JPL D-32296

Lunar Constants and Models Document

September 23, 2005

Jet Propulsion Laboratory
California Institute of Technology

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Prepared by: Ralph B. Roncoli

Ralph B. Roncoli

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9/23/2005	All		Initial release

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1. INTRODUCTION

1.1 Purpose

The primary purpose of this document is to provide a single source for the constants and models to be used in the trajectory and navigation design of missions whose objective is to orbit or land on the Moon. A secondary objective is to provide the mission analyst with some basic background information about the Moon, its orbit, and the previous missions that have explored the Moon. As a result, this document contains more information than the typical constants and models document. Some of the data are required for mission studies while other data are simply provided for "educational purposes". This document provides only brief descriptions of the constants and models. The user should consult the references if more detailed information is desired.

1.2 Scope

This document does not contain any mission-specific data or conventions. It is intended to be applicable to any mission targeted to the Moon. It is possible that modifications or additions to this document may be required as unique requirements are developed for specific missions. Special attention, however, is paid to the time period from 2009-2012 since that is the most likely time period for the next NASA missions to the Moon.

The following conventions are used in this document. All lunar coordinate systems are Moon-centered, with latitudes measured from the center of the Moon relative to the equator (i.e. selenocentric latitudes) and longitudes measured from 0-360 degrees, positive to the east. The only exception to this convention is that nearly all of the lunar maps available still depict longitudes as both east and west longitudes.

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2. MOON DATA

2.1 Lunar Gravity Field

The latest lunar gravity field, LP150Q, is a 150th spherical harmonic degree and order model [1]. This gravity field was developed using all available data from past U.S. missions to the Moon including the Lunar Orbiter missions, the Apollo 15 and Apollo 16 sub-satellites, Clementine, and all of the Lunar Prospector Doppler and range data. The Lunar Prospector data includes all of the 100 km altitude data from the primary mission (which lasted for approximately one year) and all of the extended mission data consisting of one month at an average altitude 40 km and six months at an altitude of 30 km. Appendix C lists the normalized coefficients for an 8 x 8 subset of the LP150Q gravity field (including zonals up to degree 50). In addition, Appendix C indicates where the full LP150Q field can be found.

$R_{Moon\text{-}Ref}$ = 1738.0 km (Mean radius of Moon from LP150Q)

GM_{Moon} = 4902.801076 km^3/s^2 (Gravitational parameter from LP150Q)

[Note: While the LP150Q gravity field represents the current best (complete) lunar gravity field, the GM_{Moon} value from LP150Q does not represent the single best estimate of the gravitational parameter (GM) of the Moon. Reference 2 provides a more precise estimate of the lunar GM – it is 4902.8000 ± 0.0003 km^3/s^2. For calculations that require a lunar GM value (as opposed to a complete gravity field), the value from Reference 2 should be used].

The second degree terms of LP150Q do not include permanent tide effects.

[Note: The corrections to the standard spherical harmonic coefficients (C_{nm} and S_{nm}) of a gravitational potential due to solid body tides include both a constant (time independent) correction and a periodic (time dependent) correction. The term "permanent tide", as used in this document, refers to the constant part of the tide correction calculation. See Reference 3 for more information on the treatment of permanent tide corrections].

Given the following Love Numbers for the Moon

k_{20} ($J_{2\ Love\ Number}$) = 0.0248 (Moon Love Number for 2nd degree zonal, J_2)
k_{22} ($C_{22\ Love\ Number}$) = 0.0248 (Moon Love Number for 2nd degree sectorial, C_{22})

the corrected, un-normalized J_2 and C_{22} values are given below.

$J_{2\ Moon\text{-}Tide}$ = $2.033542482111609 \times 10^{-4}$ (Zonal value adjusted for permanent tide - Rigid J_2)
$C_{22\ Moon\text{-}Tide}$ = $2.240509900845084 \times 10^{-5}$ (Sectorial value adjusted for perm. tide - Rigid C_{22})

The permanent tide corrections for other 2nd degree terms are small (i.e. smaller than the uncertainties in the coefficients themselves) and can be ignored. The normalized J_2 and C_{22} values are:

$\bar{J}_{2\ Moon\text{-}Tide}$ = $9.094278450270 \times 10^{-5}$ (Zonal value adjusted for permanent tide - Rigid J_2)
$\bar{C}_{22\ Moon\text{-}Tide}$ = $3.470983013194 \times 10^{-5}$ (Sectorial value adjusted for perm. tide - Rigid C_{22})

[Note: If an analysis is done using only J_2, the user should make sure that the permanent tide effects are included. In other words, either the program being used should automatically adjust the input (uncorrected) J_2 value to include permanent tide effects or the J_2 value adjusted for permanent tide should be input directly. The only software within Section 343 that currently can automatically include permanent tide effects is the Orbit Determination Program / Double Precision Trajectory Program (ODP / DPTRAJ) (i.e. the legacy navigation software)].

[Note: Three different Love Numbers are used to characterize the internal elastic parameters of the Moon. Tidal variations that influence the Moon's gravity and rotation are a function of the Love Number k_2, vertical displacements are a function of the Love Number h_2, and horizontal displacements are dependent on the Love Number l_2. The Section 343 ODP software takes into account the effects of gravitational tides (from k_2), but does not account for the effects of surface deformation tides (from h_2 and l_2). Tidal influences on the lunar rotation rate are part of the model used to generate the physical librations of the Moon (see Section 2.5). Analysis of lunar laser ranging data has shown that, depending on the location, the position of a point on the surface of the Moon can change by up to 0.1 m about the mean over a period of one month as a result of surface deformation from lunar tides].

$D_{SOI\ Moon}$	= 6.6 x 10^4 km	(Moon Sphere of Influence, calculated at 384400 km, the mean semi-major axis of the Moon's orbit)
$g_{Moon\text{-}Mean}$	= 1.62422 m/s^2	(Mean lunar surface acceleration of gravity, calculated using the GM_{Moon} from Reference 2 and the lunar radius from Section 2.3)

Figure 2-1 shows the lunar geoid relative to the reference sphere as given by the LP150Q gravity field. The geoid clearly shows the long wavelength features of the gravity field. Some large features in the geoid are visible on both the near-side (left side of figure) and far-side (right side of figure) of the Moon. There are, however, large uncertainties in the lunar far-side gravity for harmonic series representations greater than approximately degree and order 20. These can be seen in the lunar geoid uncertainty map illustrated in Figure 2-2. The geoid uncertainties are from the first 90th degree and order terms of the LP150Q gravity field and represent similar errors to the full degree and order of 150.

[Note: For general mission design studies involving lunar orbiters with altitudes as low as 100 km, the analysis in Reference 4 suggests that a 40x40 field is sufficient to represent the lunar gravity field. For orbits with altitudes in the range of 30-100 km, a minimum 50x50 degree and order field should be used].

