Lunar Reference Frame and Lunar Time Reference – ESA's View

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ESA's General View

- **Short term needs:**
  - definition of a Lunar Reference Frame dedicated to Lunar PNT requirements
- **Long term approach:**
  - to establish an International Lunar Reference Frame (ILRF), based on contributions of international partners and organisations
- **Transition phase:**
  - development of a roadmap for the generation of an International Lunar Reference Frame (ILRF)

Key elements

- Ensure interoperability of Lunar PNT systems
- Identify areas of coordination
- Generation of understanding of roles and interactions between different international bodies/organisations

Key phases for the realization of a reference frame

Kovalesky et al., 1989

Ideal Reference System

Definition of the fundamental property of the system

What is the fundamental characteristic that the reference system must satisfy?

Physical structure

Identification of a physical structure that can support the realization of the system

What is a suitable structure to support the lunar reference system?

→ Suitable here means that we can describe its motion in the ideal system by means of physical laws, so that the fulfilment of the fundamental property can be imposed

Reference System

Detailed definition of the relationship between the configuration of the selected physical structure and its coordinates

How do we conventionally define the reference system for the selected structure? Which physical processes do we consider?

Reference Frame

Materialization of the system

How do we realize a product that allows users to locate themselves in the reference frame? Which observations do we use? Which models do we use to represent the selected physical processes?

Secondary realizations

Dedicated realizations:

- consistent with the primary frame
- designed to meet the requirements of specific users

Established 4D reference systems/frames

Relativistic background	GCRS (TCG)	BCRS (TCB)
Ideal Reference System	The points of the domain shall exhibit no collective translation or rotation	Be inertial
Physical structure	Earth surface (ITRF Stations)	Extra galactic sources (ICRF sources)
Reference System	ITRS (TT) Axis conventions and physical processes describing the evolution of the Earth crust (IERS and IAU Conventions)	ICRS (TDB) Axis conventions and relevant fundamental physics processes (IERS and IAU Conventions)
Reference Frame	ITRF (UTC)	ICRF (No proper time, UTC)
Secondary realizations	WGS84, GTRF, IGS, SLRF, VTRF…	GAIA, USNO…

Acronyms:

BCRS: Barycentric Celestial Reference System

GCRS: Geocentric Celestial Reference System

ICRS/F: International Celestial Reference System/Frame

ITRS/F: International Terrestrial Reference System/Frame

TCB: Barycentric Coordinate Time

TCG: Geocentric Coordinate Time

TT: Terrestrial Time

UTC: Universal Coordinate Time

Time scales are indicated within brackets

Extension to the lunar case

Coordination needed to ensure interoperability!

Relativistic background	GCRS (TCG)	BCRS (TCB)	LCRS (TCL)
Ideal Reference System	The points of the domain shall exhibit no collective translation or rotation	Be inertial	Tide-free tensor of inertia is diagonal
Physical structure	Earth surface (ITRF Stations)	Extra galactic sources	Moon surface (LLRR (short term) /ILRF Stations (Long Term))
Reference System	ITRS (TT) Axis conventions and physical processes describing the evolution of the Earth crust (IERS and IAU Conventions)	ICRS (TDB) Axis conventions and relevant fundamental physics processes (IERS and IAU Conventions)	ILRS (LT) Axis conventions and relevant physical processes (e.g. extended IAU conventions or others)
Reference Frame	ITRF (UTC)	ICRF (No proper time, UTC)	Short term: Principal Axis (PA) Reference Frame (UTL=UTC+PL) Long Term: ILRF (UTL)
Secondary realizations	WGS84, GTRF, IGS, SLRF, VTRF…	GAIA, USNO…	Mean-Earth (ME) Frame

ESA's View – Lunar Reference System

Reference systems needed to operationally support LunaNet

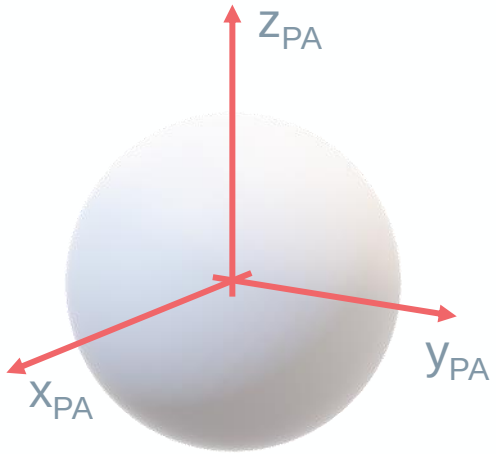
Inertial Moon-fixed system
LCRS (Time Coordinate Lunar -TCL)

- Needed to support satellite deployment and POD in low lunar orbit and for scientific applications
- Defined by adapting IAU/IERS definitions of GCRS (TCG) to the gravitational environment of the Moon

Body-fixed system
primary: Principal Axis (Universal Time Lunar - UTL) + derived Mean Equatorial

- essential to locate a point on the lunar surface and to establish accurate cartography

