Lunar Foundational Reference Systems and Time: LunaNet Perspective

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Topics

- LunaNet and Interoperability
- Lunar Foundational Reference System Components
- Lunar Time
- International Standards Bodies

Lunar Systems Relationships

LunaNet

Framework for Standardized Interoperable Services, umbrella under which many providers collectively work.
Interoperability defined in a specification.

Lunar Comm. Relay and Navigation System (LCRNS)

NASA's instantiation of LunaNet Services– a LunaNet Service Provider (LNSP)

Currently scoped for Initial Operating Capability

Moonlight

ESA's instantiation of LunaNet Services

Lunar Navigation Satellite System (LNSS)

Japan's instantiation of LunaNet Services

Others

e.g. other orbiting systems, 3GPP (surface cell towers), users

For interoperable and safe navigation, LunaNet systems shall use the Lunar Reference System (LRS). LunaNet Interoperability Spec defines an Applicable Document 5 (AD5) to define an interoperable LRS & Lunar Time System set with associated criteria (e.g. tolerances).

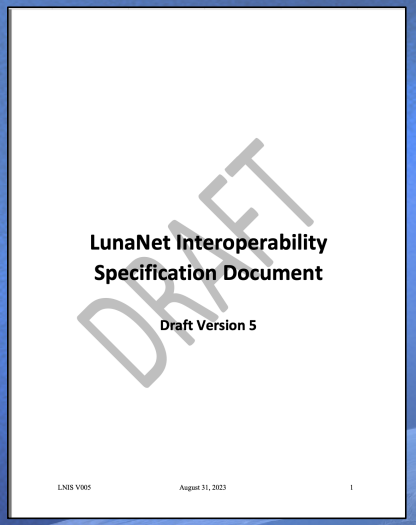
A canonically defined set of components for consistent and accurate navigation.

LunaNet Interoperability Specification

LunaNet Interoperability Specification (LNIS)

- LNIS is a set of mutually agreed-upon specifications of standards, protocols, and interface requirements that enable interoperability.
- LNIS provides a basis for operation of a network capable of interoperating with other LNIS-compliant networks.
- LNIS is being developed cooperatively with international partners through the LNIS Working Group.
- **Includes a set of Applicable Documents:**
  - AD1 LunaNet Signal-In-Space Recommended Standard (LSIS)
  - AD2 LunaNet Measurement Schema and Parameters
  - AD3 LunaNet Detailed Message Definition Document
  - AD4 LunaNet Location Services for Users
  - **AD5 Lunar Reference System and Lunar Time System Standard**
  - AD8 LunaNet Interoperability Security Specifications

LNIS v5



AD1, LSIS v1

AD5: define the interoperable parameters that LunaNet-compliant services must meet.

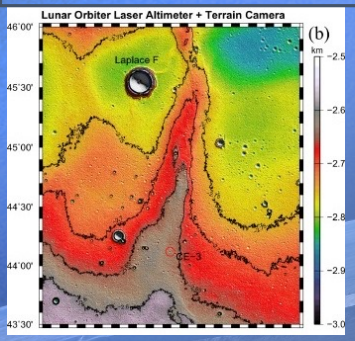
PNT Services rely on definition, adoption, and maintenance of common lunar geodetic and time systems, and transforms to other frames and UTC.

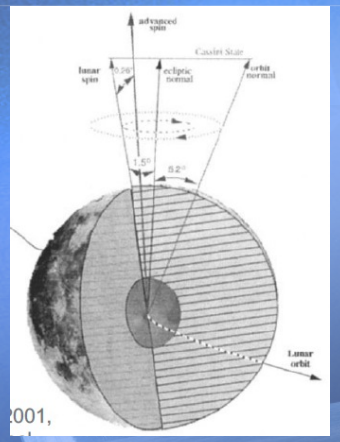
Lunar Reference System Components

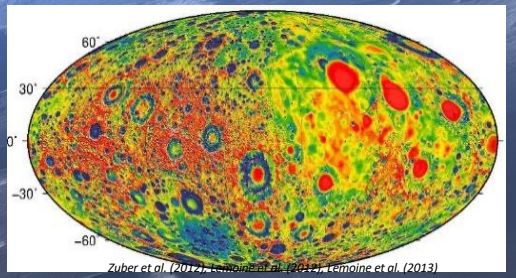
- Lunar reference ephemeris and orientation maintained by NASA/JPL and INPOP
  - JPL Development Ephemeris files, distributed through the publicly available NAIF [developed in Principal Axis]
- Lunar shape (spheroid) and Digital Elevation Maps (DEMs) informed by LRO (Laser Altimetry) and JAXA's Kaguya (stereo Terrain Camera) [Mean Earth/Rotation Axis].
- Lunar gravity potential model defined by GRAIL mission, degree and order 1500x1500, lower D/O available [Principal Axis].
- Lunar longitude/latitude grid identified by the LRO science team [Mean Earth/Rotation Axis origin].
- Need a coordinated system of <u>all</u> components (including definitions for lunar radius, lunar geoid, and lunar ellipsoid).
- Time – to be defined; current missions rely on Earth, UTC.
- Users will need to apply coordinate transforms and orientation parameters to align the information (considered as part of LunaNet Messages)

A canon for a *unified* system does not currently exist.

The lunar body-fixed reference frame, radius, geoid, shape model, gravity potential, and cartographic products must be consistent.