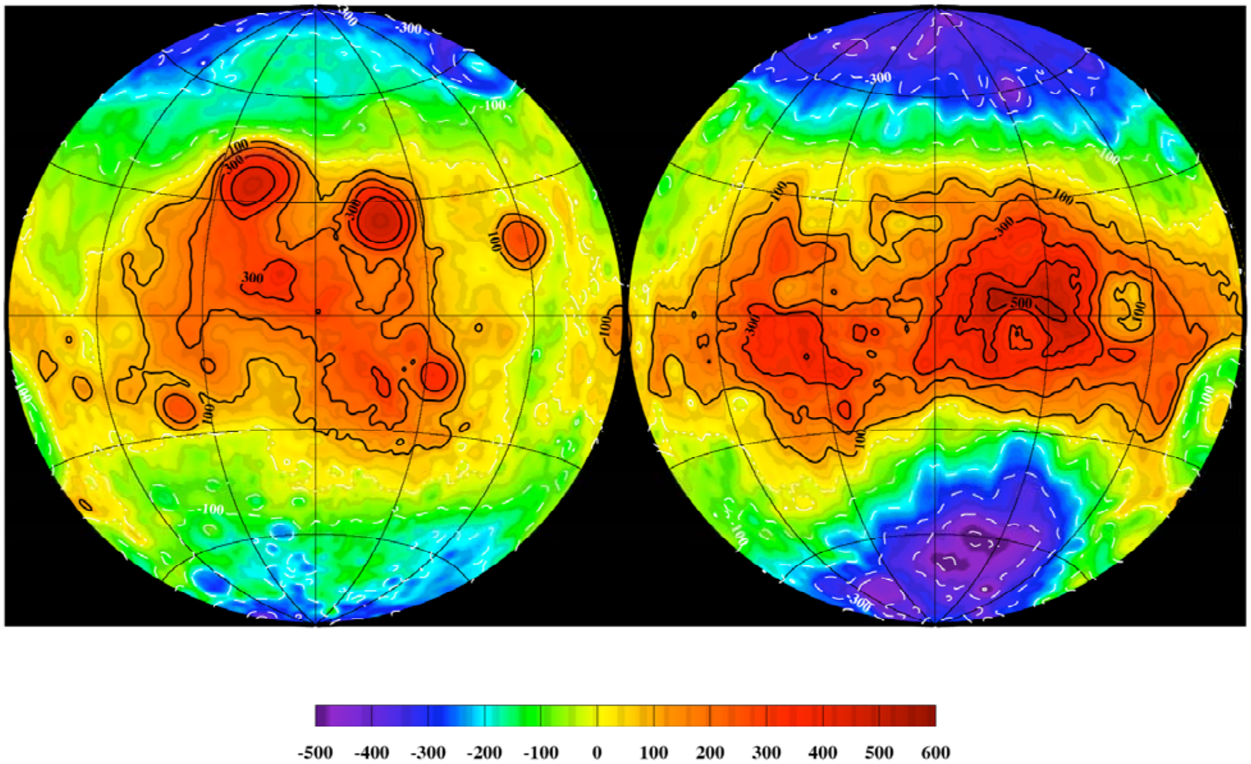


Figure 2-1: Lunar Geoid, LP150Q (meters)

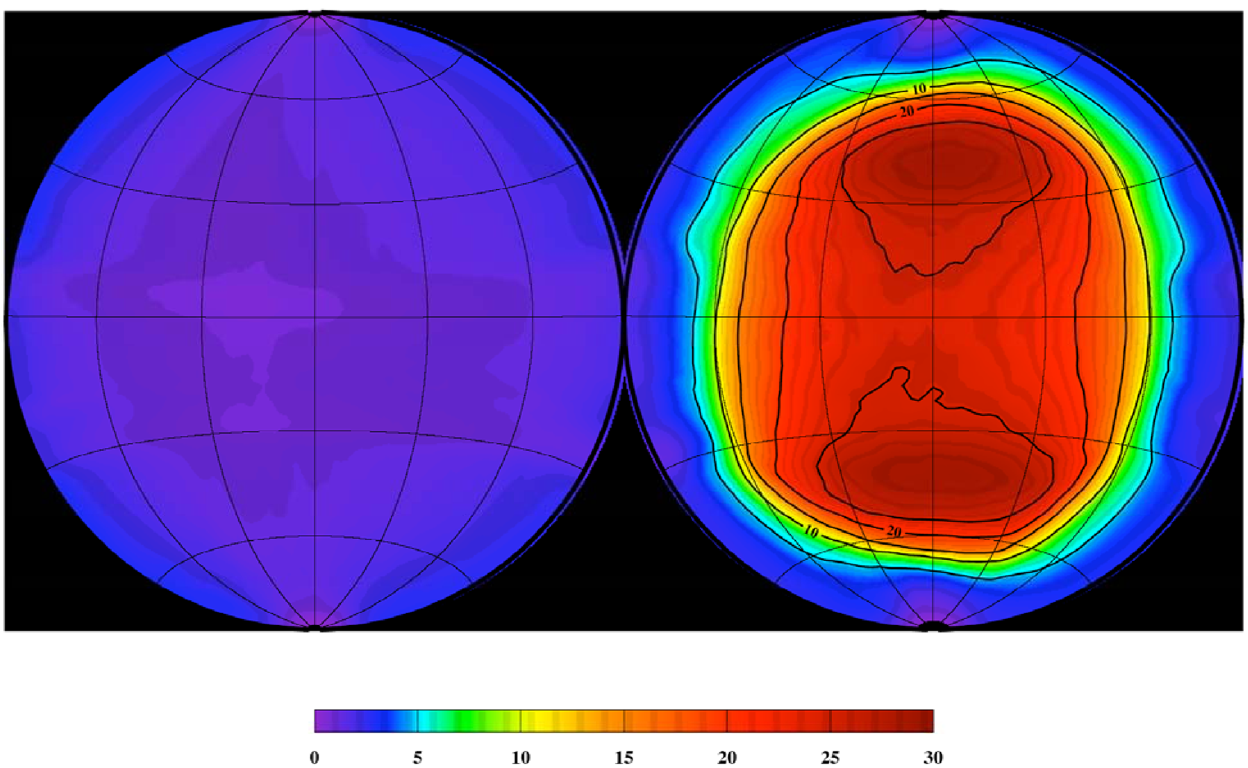


Figure 2-2: Lunar Geoid Uncertainties, LP150Q (meters, n=90)

2.2 Moon Pole and Prime Meridian

Two slightly different systems are commonly used to define a lunar body-fixed coordinate system: a mean Earth / rotation system and a principal axis system. The mean Earth / rotation system (or sometimes called the "mean Earth / polar axis" system) is a lunar body-fixed coordinate system based upon a mean direction to the Earth and a mean axis of rotation of the Moon. The principal axis system is a lunar body-fixed coordinate system aligned with the principal axes of the Moon. Due to the fact that the Moon is not really a synchronously rotating triaxial ellipsoid, the principal axes and the mean Earth / rotation axes of the Moon do not coincide. References 1 and 5 describe and compare the two different coordinate systems and indicate that at the lunar surface, the axes of the two systems differ by just under 1 km. In other words, the locations of surface features will differ by about 1 km in the two coordinate frames.

The equations indicated in this section are taken from the IAU/IAG 2000 Report [6] (International Astronomical Union / International Association of Geodesy). The IAU/IAG Report defines the direction of the Moon's north pole and prime meridian using a mean Earth / rotation axis convention. As a result, these equations only approximate the physical librations (i.e. lunar pole and prime meridian directions) obtained directly from the DE403/LE403 ephemeris file (see Section 5.1 for more information about the DE403 ephemeris). The numerically integrated librations in DE403 are expressed relative to a principal axis-based, lunar coordinate system.

[Note: The LP150Q gravity field was developed using a principal axis-based, coordinate system].

[Note: Not all of the software tools within Section 343 are capable of using both lunar body-fixed coordinate systems described above. The table below indicates the capabilities that currently exist within the section's mission analysis and navigation tools].

