LunaNet: Interoperability for Lunar PNT

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Topics

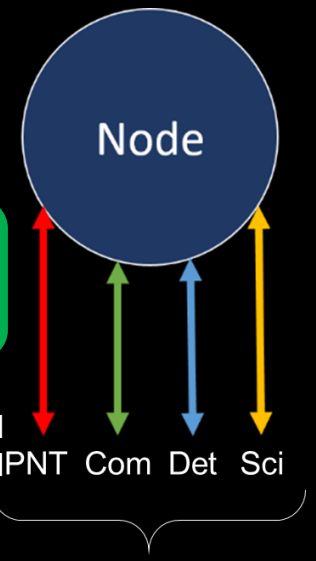
- LunaNet
- LunaNet Interoperability Specification
- Lunar Reference System Components

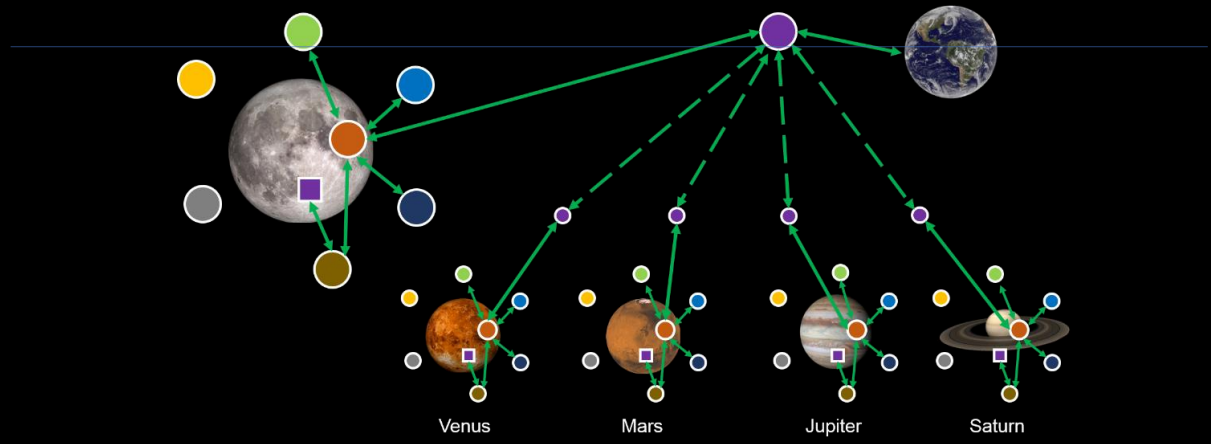
LunaNet Overview

- A flexible scalable architecture for providing communications and navigation services to all lunar missions
- Disaggregated approach allows for phased implementation of infrastructure as driven by user needs and technology developments
- Architecture implementation comprised of International and Commercial interoperable lunar surface, lunar orbiting, and earth-based elements
- Incorporates in-situ capabilities to detect events and distribute situational alerts
- Is fully compatible with and promotes future deployments at Mars or any other destination

LunaNet Service Types

1. **Communications Services (Com):** Data transfer services capable of moving addressable and routable data units between nodes in a single link or over a multi-node, end-to-end path via communications or networking services.
2. Position, Navigation, and Timing Services (PNT): Services for position and velocity determination, and time synchronization and dissemination. This includes search and rescue location services.
3. Detection and Information Services (Det): Services providing detection of events in order to generate timely alerts for human and asset safety and protection. These services publish other beneficial information to users as well.
4. Science (Sci): Services that use the RF and/or optical capabilities of the node as a science instrument or part of an instrument.





Just as the Internet and GPS have transformed our lives on Earth, LunaNet will transform lunar science and exploration.

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)

JAXA'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).

