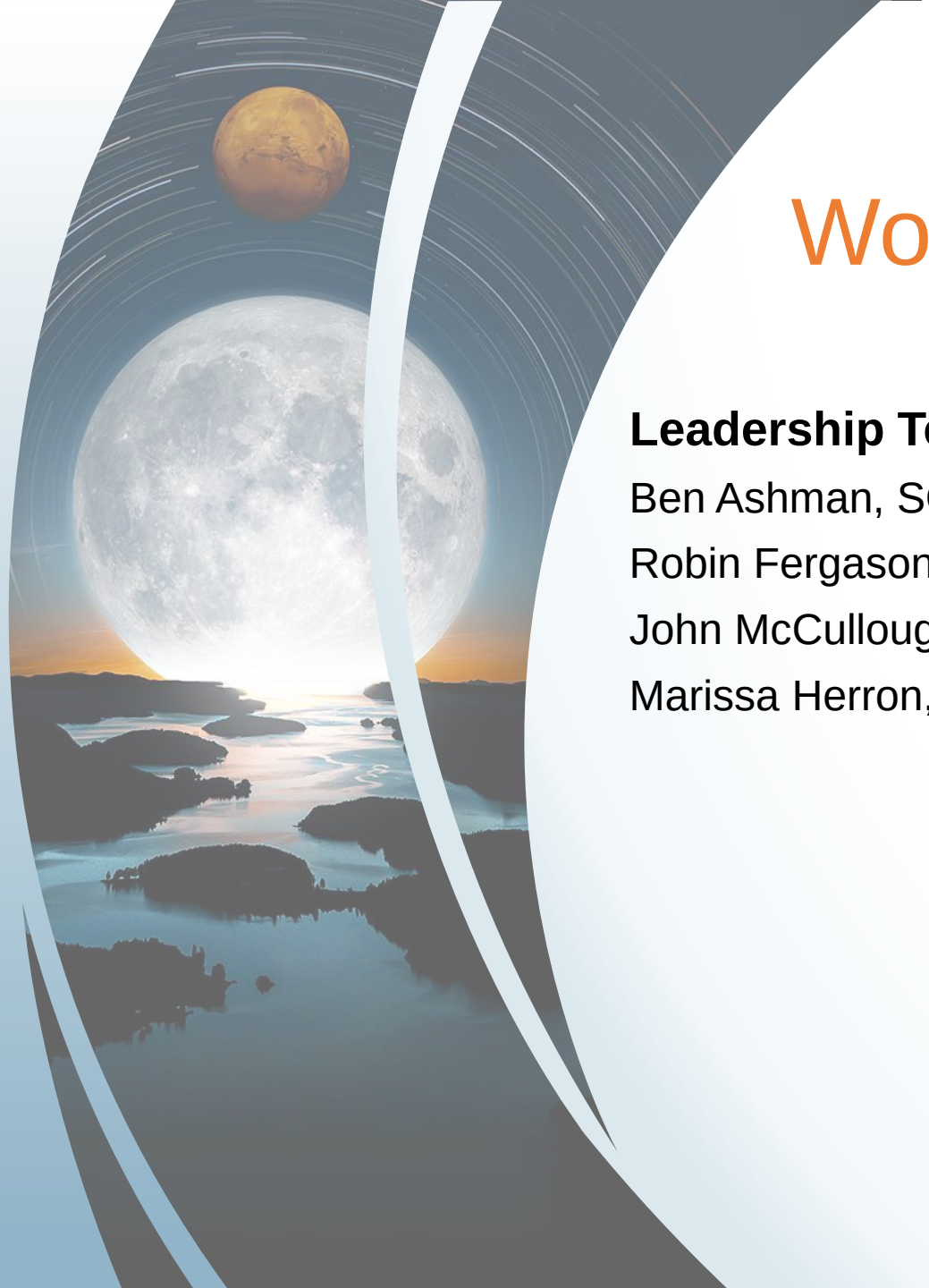
Goal, Rationale, and Solution Constraints

- Goal - Develop an internal NASA consensus on recommended lunar reference systems and frames for specific use cases.
- Why (Now)
  - Multiple use cases and architectural elements are emerging that require definition of a lunar reference system:
    - Crewed surface operations requiring accurate navigation in support of science objectives.
    - Delivery of initial radionavigation (PNT) services and completion of supporting specifications (LunaNet).
- Solution Constraints
  - Require an unambiguous approach for the use of lunar reference systems and frames to achieve Objective 4 of U.S. National Cislunar Strategy.
    - “Implement Cislunar communications and position, navigation, and timing capabilities with scalable and interoperable approaches.”
  - Require significant stakeholder engagement to ensure that the approach meets a broad set of user needs, maximizes science return, and minimizes risk to the overall system.
  - A NASA consensus position is necessary to coordinate a consistent approach in multiple interagency and international forums.

Future Efforts

- Presenting findings and recommendations to the NASA Federated Board in July 2024
- The lunar reference system impacts groups across NASA, US Federal agencies, international agencies, commercial, and academic partners.
- Continued discussion and opportunities for input:
  - Present at the LEAG, IAU General Assembly, and other relevant community meetings.
  - Integrate findings into ESDMD Architecture Description Document, Communication, Position, Navigation, and Timing (CPNT) sub-architecture book, in July/August 2024 in preparation for ACR24.
  - Coordinate with the White House Office of Science and Technology Policy (OSTP) Cislunar Technology Strategy Interagency Working Group to gain inter-agency feedback.
  - Coordinate with academic, commercial, and international partners.
  - Coordinate with related international standards organizations.
    - E.g., IAU, International Association of Geodesy (IAG), COSPAR

Stay Tuned….



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Thank You!