A Standardized Lunar Coordinate System for the Lunar Reconnaissance Orbiter and Lunar Datasets

LRO Project and LGCWG White Paper
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1.0 PURPOSE

The purpose of this White Paper is to provide a summary of a Lunar Coordinate System that is recommended for use in operational targeting, interdisciplinary science, and communication among future and ongoing U.S. and international lunar missions. The same system is recommended for use for lunar data products to be archived in the Planetary Data System (PDS).

This document was originally created by the Lunar Reconnaissance Orbiter (LRO) mission, and is specifically intended for the above uses by that mission. In mid 2008, the NASA Lunar Precursor Robotics Program (LPRP) Lunar Geodesy and Cartography Working Group (LGCWG) (Archinal, et al., 2008a, 2008b) began working with the LRO Data Working Group (LDWG) to further update and maintain this document, for further use by the LRO mission but also by all other NASA components. It is also available for use by international lunar missions.

2.0 JUSTIFICATION FOR A STANDARDIZED SYSTEM

The use of a common Lunar Coordinate System for LRO and other NASA components is important for a number of reasons. Simply stated, having only one system eliminates potential confusion among members of the LRO team and other NASA components as well as the extended data user community. For operations, this will enable LRO and other mission scientists and mission planners to communicate clearly and effectively through unambiguous identification of the geographic locations of lunar landforms and observation targets. Researchers interested in obtaining LRO and other mission archival data from the PDS in order to generate higher level products will not have to contend with conversions among systems when registering multiple data layers if the input data are all in the same system. Additionally, the use of one system simplifies the conversion process by minimizing the total number of conversions required to register data from other missions using different systems. The anticipated intensive use of LRO data products for landing site selection and advanced mission planning by the LPRP and Exploration Systems Mission Directorate (ESMD) further underscores the need for a common, unambiguous reference system for the Moon on which to base future exploration, habitation, and *in situ* resource utilization. Adoption of a standardized system for LRO and other NASA components does not preclude conversion to or use of different systems for specific applications where necessary and appropriate.

2.1 REFERENCE COORDINATE SYSTEMS AND FRAMES

This document summarizes a *Lunar Coordinate System* with the word *system* here having the general meaning of a complete scheme for describing lunar coordinates. It is however worth noting some specific terminology for reference coordinates. The terms *reference system* and *reference frame* often are used interchangeably but in precise usage have two different meanings. A *reference system* is indeed a *system* that includes some definition of a physical environment, specific terminology, and associated theories that form an idealized model for defining positions on a particular body (or in space generally). A *reference frame* is the materialization of a reference system in reality, e.g. (in most cases) a solution which defines from observational data the specific numerical location of given points in the reference system (Kovalevsky and Mueller, 1981). In the following the terms reference system and reference frame are used when these specific meanings are indicated.

3.0 PROCESS FOR REACHING CONSENSUS ON LUNAR COORDINATE SYSTEM

From April through July of 2006 a series of meetings and bi-weekly telecons was held and a consensus was reached on the Lunar Coordinate System for LRO. Specific discussions on defining a common

Lunar Coordinate System were made integral to the agendas of the Project Science Working Group (PSWG) and the LRO Data Working Group (LDWG). The membership of the LDWG was augmented by individuals with specific, relevant expertise for the purposes of defining a standard Lunar Coordinate System. The widest possible participation from key stakeholders was solicited in order to represent all opinions and arrive at the best possible decision. Key participants were as follows:

- LRO Project as represented by the LRO Project Scientist, LRO Deputy Project Scientist , the LDWG lead, and additional members of the PSWG and LDWG
- LRO Instrument PIs, their representatives and team members
- Brent Archinal (U.S. Geological Survey - Flagstaff), Vice-Chair of the International Astronomical Union (IAU) and International Association of Geodesy (IAG) Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites
- Charles Acton (Navigation and Ancillary Information Facility (NAIF) PDS support node)

Meeting minutes from the LDWG have recorded the discussions and the details of the process leading to selection of the specific coordinate and reference systems for LRO. The LDWG lead wrote a draft description of the LRO lunar coordinates approach and submitted this to Dr. Brent Archinal of the U.S. Geological Survey at Flagstaff for review. Dr. Archinal ensured that the description was technically correct and consistent. The LDWG lead sent the description to all key participants on June 26, 2006 for review and comment.

In the spring of 2008, the LGCWG realized that it would be desirable to create a NASA-wide set of recommendations regarding lunar coordinates. However, rather than create a completely new set separate from the LRO Lunar Coordinate System, the LGCWG contacted the LDWG and asked if it could simply assist instead in updating the LRO System. The LDWG agreed to this at their May 5 teleconference. The LGCWG then proposed several updates and changes to this document. These were approved by the LDWG at their September 22 teleconference, and given final approval by the LGCWG at their October 1 teleconference, bringing this document to its current state.