Lunar Reference System (LRS) Components
(includes Time)

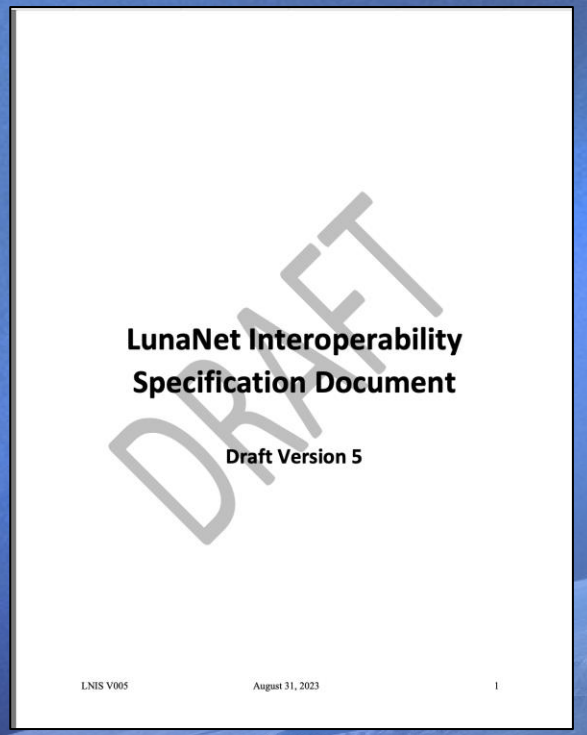
A canonically defined set of components for consistent and accurate navigation.

LunaNet Interoperability Specification

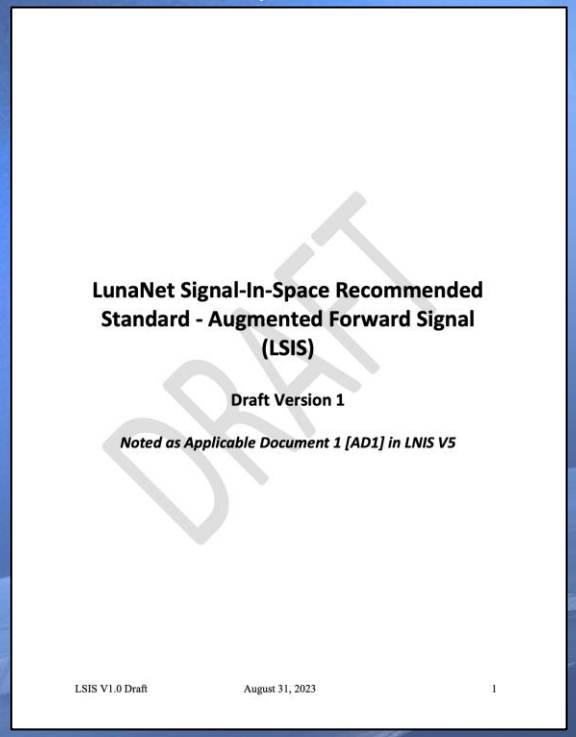
LunaNet Interoperability Specification (LNIS)

- 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 in cooperation 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
  - AD7 LunaNet LunaSAR Definition