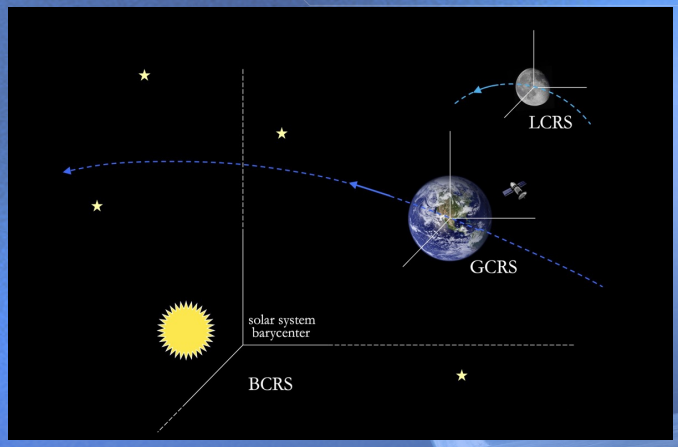


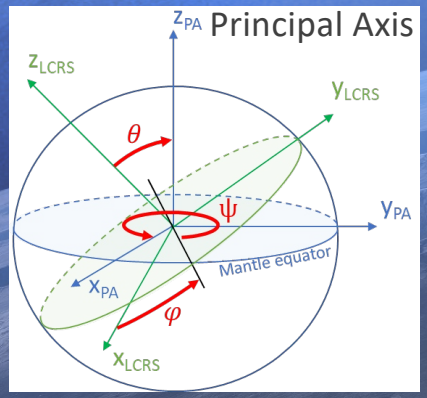


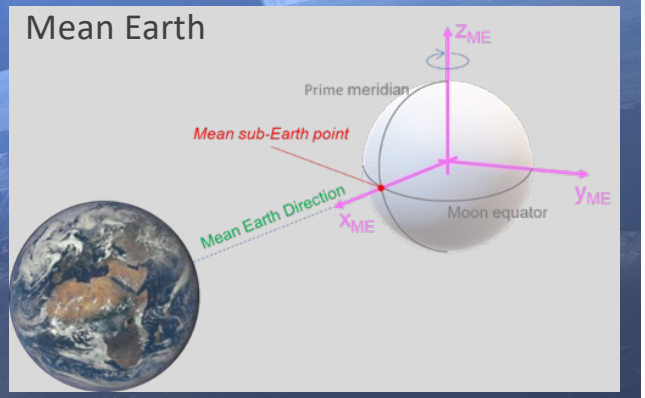
Lunar Reference Frame

- **Inertial: Lunar Celestial Reference System (LCRS)**
  - Analog to locally inertial Geocentric Celestial Reference System that is realized by International Celestial Reference Frame (ICRF).
- **Body-Fixed: International Lunar Reference System (ILRS)**
  - Would be realized by the International Lunar Reference Frame (ILRF).
  - Two currently established frames:
    - **PA**: The Principal Axes reference frame is connected to the moments of inertia of the body (and thus derived from the angular momentum vector); the system where the axes align to the directions of the three largest moments of inertia.
    - **ME**: The Mean Earth reference frame defines the z-axis as the mean rotational pole, and the prime meridian is defined by the mean Earth direction
  - A constant, three-angles rotation relates PA to the derived ME frame; the constants depend on the gravity field and a physical libration theory.
  - Differ by 860 m on the lunar surface.
  - The current ME definitions (used by LRO, etc) were established circa 2008, at the time of DE421, using pre-GRAIL gravity model LP150Q (Konopliv et al. 2001, Icarus).
  - *ILRF: Additional (including in-situ) observations likely to inform an improved frame in the future.*

Preference for Navigation







Lunar Time

Following the GNSS paradigm, LunaNet PNT services will distribute time.

Options are under evaluation; and must consider both the provider and user aspects.

Considerations:

- what accuracy is required for navigation and science precision;
- which geoid should the time scale represent;
- are there aspects to be defined by convention;
- how to format time in the message;
- ensure the ability to refer time to UTC;
- make it easy to achieve consistency among community.

Understanding of multi-body relativistic effects

Primary secular drift is ~58.7 microseconds/day from Earth Geocentric Coordinate Time (TCG) to Lunar Coordinate Time (TCL);

Periodic terms introduce additional variability.

Consultation is underway with international subject matter experts in time systems and relativity.

Lunar Foundational Reference & Time System – Current International Standards Activities

International Astronomical Union (IAU) Commission A3, Fundamental Standards

- Developing a lexicon for standardizing terms.
- IAU General Assembly in August, 2024, includes two relevant Resolutions:
  1. Recommendation to define a LCRS and a Lunar Coordinate Time (TCL).
  2. Recommendation to establish Coordinated Lunar Time by international agreement.

IAU WG on Time and Frequency informal subgroup on Lunar Time; nascent

IAU WG Cartographic Coordinates and Rotational Elements (CCRE)

- Expecting continuation on lunar cartographic and rotational elements focus on Mean Earth Rotating frame

International Association of Geodesy (IAG) established WG 1.1.3

- Agreed-upon Terms of Reference, with objective: address the issues of the connection between Celestial, Earth, and Lunar Reference Frames [and time] for the future missions in coordination with the IAG, IAU, and IERS, [and BIPM] and to formulate recommendations regarding the definition, realization, and dissemination of Lunar Reference Systems, across agencies and user communities.

LNIS Working Group (WG) convened a Technical Exchange group of Subject Matter Experts from European and US Agencies and academia (JAXA has since joined these activities)

- Focused on preliminary version of LNIS Applicable Document 5.
- Technical discussions and analyses on existing models, and appropriate body-fixed frame and time system for PNT services.

Intention is to extend the Earth analog to lunar regions, including interoperability

- "quasi-inertial" (Moon-centered) reference system
- Moon-fixed reference system/frame (rotating)
- time considerations

LunaNet recognizes the importance of establishing international standards.

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