Section 343 Software	*Lunar Libration Data*	*IAU/IAG Values*	*Comments*
ODP / DPTRAJ	*X*	*X*	*If lunar libration data are present on the ephemeris file, this software will use the libration data to determine the directions of the Moon's pole and prime meridian. If the libration data are not present on the ephemeris file, then the software defaults to using the IAU/IAG values to define the lunar pole and prime meridian.*
NAIF	*X*	*X*	*This software requires the use a binary PcK (Planetary Constants Kernel) file to use the integrated lunar libration data for pole and prime meridian calculations. Without the PcK file, this software defaults to using the IAU/IAG values to define the lunar pole and prime meridian.*
MASL		*X*	*These software tools use the IAU/IAG values to define the lunar pole and prime meridian.*
LTool		*X*	
MONTE		*X*	

- *ODP / DPTRAJ* *Orbit Determination Program / Double Precision Trajectory Program (legacy navigation s/w)*
- *NAIF* *Navigation Ancillary Information Facility*
- *MASL* *Mission Analysis Software Library*
- *LTool* *Libration Point Mission Analysis Tool*
- *MONTE* *Mission analysis, Operations, and Navigation Toolkit Environment (next generation nav s/w)*

[Note: The equations on the next page were taken from Table II in Reference 6. Table II incorrectly indicates that these equations were developed using the TCB time system. The correct time system reference for Table II (as well as the other tables in Reference 6) should be TDB. See Section 4.1.1 for a brief discussion of dynamical time systems, including TCB and TDB].

(Right ascension of Moon pole in EME2000, deg)

$$\alpha_{Moon\text{-}IAU} = 269.9949 + 0.0031*T - 3.8787*\sin E1 - 0.1204*\sin E2 + 0.0700*\sin E3 - 0.0172*\sin E4 + 0.0072*\sin E6 - 0.0052*\sin E10 + 0.0043*\sin E13$$

(Declination of Moon pole in EME2000, deg)

$$\delta_{Moon\text{-}IAU} = 66.5392 + 0.0130*T + 1.5419*\cos E1 + 0.0239*\cos E2 - 0.0278*\cos E3 + 0.0068*\cos E4 - 0.0029*\cos E6 + 0.0009*\cos E7 + 0.0008*\cos E10 - 0.0009*\cos E13$$

(Prime meridian with respect to Moon IAU-Node vector, deg – see Section 6.1 for definitions)

$$W_{Moon\text{-}IAU} = W_P + 3.5610*\sin E1 + 0.1208*\sin E2 - 0.0642*\sin E3 + 0.0158*\sin E4 + 0.0252*\sin E5 - 0.0066*\sin E6 - 0.0047*\sin E7 - 0.0046*\sin E8 + 0.0028*\sin E9 + 0.0052*\sin E10 + 0.0040*\sin E11 + 0.0019*\sin E12 - 0.0044*\sin E13$$

where $W_P = 38.3213 + \dot{W}_{Moon} * D - 1.4 \times 10^{-12} * D^2$

$E1 = 125.045 - 0.0529921*D$
$E2 = 250.089 - 0.1059842*D$
$E3 = 260.008 + 13.0120009*D$
$E4 = 176.625 + 13.3407154*D$
$E5 = 357.529 + 0.9856003*D$
$E6 = 311.589 + 26.4057084*D$
$E7 = 134.963 + 13.0649930*D$
$E8 = 276.617 + 0.3287146*D$
$E9 = 34.226 + 1.7484877*D$
$E10 = 15.134 - 0.1589763*D$
$E11 = 119.743 + 0.0036096*D$
$E12 = 239.961 + 0.1643573*D$
$E13 = 25.053 + 12.9590088*D$

$\dot{W}_{Moon}$ = 13.17635815 deg/day (1st order rotational rate of Moon)

$T = \dfrac{D}{36525}$ (Julian centuries past epoch of J2000)

D = (Julian Day – J2000) (Days past epoch of J2000)

J2000 = 2451545.0 (Reference epoch of J2000 in Julian days)
= Jan. 1, 2000 12:00:00 ET (Calendar date of J2000 reference epoch. See Section 4.1.1 for a description of ET)

[Note: Reference 1 indicates the relationship between the lunar body-fixed DE403 principal axis system and the IAU/IAG mean Earth / rotation system. The two systems are related (approximately) by three small rotation angles. The conversion from the mean Earth / rotation system (M) to the principal axis system (P) is given by

$$P = R_Z(63.8986'')\, R_Y(79.0768'')\, R_X(0.1462'')\, M\ .$$

Using spherical trigonometry relationships, these three small rotation angles can be included in the IAU/IAG right ascension, declination, and prime meridian equations indicated above, by adding additional terms, in order to produce directions that approximate the principal axis system. The modified equations from Reference 1 are:

$$\alpha_{Moon\text{-}PA\text{-}Approximate} = \alpha_{Moon\text{-}IAU} + 0.0553*\cos W_P + 0.0034\cos(W_P + E1)$$
$$\delta_{Moon\text{-}PA\text{-}Approximate} = \delta_{Moon\text{-}IAU} + 0.0220*\sin W_P + 0.0007\sin(W_P + E1)$$
$$W_{Moon\text{-}PA\text{-}Approximate} = W_{Moon\text{-}IAU} + 0.01775 - 0.0507\cos W_P - 0.0034\cos(W_P + E1)\ ].$$

2.3 Moon Shape Parameters

The general shape of the Moon is very nearly a perfect sphere, excluding local topography variations. In fact, the magnitude of the local topography variations are much larger than the overall flattening of the lunar poles or any ellipticity of the lunar equator. Based upon the data presented in Reference 7, the magnitude of the lunar flattening relative to the equatorial radius is about 2 km. This memo, however, recommends representing the overall shape of the Moon for any mission design and navigation analyses as a perfect sphere for the following reasons.

First, the IAU/IAG 2000 Report recommends using the same radius value for both the lunar equator and the lunar pole (i.e. a sphere). Second the lunar topography data, discussed in Section 2.6.1, are expressed relative to a sphere with the same radius as recommended by the IAU/IAG 2000 Report. The values in the IAU/IAG 2000 Report are listed below.

[Note: The radius recommended here is different than the reference radius for the LP150Q gravity field].

$R_{Moon\text{-}Equator}$	= 1737.4 km	(Radius of Moon equator from IAU/IAG)
$R_{Moon\text{-}Pole}$	= 1737.4 km	(Radius of Moon pole from IAU/IAG)
f_{Moon}	= 0.0	(Moon flattening factor, derived from IAU/IAG values $((R_{Moon\text{-}Equator} - R_{Moon\text{-}Pole})/ R_{Moon\text{-}Equator})$)

2.4 Lunar Orbit

Unlike the orbits of most artificial satellites about the Earth, the principal perturbation on the Moon's orbit is due to the third-body, gravitational attraction of the Sun as opposed to the non-spherical nature of the Earth's gravity field. In fact, it turns out that even the periodic perturbations (on the radial distance of the Moon) caused by Jupiter and Venus are both slightly larger than the perturbation caused by the Earth's J_2 [8]. As a result, the orbit of the Moon is very complex and cannot be described using the simple "precessing, inclined ellipse" model so often used to describe the orbits of low-altitude Earth satellites.

In simple terms, the lunar orbit is slightly elliptical (mean eccentricity = 0.05490) with a mean semi-major axis of about 384,400 km. Its inclination is nearly constant with respect to the ecliptic (mean inclination = 5.15 deg), but its inclination with respect to the Earth's equator varies from approximately 18-29 degrees [8,9]. All three of these orbital elements (a, e, and i) are subject to periodic variations due to solar perturbations.