LNIS v5



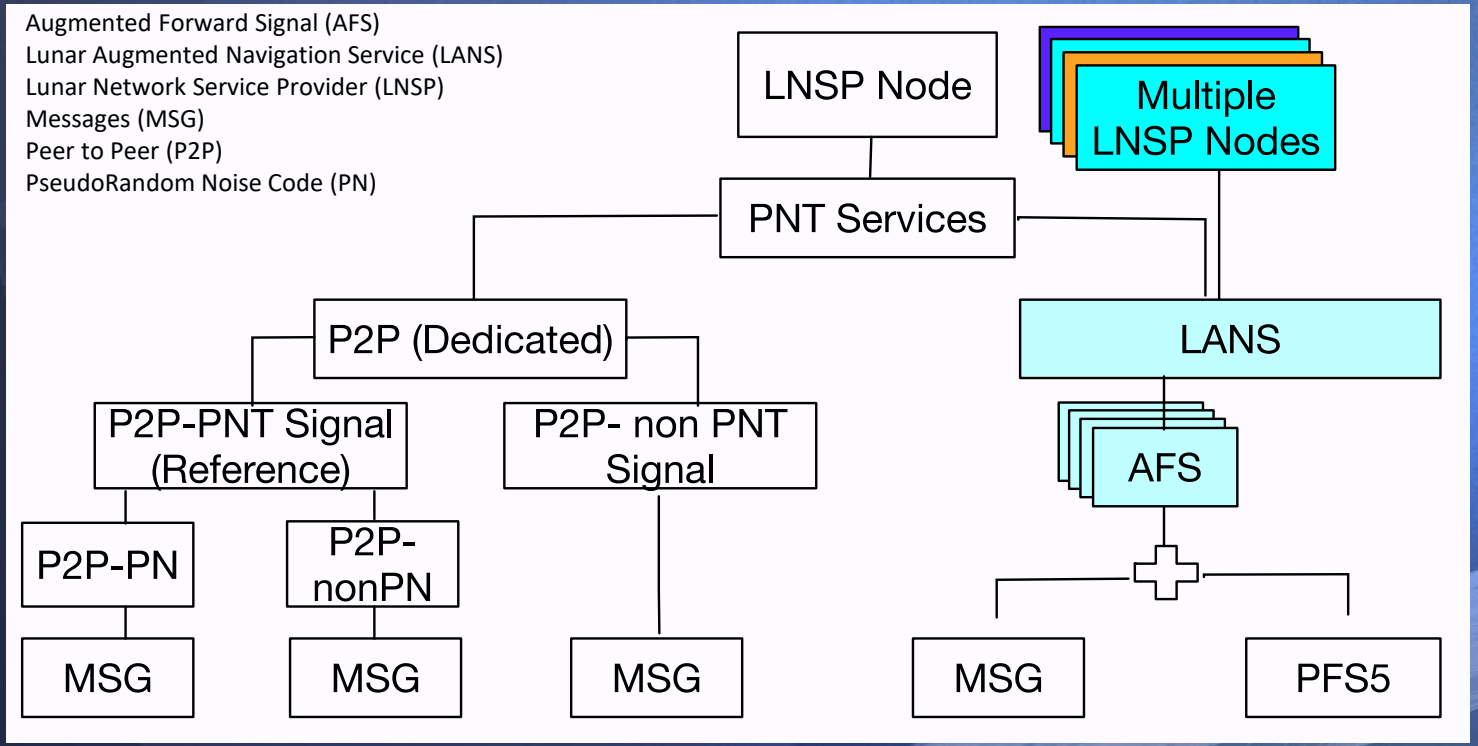
AD1, LSIS v1



LNIS version 5 and LSIS version 1 are available in Draft form for public comment.
https://www.nasa.gov/directorates/heo/scan/engineering/lunanet_interoperability

* Technical paper and presentation available in ION GNSS+ 2023 proceedings:
https://www.ion.org/gnss/abstracts.cfm?paperID=12341

LunaNet Framework PNT Services



2483.5-2500 MHz

LunaNet PNT services:

- Peer-to-Peer navigation services (direct links between the user and the provider)
- Lunar Augmented Navigation Service (LANS)

LANS characteristics:

- The concept is similar to GNSS (maximum reuse of GNSS techniques and technologies).
- This service is provided from multiple providers nodes to multiple users at the same time.

LANS Interoperability[1]: each service provider that claims to be LunaNet compliant (becoming a LunaNet Service Provider, LNSP) for the LANS service, must:

- Be compliant to a common signal and message structure (Augmented Forward Signal, AFS).
- Be compliant to Signal In Space Error requirements.

PNT Services rely on definition, adoption, and maintenance of common lunar geodetic and time systems.

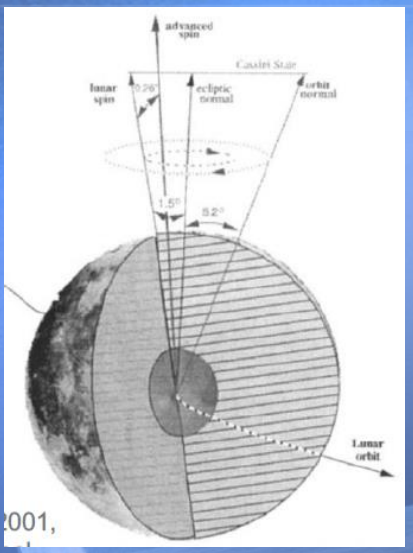
[1] *ICG SSV booklet: "(interoperability is defined as) the ability of global and regional navigation satellite systems, and augmentations and the services they provide, to be used together to provide better capabilities at the user level than would be achieved by relying solely on the open signals of one system"*