4.0 LUNAR COORDINATE SYSTEM SELECTION CRITERIA

Members of the LDWG and PSWG worked to define a common Lunar Coordinate System for the LRO mission. A consensus was reached that planetocentric coordinates should be used and that the selected Lunar Coordinate System should be compatible with the one used within the PDS for Clementine data. Working group members strongly advocated adoption of a system that would meet several specific criteria:

- Straightforward conversion to and from other systems that might be used within the LRO Instrument Science Operations Centers (SOC) or for other specific applications
- Commonality with or ease of translation to and from systems used in previous missions
- Adherence to conventions and standards recommended by the IAU / IAG and adopted for use by the PDS in consultation with the NASA Planetary Cartography Working Group (PCWG)

The approach that was adopted meets all of the above criteria. The initial system was consistent with recommendations of the 2000 and 2003 IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites, and has been updated to be consistent with their 2006 recommendations (Seidelmann, et al., 2002, 2005, and 2007). There is a strong push within the planetary community to adopt this system wherever possible. The LGCWG also has accepted the above criteria and approach.

5.0 PLANETOCENTRIC COORDINATES

For the LRO mission and as a LGCWG recommendation, planetocentric coordinates will be used. This approach, together with Cartesian coordinates, is one of two options (the other being the use of planetographic coordinates) in planetary computations. These are right-handed spherical coordinates where the *z*-axis is the mean axis of rotation and the *x*-axis is the intersection of the Equator and the Prime Meridian. The *x*-axis is normal to the *z*-axis through the origin of the system, which is the Moon's center of mass. The *y*-axis is orthogonal to the *x*- and *z*-axes. Latitude is the angle between a line extending from the origin to the planetary equator and a vector from the origin to the point of interest. Longitude is the angle between this vector and the plane of the Prime Meridian measured in an eastern direction. Radius is the distance from Moon's center of mass to the point of interest.

Planetocentric coordinates are illustrated in Figure 1 on Page 5.

5.1 RADIUS

Where possible, Radius should be expressed as the total distance from the Moon's center of mass to the point of interest. If necessary, for example for avoiding round-off error in a large digital terrain model in 4 byte format, the distance of a point from the Moon's center of mass can be expressed as the distance along the radius vector above (positive) or below (negative) a reference sphere of radius 1737.4 km (the Report of the IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements 2000 and 2006 value). The given reference sphere radius should be used until some updated value is accepted internationally, for example following the LRO mission.

6.0 LUNAR FIXED REFERENCE SYSTEM

Two slightly different reference systems are commonly used to define the lunar body-fixed coordinate system. One is the Mean Earth/Polar Axis (ME) reference system that will be used at all times for PDS archival products. The other is the axis of figure reference system, also called the Principal Axis (PA) reference system, which may be used internally to the SOCs and LRO instrument teams and others for specific applications. These reference systems are described below.

6.1 MEAN EARTH / POLAR AXIS LUNAR REFERENCE SYSTEM

The Mean Earth/Polar Axis (ME) reference system defines the *z*-axis as the mean rotational pole. The Prime Meridian (0° Longitude) is defined by the mean Earth direction.

The intersection of the lunar Equator and Prime Meridian occurs at what can be called the Moon's "mean sub-Earth point". The concept of a lunar "sub-Earth point" derives from the fact that the Moon's rotation is tidally locked to the Earth. The actual sub-Earth point on the Moon varies slightly due to orbital eccentricity, inclination, and other factors. So a "mean sub-Earth point" is used to define the point on the lunar surface where Longitude equals 0°. This point does not coincide with any prominent crater or other lunar surface feature.

LRO instrument teams shall deliver data to the PDS with planetocentric coordinates in the ME reference system only. The LGCWG recommends that other data providers do the same. This is consistent with heritage PDS datasets like those from Clementine. Using coordinates in the ME reference system is consistent with the recommendations of the IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites.

The ME reference system with planetocentric coordinates shall also be adopted by the LRO Project and instrument teams – and the LGCWG recommends that other do the same – for the purposes of

operations planning, observational targeting, geographic identification of lunar landforms, and inter-mission communications.

