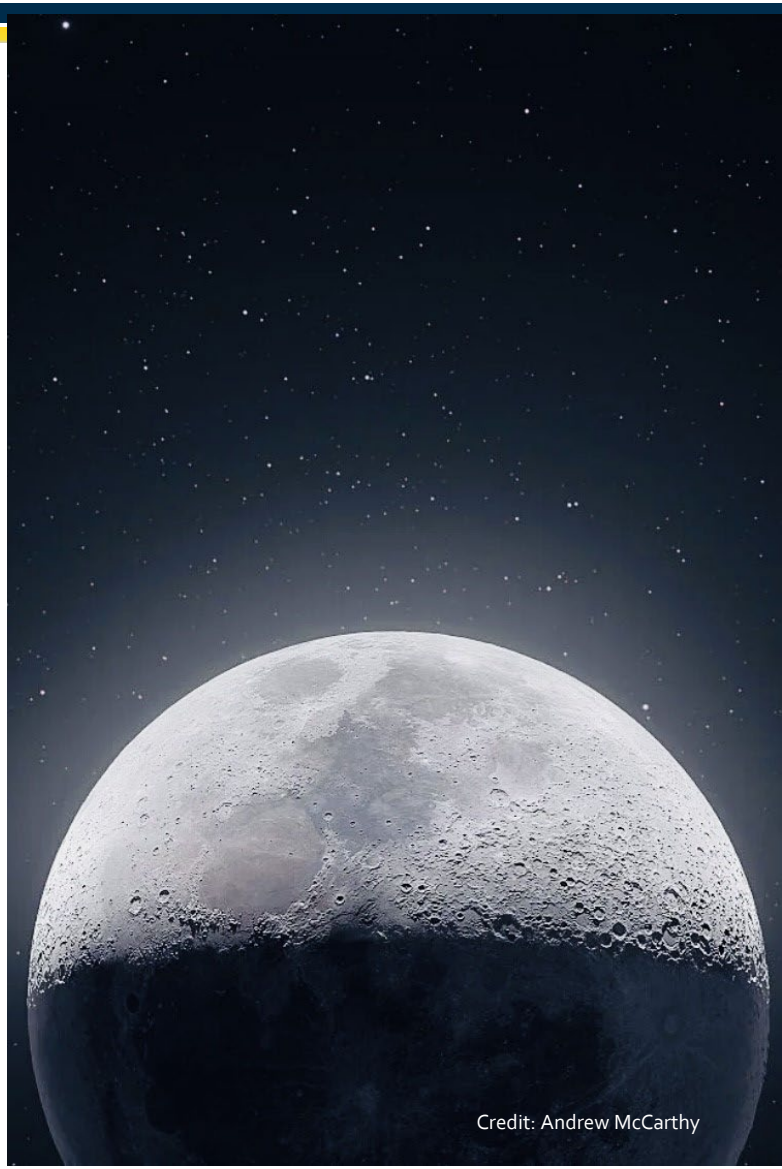
IAU Status Update: Lunar Standards

ICG-IOAG Lunar PNT WG
12 February 2025

Dr. Susan Stewart
Commission A3 Fundamental Standards
International Astronomical Union


Credit: Andrew McCarthy

Foundational Navigation Parameters

Reference Systems & Frames

Position & Orientation of bodies

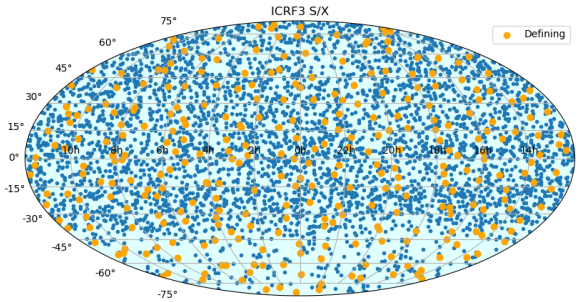
- International Earth Rotation Service (IERS)
- IAU Working Groups & Commissions (e.g. Cartographic Coordinates , WGCCRE; A_3 Fundamental Standards; X_2 Ephemerides)
- International GNSS Service (IGS)
- International VLBI Service (IVS)
- International Union of Geodesy and Geophysics (IUGG)
- International Association of Geodesy (IAG)

Time

- Bureau International des Poids et Mesures (BIPM), Consultative Committee on Time and Frequency (CCTF)
- International Telecommunication Union (ITU)
- IAU Working Group on Time and Metrology Standards

Standards provide interoperability for safety and integrity of operations.