The remaining orbital elements describing the orientation of the lunar orbit with respect to a particular coordinate system (i.e. longitude of the ascending node and argument of periapsis) both undergo secular and periodic changes. The durations of those periodic variations are indicated below.

With respect to an ecliptic and equinox referenced coordinate system (e.g. EMO2000):
- The period of regression of the longitude of the ascending node (Ω) = 18.6 years
- The period of precession of the argument of periapsis (ω) = 6.0 years
- *[Note: The period of precession of the longitude of periapsis ($\Omega+\omega$) = 8.85 years]*

With respect to an Earth equator and equinox referenced coordinate system (e.g. EME2000):
- The period of precession of the argument of periapsis (ω) = 8.85 years

[Note: With respect to an Earth equator and equinox referenced coordinate system, the longitude of the ascending node does not regress through 360 degrees. It oscillates about a right ascension of 0 deg with a period of 18.6 years (see Figure 2-4H). Thus, there is no secular rate for the longitude of the ascending node. As a result, the period of precession of the argument of periapsis (ω), when measured relative to an Earth equator and equinox referenced coordinate system, is equal to the period of precession of the longitude of periapsis (Ω+ω), when measured relative to the ecliptic and equinox referenced coordinate system].

Figure 2-3 illustrates the relationship between the ecliptic north pole, the Earth north pole, and the lunar orbit pole.

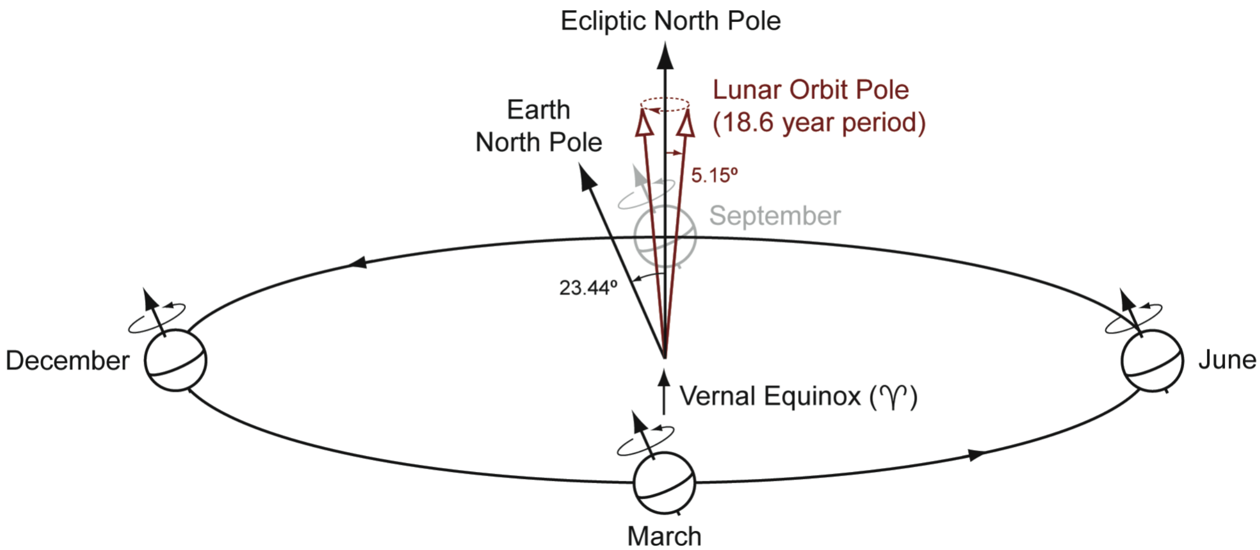


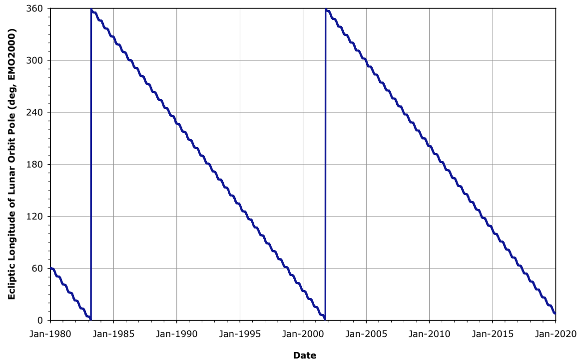
Figure 2-3: Orientation of Lunar Orbit Pole

Figure 2-4 illustrates the evolution of the lunar orbit over a 40 year time span from 1980-2020 – long enough to see the characteristics of the long period changes in the orbital elements. A few of the parameter time histories are provided relative to both the ecliptic plane (EMO2000) and the Earth equator plane (EME2000). The same data are presented in Figure 2-5, but the time scale of the plots is only 3 years, from 2009 through 2012.

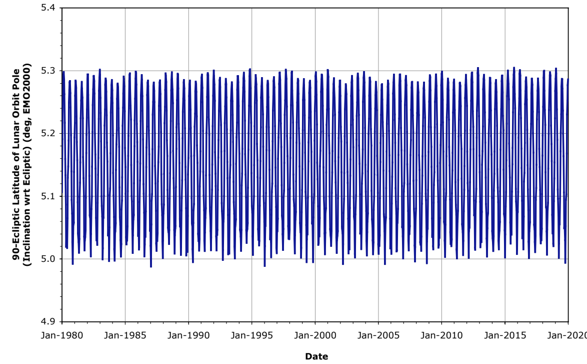
[Note: The data presented in Figures 2-4 and 2-5 were generated using the DE403/LE403 ephemeris – which is currently the best lunar ephemeris available (see Section 5.1)].

There are a number of different ways to define the period of one revolution of the Moon in its orbit. The following table, taken from Reference 9, indicates several of the more common types of lunar "months" (mean values are shown).

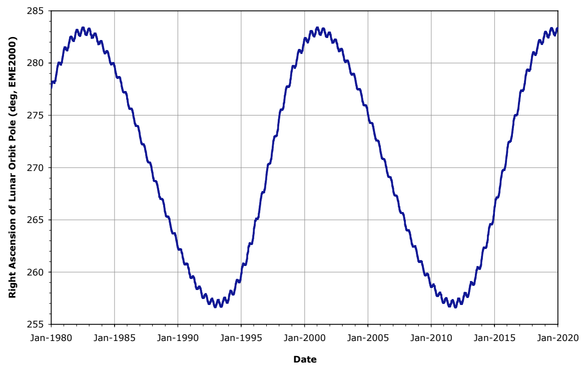
Month	Duration (Earth days)	Duration (days	hrs	min	sec)
Synodic Month (new Moon to new Moon)	29.53059	29	12	44	03
Anomalistic Month (perigee to perigee)	27.55455	27	13	18	33
Sidereal Month (fixed star to fixed star)	27.32166	27	07	43	12
Tropical Month (Equinox to Equinox)	27.32158	27	07	43	05
Nodical (Draconic) Month (node to node)	27.21222	27	05	05	36



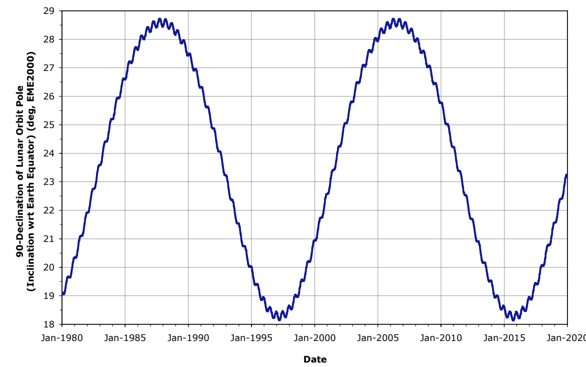
(A: Ecliptic Long of Lunar Orbit Pole)