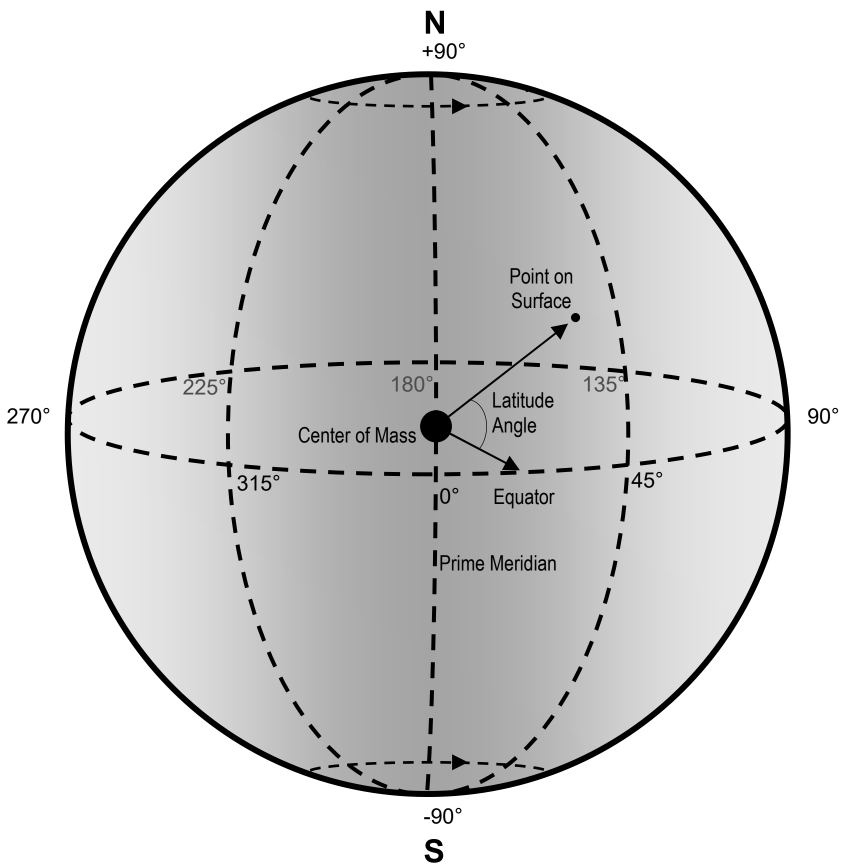

Figure 1. Planetocentric coordinates are expressed as right-handed coordinates with the origin at the center of mass of the body.

Planetocentric Longitude is measured from the Prime Meridian (0° Longitude) toward the East (to the right), in the direction of rotation for a prograde body, with the Longitude values increasing from 0° toward 360°. Conversion to lunar map and image products that use the planetocentric ME system with the +180° East / -180° West convention is easily performed with the appropriate arithmetic.

Planetocentric Latitude is the angle between the equatorial plane and a vector from the center of mass to the point on the surface. Planetocentric Latitude is measured from 0° at the Equator to 90° at either pole, and is defined as positive in the northern hemisphere and negative in the southern hemisphere. Planetocentric North is in the hemisphere of the north pole of the Ecliptic.

6.2 PRINCIPAL AXIS LUNAR REFERENCE SYSTEM

The Principal Axis (PA) reference system is a lunar body-fixed rotating coordinate system whose axes are defined by the principal axes of the Moon. Due to the fact that the Moon is not truly a synchronously rotating triaxial ellipsoid, the PA and ME rotation axes do not coincide. The axes of the two systems differ by about 1 km at the lunar surface.

The PA reference system is especially useful for dynamical studies in areas such as gravity field determination and lunar laser ranging (LLR). LRO instrument teams may use either the ME or PA reference systems internally. However, data will be delivered to the PDS with coordinates in the ME reference system only. The LGCWG recommends that others do the same.

Data for any epoch can be oriented into the PA reference system by using the current Jet Propulsion Laboratory (JPL) ephemeris, referred to as a Developmental Ephemeris (DE). Such a specific ephemeris defines a *reference frame* that (as discussed in section 2.1) can be used to realize the PA reference system. DE421 is the ephemeris selected by the LRO Data Working Group (LDWG) for the LRO mission at the time of this writing, but the LDWG could adopt a successor DE for the LRO mission in the future. General information on DE421 is available from Folkner, et al. (2008), and lunar information on the DE421 is available from Williams, et al. (2008). Data can be oriented into the ME system – and thus a reference frame in the ME system is defined – by applying the rotational difference to that system appropriate to the given ephemeris.

Specifically for DE421 – and following Williams, et al. (2008) – if M is a vector of Cartesian coordinates in the ME reference frame and P is a coordinate vector in the PA reference frame, then the derived rotation between reference frames is:

$$M = R_x(-0.30'') \, R_y(-78.56'') \, R_z(-67.92'') \, P$$

where the angles are in seconds of arc and the rotations are around the body X, Y and Z axes.