Established Reference Systems: Inertial Frame



International Celestial Reference System (ICRS)

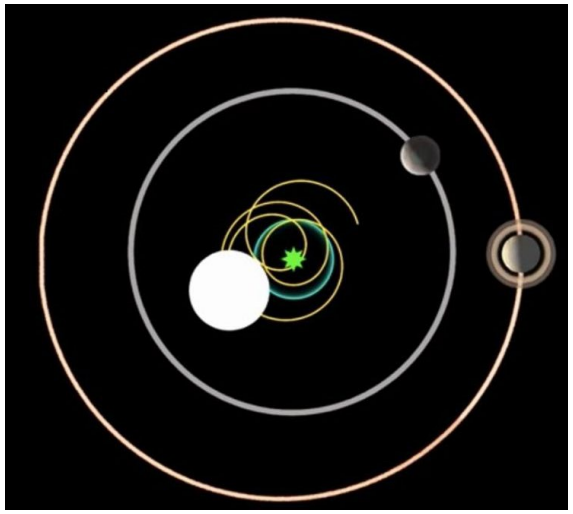
- Coordinate System origin at the barycenter of the solar system, ICRS coordinates
- Axes *show no global rotation with respect to set of distant extragalactic objects "space-fixed axes"*
- **Adopted by IAU in 1998, 2006**

International Celestial Reference Frame (ICRF)

- Celestial sources (quasars) at radio wavelengths "realize" the ICRS it's frame.

Reference System: conventions, algorithms and numerical constants, and models
Reference Frame: attaches system to the real world; establishment of real positions; "realizes" a coordinate system

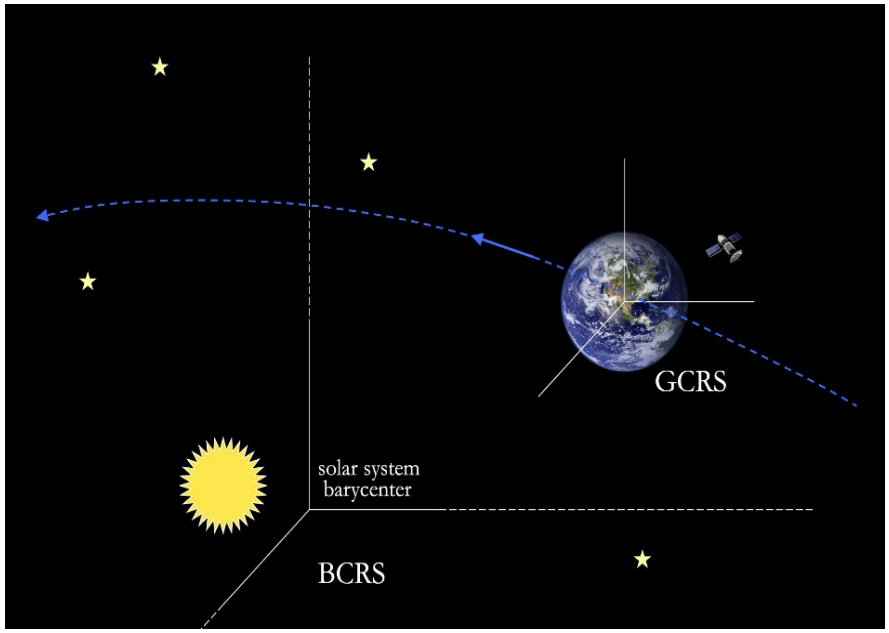
Established Reference Systems: BCRS



Barycentric Celestial Reference System (BCRS)

- Coordinate system origin at solar system barycenter, barycentric coordinates
- Inertial within framework of General Relativity (galactic and extragalactic masses ignored)
- Planetary ephemerides, astrometric catalogs, deep space mission trajectories, etc.
- **Adopted by IAU in 2000**
- The International Celestial Reference Frame (ICRF) "realizes" the BCRS as its frame.
- Coordinate time is Barycentric Coordinate Time (TCB)