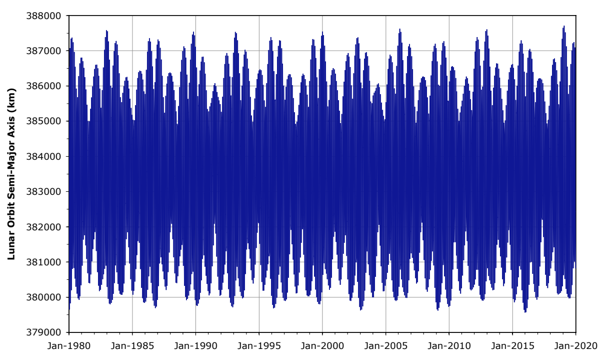
(B: Inclination wrt Ecliptic)



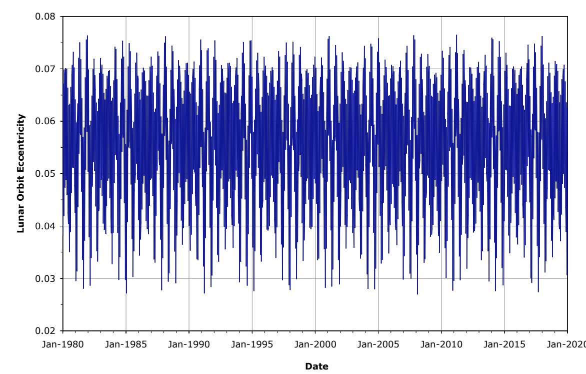
(C: Right Asc of Lunar Orbit Pole)



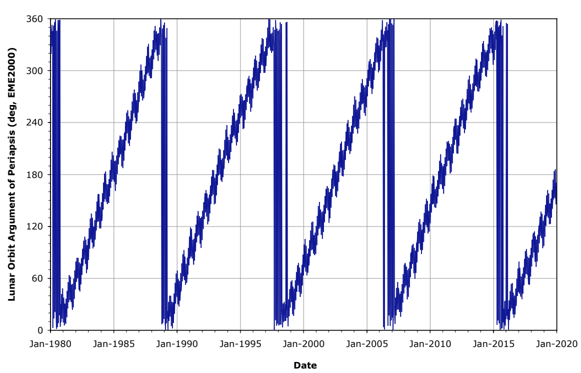
(D: Inclination wrt Earth Equator)



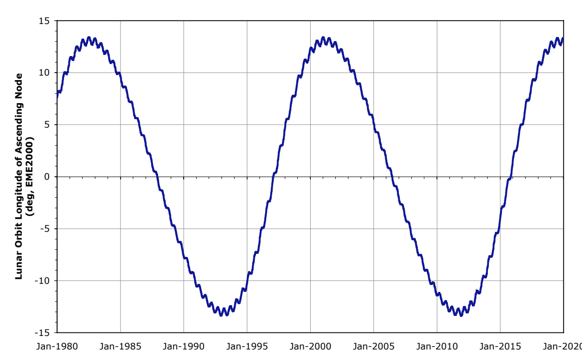
(E: Semi-Major Axis)



(F: Eccentricity)

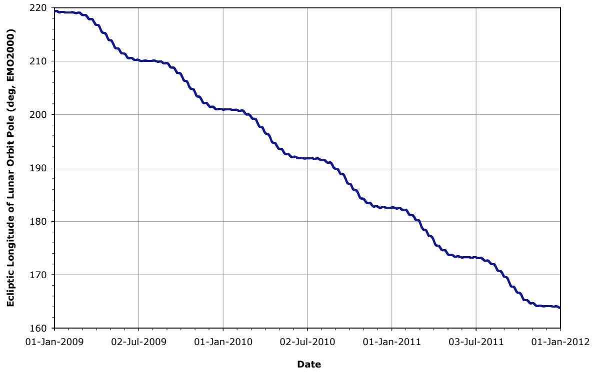


(G: Argument of Periapsis, EME2000)

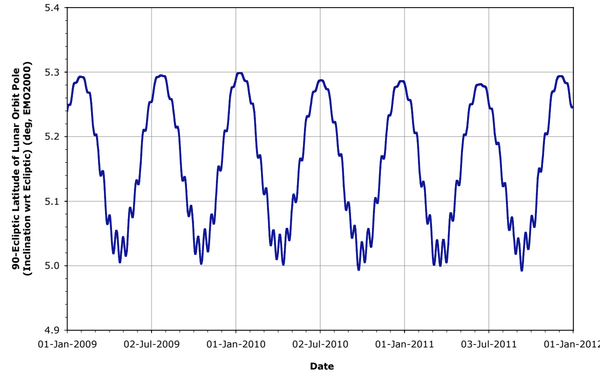


(H: Longitude of Asc Node, EME2000)

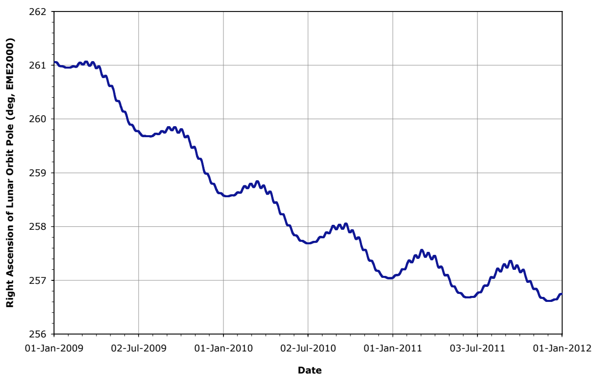
Figure 2-4: Lunar Orbit Evolution - 1980-2020



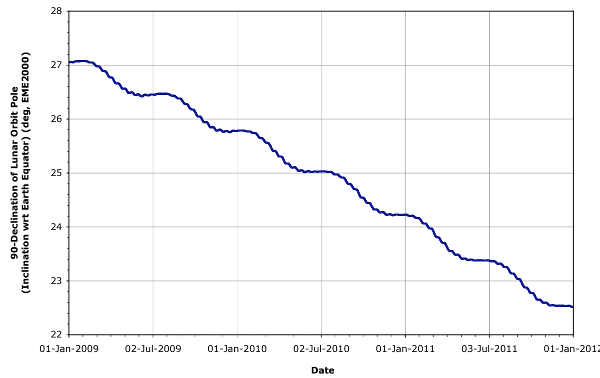
(A: Ecliptic Long of Lunar Orbit Pole)



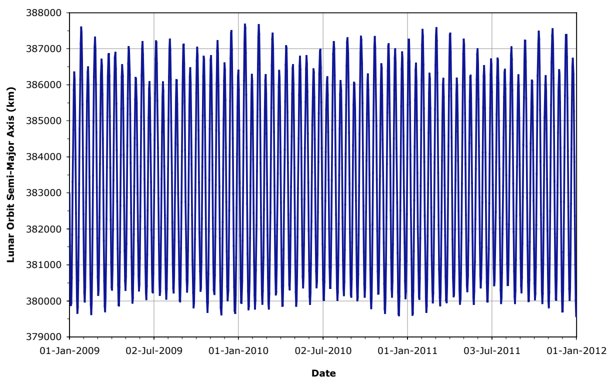
(B: Inclination wrt Ecliptic)