Principal axis reference system



$$I = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix}$$

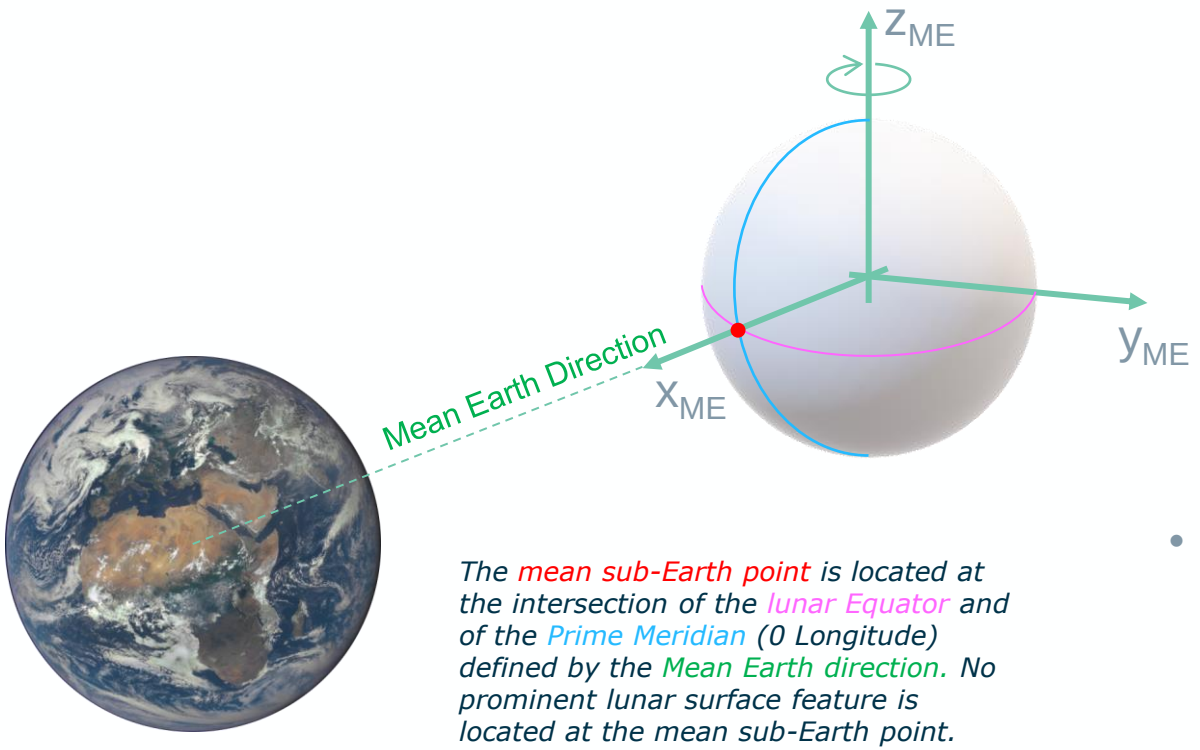
The tide-free lunar tensor of inertia is diagonal in the PA system

- The Principal Axis (PA) reference system is a selenocentric reference system defined by the principal axes of the lunar tensor of inertia with constant tide contributions
- Natural reference system for dynamical studies including e.g., gravity field determination
- Relation to LCRS:

  3D rotation parametrized by a precession angle (φ), a nutation angle (θ), and a proper rotation angle (ψ)

$$\vec{x}_{PA} = R_z(\psi)R_x(\theta)R_z(\varphi)\vec{x}_{LCRS}$$

Mean Earth Reference System



The mean sub-Earth point is located at the intersection of the lunar Equator and of the Prime Meridian (0 Longitude) defined by the Mean Earth direction. No prominent lunar surface feature is located at the mean sub-Earth point.

- Right-handed spherical coordinate system:
  - origin in the Moon centre of mass
  - z-axis aligned with the mean rotational axis
  - x-axis directed to the mean sub-Earth point
  - the y-axis completes the right-handed orthogonal system.
- Adopted since the beginning of lunar observation, the ME system is typically used for data archiving and for product distribution (e.g. topography and maps).
- The PA → ME transformation is realised by three static Euler angles that shall be always distributed together with the realization of the primary frame (PA).

ESA's View – Lunar Reference Time

- Different Lunar Time scales are of interest related to the realization of the Lunar Reference Time
- Important is that
  - the realization of the Lunar Reference Time is interoperable by definition
  - the Lunar Reference Time should be linked directly to the Universal Coordinate Time - UTC
  - take into account the infrastructure deployed on the Moon

ESA's proposal

UTL: Lunar Universal Time

UTL = UTC + PL

Where PL is the periodic component of the frequency shift caused by the difference of potential between the Earth geoid and the Moon center of mass. There is also a dominant linear drift that could be set by convention (while PL could be calculated and disseminated via the navigation message

In case of existing infrastructure on the Moon, this concept can be adopted accordingly by synchronizing the clocks on the Moon with UTC

Conclusion

- Interoperability of reference frames and time reference realization for different PNT systems is key
- International coordination between all involved organizations is fundamental
- Usage of interoperable PNT systems – Earth, Moon, Mars etc. and deployed infrastructure including respective evolution shall be considered from the outset