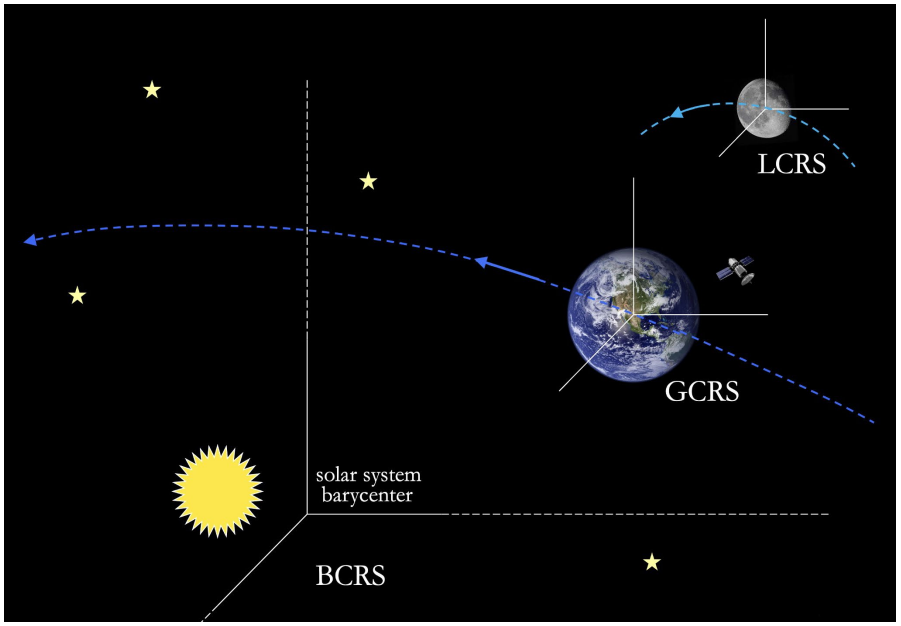
Established Reference Systems: GCRS



Geocentric Celestial Reference System (GCRS)

- Origin at geocenter, geocentric coordinates
- Quasi-inertial; kinematically non-rotating
- General relativistic transformation from BCRS
- ICRF as frame realizes the GCRS (or a group of geodetic satellites or GNSS satellites realizes it?)
- Coordinate time is Geocentric Coordinate Time (TCG)
- **Adopted by IAU in 2000**
- Earth-based astrometry; LEO and MEO orbit calculations; Earth orientation

Established Reference Systems: LCRS



Lunar Celestial Reference System (LCRS)

- Origin at moon center of mass, lunacentric coordinates
- Moon-based astrometry; LLO orbit calculations
- Quasi-inertial; kinematically non-rotating
- General relativistic transformation from BCRS
- ICRF realizes the LCRS as a frame
- **Adopted by IAU in August 2024**
- Time scale Lunar Coordinate Time (TCL)

Established Reference Systems: Coordinate Times

Proper time:
time kept by a perfect clock

Coordinate time:
time dimension of a reference system
Idealized mathematical construct
not physically measurable

$$d = v_o t + \tfrac{1}{2} a t^2$$

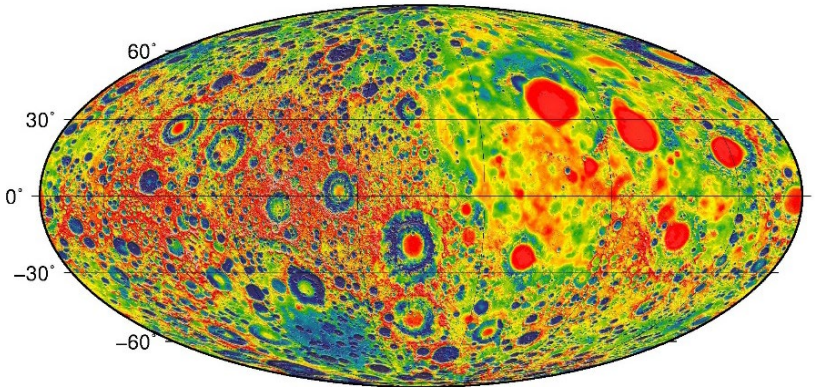
TCL (LCRS) ⟷ ***4D*** ***TCB (BCRS)*** ⟷ ***4D*** ***TCG (GCRS)***

Lunar Coordinate Time Adopted 2024

Barycentric Coordinate Time

Geocentric Coordinate Time

Reference Systems: Future Considerations



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

Lunar Reference (Surface) System & Frame

- Body-fixed frame
- Aim for standardized similar to WGS 84 for the Earth
- Incorporates coordinate system, orientation model, gravity model, shape model, reference frame, etc.
- Time system, TL (analogous to TT)