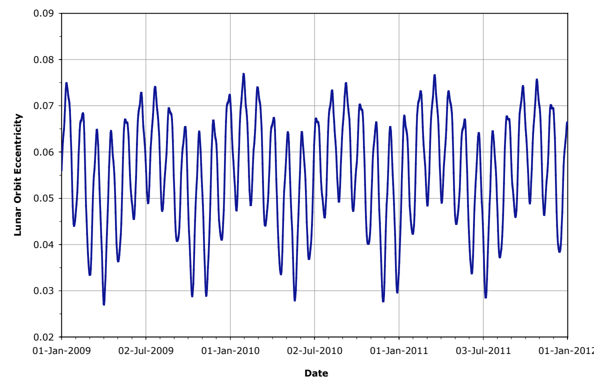
(C: Right Asc of Lunar Orbit Pole)



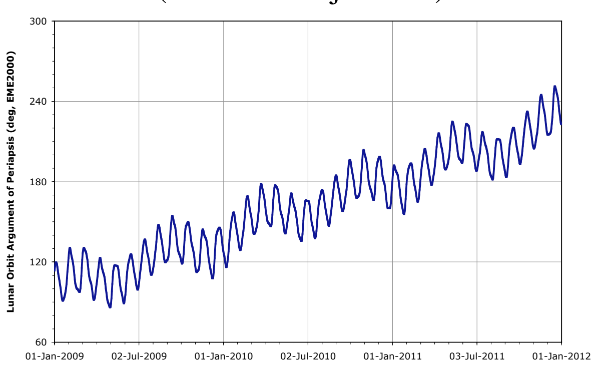
(D: Inclination wrt Earth Equator)



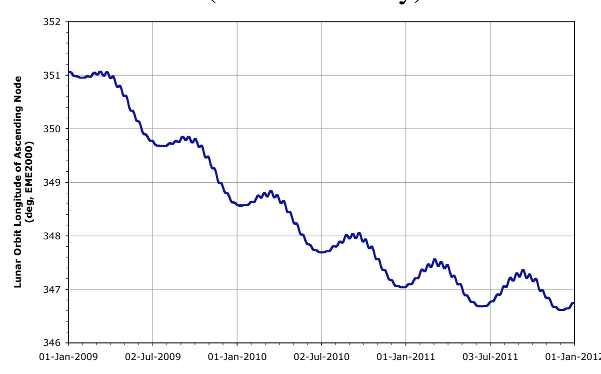
(E: Semi-Major Axis)



(F: Eccentricity)



(G: Argument of Periapsis, EME2000)



(H: Longitude of Asc Node, EME2000)

Figure 2-5: Lunar Orbit Evolution - 2009-2012

For reference, Table 2-1 indicates the times of the new Moon for every month during the years 2009-2012.

[Note: The strict definition of a new Moon is when the apparent ecliptic longitude of the Moon and the Sun as viewed from the center of the Earth are equal. Apparent ecliptic longitudes are measured eastward in the ecliptic plane from the vernal equinox of epoch (the epoch, or date, of the observation) taking into account the light-times from the Moon and the Sun to get their apparent positions [9]].

The new Moon times were generated using the DE403/LE403 ephemeris (see Section 5.1).

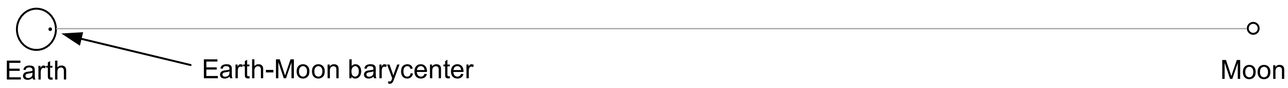
The table also indicates the variation in the duration of time between new Moons during the three-year period. The duration can vary by as much as approximately 3 hours from one month to the next. In addition, the duration of an actual synodic month can be as much as approximately 7 hours longer or 6 hours shorter than the duration of the mean synodic month.

Table 2-1: Synodic Month Variation from 2009-2012

New Moon Time (UTC) *	Time to Next New Moon (Earth days)	Synodic Month Variation (hours)	Difference from Mean Synodic Month (hours)
26-Jan-2009 07:55:19			
	29.73596		4.929
25-Feb-2009 01:35:06		-3.149	
	29.60476		1.780
26-Mar-2009 16:05:57		-3.237	
	29.46988		-1.457
25-Apr-2009 03:22:35		-2.470	
	29.36698		-3.927
24-May-2009 12:11:02		-1.408	
	29.30831		-5.335
22-Jun-2009 19:35:00		-0.406	
	29.29141		-5.740
22-Jul-2009 02:34:38		0.456	
	29.31041		-5.284
20-Aug-2009 10:01:37		1.263	
	29.36301		-4.022
18-Sep-2009 18:44:21		2.101	
	29.45053		-1.921
18-Oct-2009 05:33:07		2.865	
	29.56990		0.943
16-Nov-2009 19:13:46		3.129	
	29.70025		4.072
16-Dec-2009 12:02:08		2.348	
	29.79810		6.420
15-Jan-2010 07:11:24		0.511	
	29.81941		6.932
14-Feb-2010 02:51:21		-1.503	
	29.75678		5.429
15-Mar-2010 21:01:07		-2.699	
	29.64433		2.730
14-Apr-2010 12:28:57		-2.873	
	29.52463		-0.143
14-May-2010 01:04:25		-2.421	
	29.42375		-2.564
12-Jun-2010 11:14:37		-1.739	
	29.35130		-4.303
11-Jul-2010 19:40:29		-0.969	
	29.31090		-5.272
10-Aug-2010 03:08:11		-0.101	
	29.30671		-5.373
08-Sep-2010 10:29:51		0.883	
	29.34352		-4.490
07-Oct-2010 18:44:31		1.877	
	29.42174		-2.612
06-Nov-2010 04:51:49		2.610	
	29.53050		-0.002
05-Dec-2010 17:35:44		2.717	
	29.64369		2.714
04-Jan-2011 09:02:39		2.019	
	29.72780		4.733
03-Feb-2011 02:30:41		0.786	
	29.76057		5.519
04-Mar-2011 20:45:54		-0.479	
	29.74059		5.040
03-Apr-2011 14:32:21		-1.468	
	29.67943		3.572
03-May-2011 06:50:44		-2.108	
	29.59161		1.464
01-Jun-2011 21:02:39		-2.344	
	29.49396		-0.879
01-Jul-2011 08:53:57		-2.090	
	29.40686		-2.969
30-Jul-2011 18:39:50		-1.360	
	29.35021		-4.329
29-Aug-2011 03:04:08		-0.329	
	29.33652		-4.658
27-Sep-2011 11:08:43		0.709	
	29.36605		-3.949
26-Oct-2011 19:55:50		1.446	
	29.42631		-2.503
25-Nov-2011 06:09:43		1.714	
	29.49772		-0.789
24-Dec-2011 18:06:26			

* Assumes ET-UTC = 64.184 s

The simple diagram below illustrates, to scale, the sizes of the Earth, the Moon, and the distance between them. The Earth/Moon barycenter lies within the Earth at a distance of approximately 4670 km from the Earth's center toward the Moon. The current best estimate of the Earth-Moon mass ratio is 81.300570±0.000005 [2].



2.4.1 Lagrange Points

In the study of the circular, restricted three-body problem, much has been written about the existence of five special equilibrium points in which a small body (e.g. a spacecraft) can essentially maintain a fixed distance away from two larger orbiting bodies. These points are called Lagrange points or sometimes Libration points. There are three collinear Lagrange points with the two primary bodies and two points that form equilateral triangles with the two primary bodies. For a more detailed description about the characteristics of these points, particularly regarding the stability of a body placed at these points, the reader can refer to any of a number of celestial mechanics or orbital dynamics references, including References 10 and 11.