The inverse rotation is:

$$P = R_z(67.92'') \, R_y(78.56'') \, R_x(0.30'') \, M$$

Note that rotation of coordinates of the above equations and the corresponding rotation of the frames have the opposite sense. Also note that these angles apply only when using DE421.

Data can also be oriented to the ME or PA reference systems by directly tying the data to previously established reference frames in the given system (e.g., LLR or image-based reference frames in either system). Williams, et al. (2008) give LLR retroreflector array coordinates in the ME system (their Table 4). Such a set of coordinates therefore defines an LLR based reference frame to which data can be tied, as an alternative to using an ephemeris-based reference frame. Data providers should always specify the reference frame to which their data has been tied or any new frame in which it has been produced.

7.0 IMPLEMENTATION

The PDS NAIF support node at JPL maintains SPICE (Spacecraft, Planet, Instruments, C-matrix, and Events) data to support use of the two lunar reference systems. NAIF provides SPICE DE-based binary lunar planetary constants kernels (PcK) using planetocentric coordinates and SPICE frame specification kernels (FK). (Note however that in the terminology of Section 2.1 NAIF frames are used to specify both reference systems and reference frames.) The FKs provide definitions of the NAIF frames, NAIF frame names to be used within SPICE software, and matrices to be used to rotate between the PA system and the ME system. The binary PcK files are useful only with SPICE Toolkit software. The FK files are provided for use with SPICE Toolkit software, but since these are simple ASCII files, the rotation matrices can be extracted from them for use in another context. Detailed information about the frames and the use of the PcK and FK files is found within the files themselves.

More information about the SPICE system, including a number of tutorials can be obtained from the NAIF website: http://naif.jpl.nasa.gov/naif/pds.html. This site also contains specific information about the use of the DE421 ephemeris (NAIF, 2008).

8.0 IMPROVED LUNAR REFERENCE FRAMES

The existing lunar reference frames that define the coordinates of surface features are expected to undergo improvement, some significantly, during the LRO mission as a result of the measurements and observations LRO is expected to acquire. These measurements, coupled with a precise spacecraft trajectory will, at the conclusion of the LRO mission, provide an improved global reference frame upon which all LRO and previous lunar observations can be placed. The parameters describing the reference frame and coordinate system will be updated at least once during the early- to mid-phases of the LRO mission, and also at the end of the baseline mission. The improved values can be expected to change the coordinates of lunar features at the kilometer level.

The LGCWG expects that other missions may also create new or improved reference frames for their data in the ME coordinate system. It also appears likely that any "final" LRO reference frame will be further improved in the future following the end of the LRO mission. The LGCWG urges data providers to work toward placing their data into a common or unified frame where possible, and also urges that all space agencies work toward placing their existing, current, and future datasets into such a common or unified frame so that the datasets can be properly used together and intercompared.

9.0 SUMMARY

On June 26, 2006 the LDWG lead sent a summary description of the LRO coordinate system agreement to the LRO PIs, SOCs, PDS, and the U.S. Geological Survey at Flagstaff for review and concurrence. The summary was received positively, and the LRO Project concurs with the approach based upon the open and fully documented process, the technical review and description of the selected system, and the consensus that the process has resulted in the selection of the appropriate Lunar Coordinate System for LRO. The LRO coordinate system approach as described in this document is summarized as follows:

• For PDS archival products, operations planning, observational targeting, geographic identification of lunar landforms, and inter-mission communications, the Mean Earth / Polar Axis (ME) lunar reference system shall be used, with geographic locations of surface features expressed in planetocentric coordinates

• For specific applications internal to the SOCs or elsewhere, the Principal Axis (PA) lunar reference system may be employed. All SOC products to be archived in the PDS must be converted to the ME system prior to transmission to the PDS

APPENDIX A. REFERENCES

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APPENDIX B. ACRONYMS

DE	Developmental Ephemeris
ESMD	Exploration Systems Mission Directorate
FK	Frame Specification Kernels
IAG	International Association of Geodesy
IAU	International Astronomical Union
JPL	Jet Propulsion Laboratory
LDWG	LRO Data Working Group
LGCWG	Lunar Geodesy and Cartography Working Group
LLR	Lunar Laser Ranging
LPRP	Lunar Precursor and Robotics Program
LRO	Lunar Reconnaissance Orbiter
ME	Mean Earth/Polar Axis
NAIF	Navigation and Ancillary Information Facility
PA	Principal Axis
PcK	Planetary Constants Kernels
PCWG	Planetary Cartography Working Group
PDS	Planetary Data System
PI	Principal Investigator
PSWG	Project Science Working Group
SOC	Science Operations Center
SPICE	Spacecraft, Planet, Instruments, C-matrix, and Events