Lunar Standards: Under Consideration

IAU leadership on development of lunar standards

- International Association of Geodesy (IAG) Working Group 1.1.3 on Lunar Reference Frames
- Commission A3 Fundamental Standards
- IAU Symposium: "*Advancing Reference Systems, Ephemerides, and Standards: from the Earth and the Moon to Solar System bodies*" August 2025
- IAU WG Time and Frequency, Lunar Time Subgroup
- IAU WG Cartographic Coordinates and Rotational Elements (WGCCRE)

IAU Lunar Standards: Under Consideration

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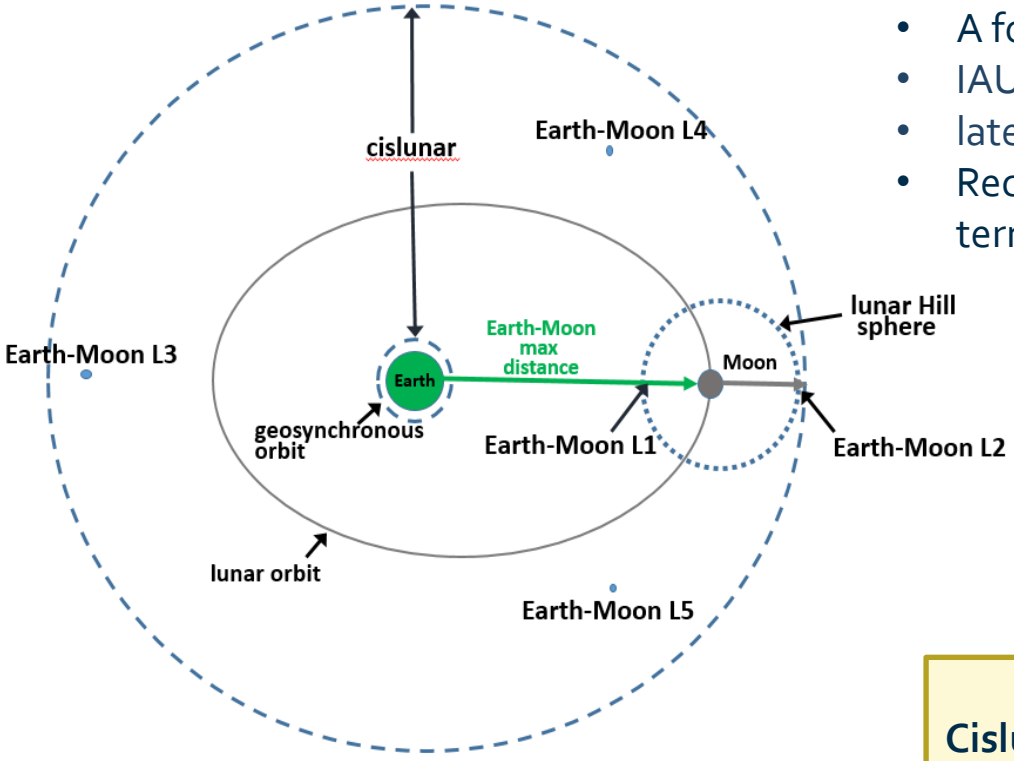
- IAU WG Time and Frequency, Lunar Time Subgroup
- IAU WG Cartographic Coordinates and Rotational Elements (WGCCRE)
  - makes recommendations on "the cartographic coordinates and rotational elements of the planets and satellites," including the Moon
  - Currently, the WG recommends using the JPL DE 421 ME frame to serve as the lunar surface fixed reference frame for mapping, and by common use for lunar navigation purposes (2008, 2011, 2018) recommendations
  - Expect discussion soon on LRF recommendations