For missions that operate in the vicinity of the Earth-Moon system, there are often two different three-body systems that need to be taken into account: the Sun-Earth-spacecraft system and the Earth-Moon-spacecraft system. Naturally, this is really best represented by a four-body system, but much of the terminology used is derived from studying the two different three-body systems.

Figure 2-6 [courtesy of Martin Lo] illustrates the two collinear Lagrange points in the Sun-Earth system near the Earth, labeled EL_1 and EL_2, as well as all five Lagrange points in the Earth-Moon system. The EL_1 and EL_2 points are approximately 1.5 million kilometers away from the Earth or about 1% of the distance from the Earth to the Sun. Low energy transfers from the Earth to Moon or from the Moon to the Earth often involve trajectories that pass near or around the EL_1 and/or EL_2 points. The collinear Lagrange points in the Earth-Moon system near the Moon, labeled LL_1 and LL_2 in Figure 2-6, are approximately 60000 km from the center of the Moon or about 16% of the distance from the Moon to the Earth.

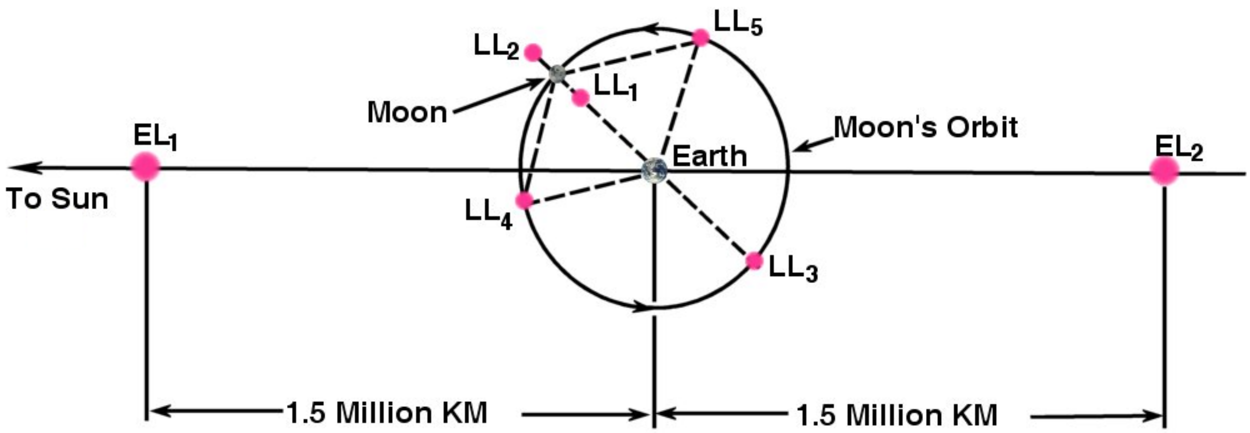


Figure 2-6: Lagrange Points in the Vicinity of the Earth-Moon System

2.4.2 Lunar Eclipses

A specific geometry must exist between the Sun, the Earth, and the Moon for a lunar eclipse to occur (see the simple diagram below). The Moon must lie in the ecliptic plane (or be very near it – within a couple lunar diameters of the ecliptic) and the line of nodes of the Moon's orbit with respect to the ecliptic plane must lie along the Sun-Earth line. Since the Earth revolves about the Sun (in 1 year) much faster than the lunar orbit pole revolves about the ecliptic north pole (in 18.6 years), the Earth crosses the line of nodes of the Moon's orbit approximately every six months. Thus, approximately every six months there is an opportunity for a lunar eclipse.

Table 2-2 indicates all of the lunar eclipses that will occur during the period from 2009 through 2012. The table was constructed from data available at the following NASA website *http://sunearth.gsfc.nasa.gov/eclipse/lunar.html* . The website includes a wealth of data for each lunar eclipse – including figures such as Figure 2-7. The reader should consult the website if more information or explanation is desired regarding lunar eclipses.

Table 2-2. Lunar Eclipses from 2009-2012

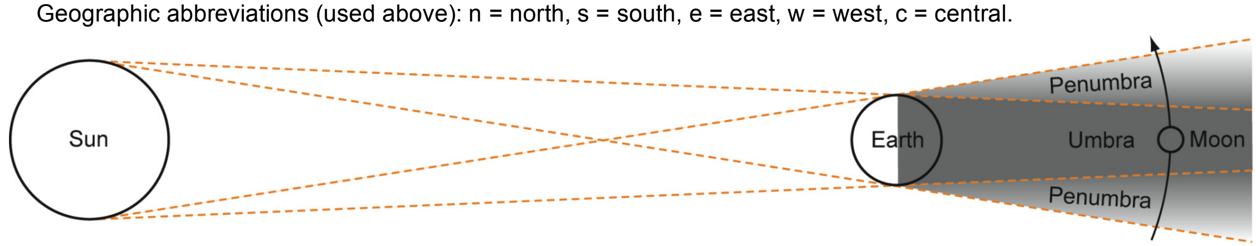
Date	Eclipse Type	Saros [1]	Umbral Magnitude [2]	Eclipse Duration [3]	Geographic Region of Eclipse Visibility [4]
2009 Feb 09	Penumbral	143	-0.083	-	e Europe, Asia, Aus., Pacific, w N.A.
2009 Jul 07	Penumbral	110	-0.909	-	Aus., Pacific, Americas
2009 Aug 06	Penumbral	148	-0.661	-	Americas, Europe, Africa, w Asia
2009 Dec 31	Partial	115	0.082	01h02m	Europe, Africa, Asia, Aus.
2010 Jun 26	Partial	120	0.542	02h44m	e Asia, Aus., Pacific, w Americas
2010 Dec 21	Total	125	1.262	03h29m **01h13m**	e Asia, Aus., Pacific, Americas, Europe
2011 Jun 15	Total	130	1.705	03h40m **01h41m**	S.America, Europe, Africa, Asia, Aus.
2011 Dec 10	Total	135	1.110	03h33m **00h52m**	Europe, e Africa, Asia, Aus., Pacific, N.A.
2012 Jun 04	Partial	140	0.376	02h08m	Asia, Aus., Pacific, Americas
2012 Nov 28	Penumbral	145	-0.184	-	Europe, e Africa, Asia, Aus., Pacific, N.A.

[1] The **Saros** cycle is the periodic recurrence of solar and lunar eclipses with a period of approximately 6,585.3 days (18 years 11 days 8 hours). When two eclipses are separated by a period of one Saros, they share a very similar geometry. The eclipses occur at the same node with the Moon at nearly the same distance from Earth and at the same time of year. Thus, the Saros is useful for organizing eclipses into families or series. Each series typically lasts 12 to 13 centuries and contains 70 or more eclipses.

[2] **Umbral Magnitude** is the fraction of the Moon's diameter obscured by Earth's umbra. For penumbral eclipses, the umbral magnitude is always less than 0. For partial eclipses, the umbral magnitude is always greater than 0 and less than 1. For total eclipses, the umbral magnitude is always greater than or equal to 1.

[3] **Eclipse Duration** is the duration of a partial eclipse. If the eclipse is total, the duration of totality is given in bold.

[4] **Geographic Region of Eclipse Visibility** is the portion of Earth's surface where a lunar eclipse can be seen. Geographic abbreviations (used above): n = north, s = south, e = east, w = west, c = central.