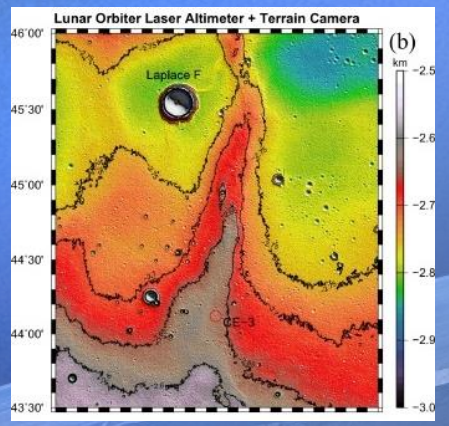
Lunar Reference System Components

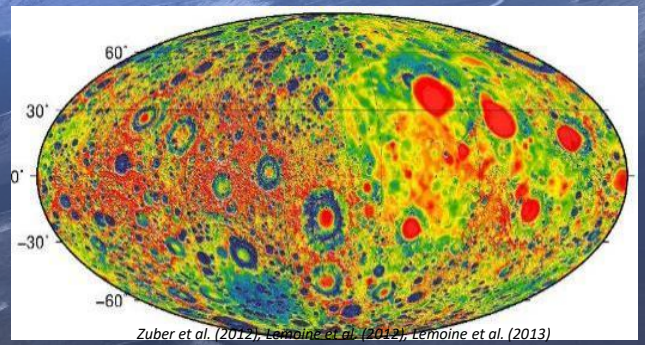
- Lunar reference ephemeris and orientation maintained by NASA/JPL and INPOP
  - JPL Development Ephemeris files, distributed through the publicly available NAIF [developed in Principal Axis]
- Lunar longitude/latitude grid identified by the LRO science team [Mean Earth/Rotation Axis].
- Lunar shape and maps informed by LRO (Laser Altimetry) and JAXA's Kaguya (stereo Terrain Camera) [Mean Earth/Rotation Axis].
- Need concrete definitions for lunar radius, lunar geoid, and lunar ellipsoid.
- Lunar gravity potential model defined by GRAIL mission, degree and order 1500x1500, lower D/O available [Principal Axis].
- Time – no definition to date.

- Users will need to apply coordinate transforms and orientation parameters to align the information (considered as part of LunaNet Ancillary Message)

The lunar reference frame, radius, geoid, grid, potential, and maps must be consistent.





