Reference Frames for Interoperability within LunaNet

Contributors: * - presenter
Sara Bruni/ESA
Juan Crenshaw/NASA-GSFC
*Cheryl Gramling/NASA-HQ
Floor Melman/ESA
Masaya Murata/JAXA
Suzuna Okamoto/JAXA
Erik Schoenemann/ESA
Cosimo Stallo/ESA
Richard Swinden/ESA
Vishnu Viswanathan/NASA UMBC

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Outline

- Purpose of Applicable Document 5 (AD5)
- International Lunar Reference Frame, +
- Error Contributors
- Evolving Operational Needs
- Timeline for AD5 Document

Purpose of AD5

- LunaNet Interoperability Specification (LNIS) includes a set of Applicable Documents (AD) to identify the standards for signals, interfaces, and protocols needed to ensure interoperability.
- Applicable Document 5 (AD5): “Lunar Reference Systems and LunaNet Reference Time System Standard”

  PURPOSE of AD5: Focus on what needs to be identified for *interoperability* among LunaNet Service Providers, referring to standards and definitions available in the literature. Consistent with LNIS approach: unless strictly needed, no standard will be originally defined in AD5.

- The prescribed value of the Signal in Space Error (SISE) gives the bounding error all LNSPs must meet to achieve service interoperability.

LNIS Philosophy in AD1 & AD5

From LNIS (main) v5, Section 3.2.1.1:

As with all other PNT services, a common lunar-centric reference frame and time system is defined (further detailed in [AD5]). Each LNSP shall ensure they either implement these reference systems directly (e.g., signals are synchronized with the LRT and the lunar reference frame with associated geodetic system components is used in the navigation products), or provide sufficient information to the user in the broadcast navigation messages to refer to these common reference systems (e.g., broadcast of the time offset of the specific LNSP system time to the LRT as shown in Section 2.1 and/or provide the transformation and/or rotation between the reference frame adopted by the LNSP and the reference system specified within [AD5]).

From LunaNet Signal in Space Recommended Standard for Augmented Forward Signal (AD1-VolA):

The interoperability among different LNSPs is ensured by the compliance with the specifications in this document, including the Signal-in-Space Error (SISE) specifications, and compliance with the Lunar Reference System and Lunar Time System Standard described in LNIS AD5 .... The compliance to the SISE ...will ensure that the errors under control of the ...are within a limit, guaranteeing the users that the errors remain within a predefined envelope.

SISE, From AD1-VoIA

SISE position error contribution defined as the difference between:

a. True position of signal transmission location at the LNSP node (e.g., antenna phase center or reference point) in the lunar reference system [AD5];

b. Position as provided in the node's navigation messages to the user, which is affected by knowledge errors (combination of position estimation and prediction), antenna reference point offsets, representation errors (i.e., due to navigation message fitting), and reference frame conversion errors.

SISE time error contribution represented as a distance and defined as the difference between:

a. True time of signal transmission at the LNSP node represented in LunaNet Reference Time (LRT) [AD5];

b. Time of transmission as provided in the node's navigation message to the user, represented in LRT. This is affected by clock offsets due to a combination of clock estimation, prediction and quantization errors; the effects of uncalibrated and unknown "group" delays; and time conversion errors between LNSP Node Time (NT), LNSP System Time (LST) and LRT.

Table 1 - LNSP SISE Position

Error	Value
SISE pos	≤ 20 m; calculated as the 95th percentile of the time series of instantaneous SISE values over a 24 hours period.

← maximum SISE position error values for all LNSPs. Different providers may have tighter requirements to meet the needs of their user community

International Lunar Reference Frame (ILuRF)

International Association of Geodesy (IAG) Working Group 1.1.3 applied Variance Component Estimation to three ephemeris realizations for the Moon (INPOP21a, DE430, and EPM2021) to estimate a body-centered, body-fixed Principal Axes

International Lunar Reference Frame (ILuRF)

- Lunar center of mass Origin; lunar Orientation angles
- Transformation from the ILuRF_PA to an ME frame (DE421_ME (TBD))
- Radius, lunar equipotential (lunar geoid), gravity model
- Acknowledge the ILuRF alignment with lunar time scale

LunaNet Messages to disseminate:

- Time varying transformation from ILuRF_PA to ME;
- Time varying Lunar Orientation Parameters.

Application of the ILuRF ensures interoperability and consistency in ephemeris solutions for the LNSP and for the users.

Errors When Applying Something Other Than ILuRF

Assuming interoperability as a baseline approach...

If an LNSP decides to use a lunar reference system based on something other than the ILuRF for the LunaNet PNT services they provide, AD5 includes a list of error contributors the LNSP must consider within their respective [interop] SISE error budget. Example error contributors:

- Origin of Earth and Moon
- GM of Earth and Moon
- GM of major solar system bodies
- Fitted value of Earth-Moon mass ratio
- LLR data weights and adjustments
- J2 of Sun
- Low degree lunar gravity field
- Average Moon rotation rate
- Transformation: LNSP's reference frame to ILuRF
- Fitted interval of ephemeris predictions

IERS Lunar Product Center

- Current IAG WG products represent an approach that assures interoperability.
- A sound, safe operational system relies on configuration managed products readily available to those who employ these products, such as LNSPs.
- IAG is currently considering establishing a Lunar Product Center as a function in the International Earth Rotation Service (IERS)

The LNIS Working Group strongly endorses the need for a service/product center to provide operationally & internationally sanctioned lunar reference system products.

- Considering a near term work-around for LunaNet:

  Include the ILuRF as an Annex to AD5 along with the supporting scripts to verify proper interpretation of the ILuRF.

LNIS AD5 Schedule

- mid-March 2026: draft of AD5 available for select review
- mid-March-mid April 2026: Desire subject matter expert review of draft document (in the context of interoperability)
- End April 2026: SME feedback incorporated
- May 2026: Draft version available for LNSP vendor review
- Nov 2026: v1 publicly available

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