IAU Lunar Standards: Under Consideration

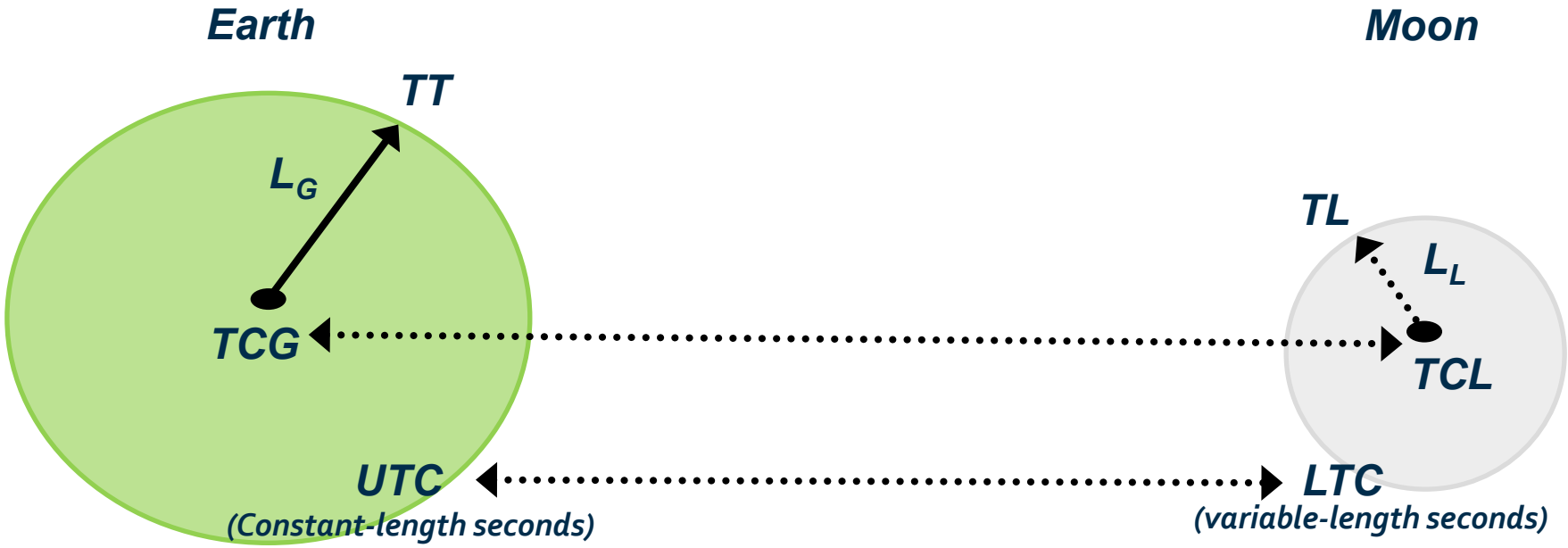


Nomenclature for Fundamental Astronomy (NFA)

- A former IAU Working Group
- IAU 2006 NFA GLOSSARY
- latest revision: 20 November 2007
- Recommendation: establish new WG for updated terms

Cislunar: located in the spherical volume of space defined by the distance from Earth *geosynchronous orbit* to the Earth-Moon *L2 Lagrange Point,* approximately 465,000 km.

IAU Lunar Standards Summary



- ✓ **LCRS** : Lunar Celestial Reference System : (GCRS)
- ✓ **TCL** : Lunar Coordinate Time : (TCG)

L_L : Rate difference at center of Moon versus surface : (L_G)

TL: Time on lunar surface : (TT)

LTC : Coordinated Lunar Time : (UTC)

LRS : Lunar Reference System/Frame : (LRS/LRF)

IAU Lunar Standards Summary

IAU Lunar Reference Frame Recommendation:

- The standard Lunar Celestial (lunacentric) Coordinate System (LCRS) and Lunar Coordinate Time (TCL) using the model of the GCRS given in IAU Resolutions B1.3-B1.5 of the XXIV General Assembly (2000).

- The relationships between the possible versions of a lunar reference time scale and other time scales, in particular a lunar coordinate time (LTC) and UTC, are pursued in collaborative agreement among the relevant international organizations.

IAU Future Recommendations and Considerations Needed

- **Update standard terminology** to include cislunar terms
- **Define L_L** and relationship between TL and TCL
- **Define a convenient analytical approximation** between TCB and TCL
- **Endorse a coordinated lunar time (LTC)** as an international standard, related to UTC
- **Endorse a unified standard lunar body-fixed (surface) reference system (LRS)** with coordinate system, reference frame, reference ellipsoid, topography model, gravity model, etc. specified.
- **Extend** to other solar system bodies

Thank you for your attention

Established Reference Systems: LCRS

The XXXIInd International Astronomical Union (IAU) General Assembly,
August 2024, Cape Town SA
"*to establish a standard Lunar Celestial Reference System (LCRS) and Lunar Coordinate Time (TCL)*"

- The same techniques used to construct the Geocentric Celestial Reference System (GCRS) analogous Lunar Celestial Reference System (LCRS); locally inertial
- Time coordinate designated Lunar Coordinate Time (TCL), zero point defined exactly when the reading of TCB be 1977 January 1, 0h 0 m 32.184s at the center of the Moon
- The unit of measurement of TCL be consistent with the SI second
- LCRS origin at Moon center of mass used for Moon-based astrometry; LLO orbit calculations
- A well-defined method that can be used for any celestial body in the solar system.