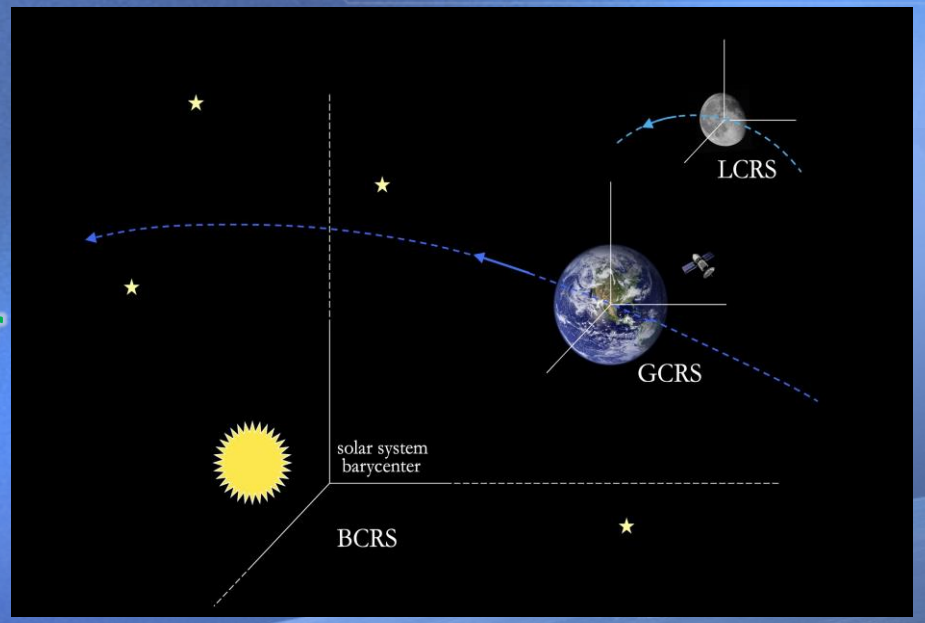


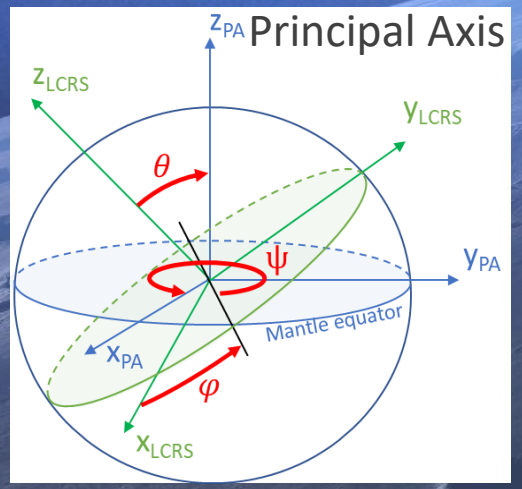
Zuber et al. (2012), Lemoine et al. (2012), Lemoine et al. (2013)

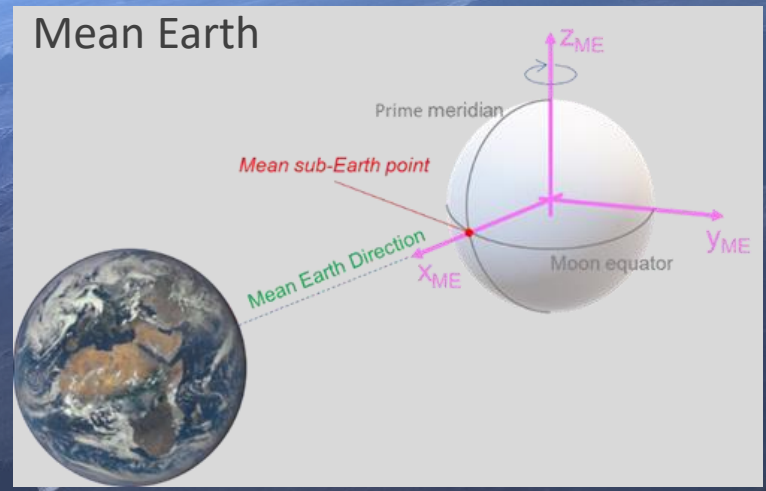
Lunar Reference Frame

- **Inertial: Lunar Celestial Reference System (LCRS)**
  - Analog to locally inertial Geocentric Celestial Reference System that is realized by International Celestial Reference Frame (ICRF).
  - Recommend that the astronomical & geodetic communities define an International Lunar Reference System (ILRS).
- **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); is the system where the axes are along 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).

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:

- **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.**

Need deeper understanding of multi-body relativistic effects

Primary secular drift is ~58.7 microseconds/day from Earth UTC

Periodic terms provide additional variability

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

Lunar Reference System Components – Current Activity

Under auspices of LNIS WG, ESA and NASA convened a Technical Exchange group of Subject Matter Experts from European and US Agencies and academia

- Drafted preliminary version of LNIS Applicable Document 5.
- Several technical discussions and analyses focusing on appropriate frame for PNT and the relativity aspects for time at the Moon.
- JAXA now joining these activities.

IAU Commission A3, Fundamental Standards

- Developing a lexicon for standardizing terms.
- Recently adopted LCRS as a recommendation.
- Plan is to provide recommendations to IAU for lunar reference system components and lunar time for their review.

IAU WG on Time and Frequency informal subgroup on Lunar Time

IAU WGCCRE

- Expecting continuation on lunar cartographic and rotational elements

Interagency Operations Advisory Group (IOAG)

- Established a Committee to Study LunaNet Governance

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

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

Recognition is given to the importance of establishing international standards.

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