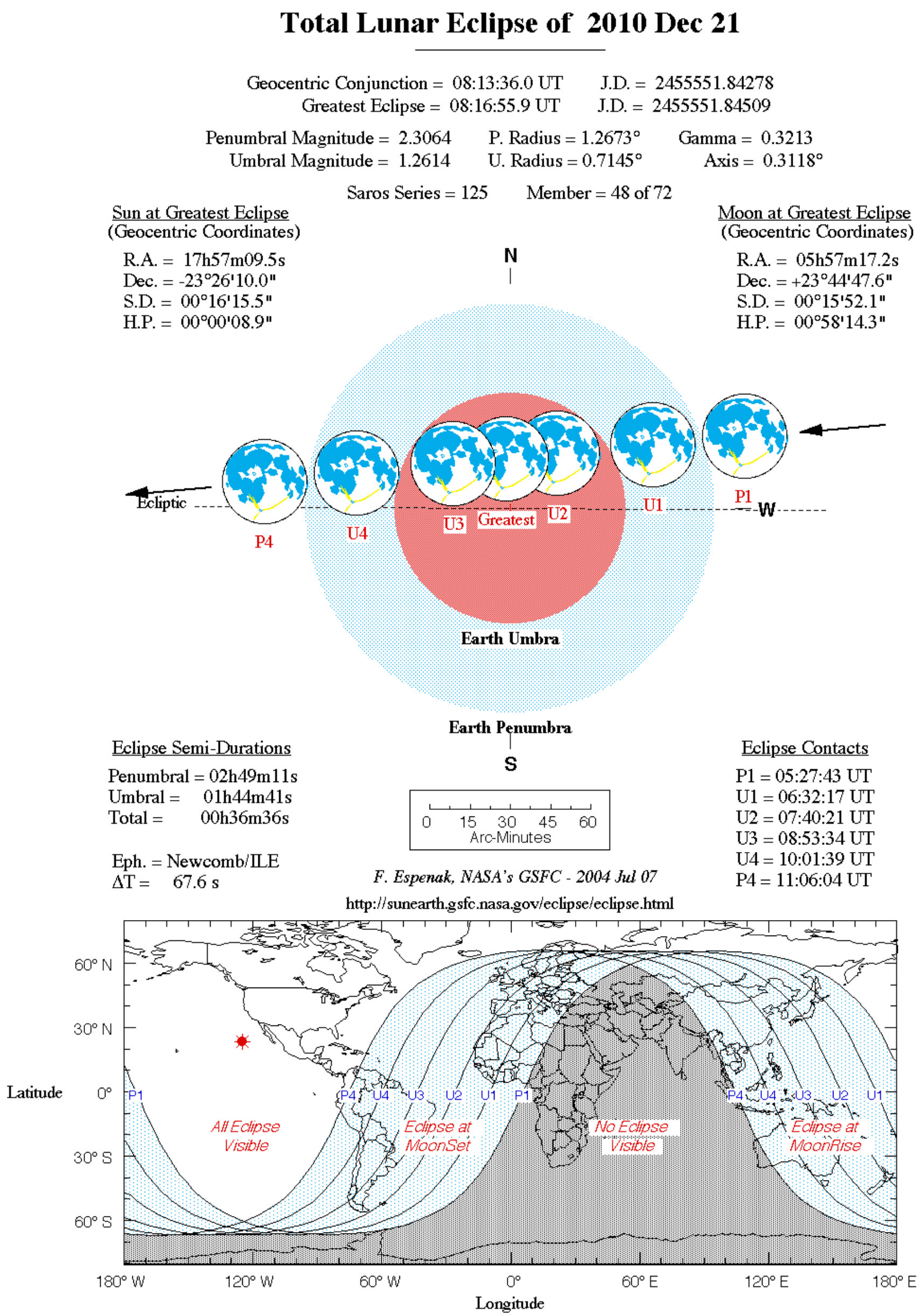


Figure 2-7: Example of Lunar Eclipse Data Available at NASA Website
http://sunearth.gsfc.nasa.gov/eclipse/lunar.html

2.5 Lunar Librations

Any casual observer of the Moon knows that the Moon only presents one face towards the Earth. This is due to the fact that the Moon rotates at a rate equal to the sidereal rate of the Moon in its orbit about the Earth. For a variety of reasons, however – some geometric and some physical – more than 50% of the Moon is visible from Earth over time. The motions of the Moon and the Earth that allow observers on Earth to see slightly different parts of the Moon's surface at different times are called librations.

<u>Geometric (or Optical) Librations</u>

There are three different types of librations that are based solely on the geometry between the Earth (or an observer on the Earth) and the Moon. They are librations in longitude, librations in latitude, and diurnal librations. See Reference 12 or probably any textbook describing the Moon's orbit for more information. All three librations are illustrated in Figure 2-8.

Figure 2-8A illustrates librations in longitude. The figure shows that while the Moon rotates at a constant rate, its velocity about the Earth is not constant due to the fact that Moon's orbit is elliptical. For example, in the time it takes for the Moon to rotate 90 degrees, the Moon has traveled less than 90 degrees in its orbit (from position ① to ② in the figure). This leads to an apparent east-west "rocking" motion of the Moon over one complete orbit as viewed from Earth allowing an observer on the Earth to see a little bit around to the "back-side" or "far-side" of the Moon.

[Note: The maximum longitudinal libration of 8.16 degrees depicted in Figure 2-8A is considerably larger than the value that appears in most textbooks (usually quoted as 6.28 degrees). The maximum angle is produced as a result of multiple, periodic perturbations on the Moon's orbit, primarily due to the Sun [13]. Considering the Moon's orbit as a simple, two-body elliptical orbit produces the more commonly referenced 6.28 degree value].

Figure 2-8B illustrates librations in latitude. This libration results from the fact that the Moon's equator is inclined to the plane of its orbit by 6.69 degrees. (The total angle can be represented by the sum of the inclination of the Moon's orbit to the ecliptic plane and the inclination of the Moon's equator to the ecliptic plane). Over the course of one month, the total inclination produces an apparent north-south "nodding" motion of the Moon allowing an observer on the Earth to see a little bit beyond the north and south poles of the Moon.

[Note: The maximum latitudinal libration of 6.87 degrees depicted in Figure 2-8B is slightly larger than the value that appears in most textbooks (usually quoted as 6.69 degrees) for the same reason discussed in the previous paragraph – perturbations on the Moon's orbit due to the Sun [13]].

Figure 2-8C illustrates diurnal librations (sometimes also called topocentric librations). This libration is caused by the fact that an observer on the Earth sees the Moon from different angles due to the rotation of the Earth. For example, over a 12 hour period, an observer at the Earth's equator can see a total of almost 2 degrees more of the Moon in longitude than at any instant in time during the day.

The geometric librations allow 59% of the Moon's surface to be visible from Earth; 41% of the surface is always visible, 41% is never visible, and 18% is alternately visible and not visible.

<u>Physical Librations</u>

As stated in Section 2.3, the Moon's shape is very nearly spherical. Nevertheless, it is not a perfect sphere. As a result, the Earth's gravitational attraction on the slight "bulges" on the Moon produce small irregularities in the rotation rate of the Moon. These irregularities produce very small physical librations – occasionally displacing surface positions by just over a kilometer, with the libration periods ranging from a month to many years [8]. In contrast to the magnitude of the geometric librations, the maximum amplitude of the physical librations is less than approximately 125″ (arcseconds) or less than about 0.035 degrees.

The libration discussion included here is largely for background information. Since the DE403/LE403 ephemeris file includes all of the physical lunar librations, the mission analyst does not need to do anything to try to explicitly keep track of these effects. In fact, they could be ignored for all mission design studies and all but the most precise navigation analyses.

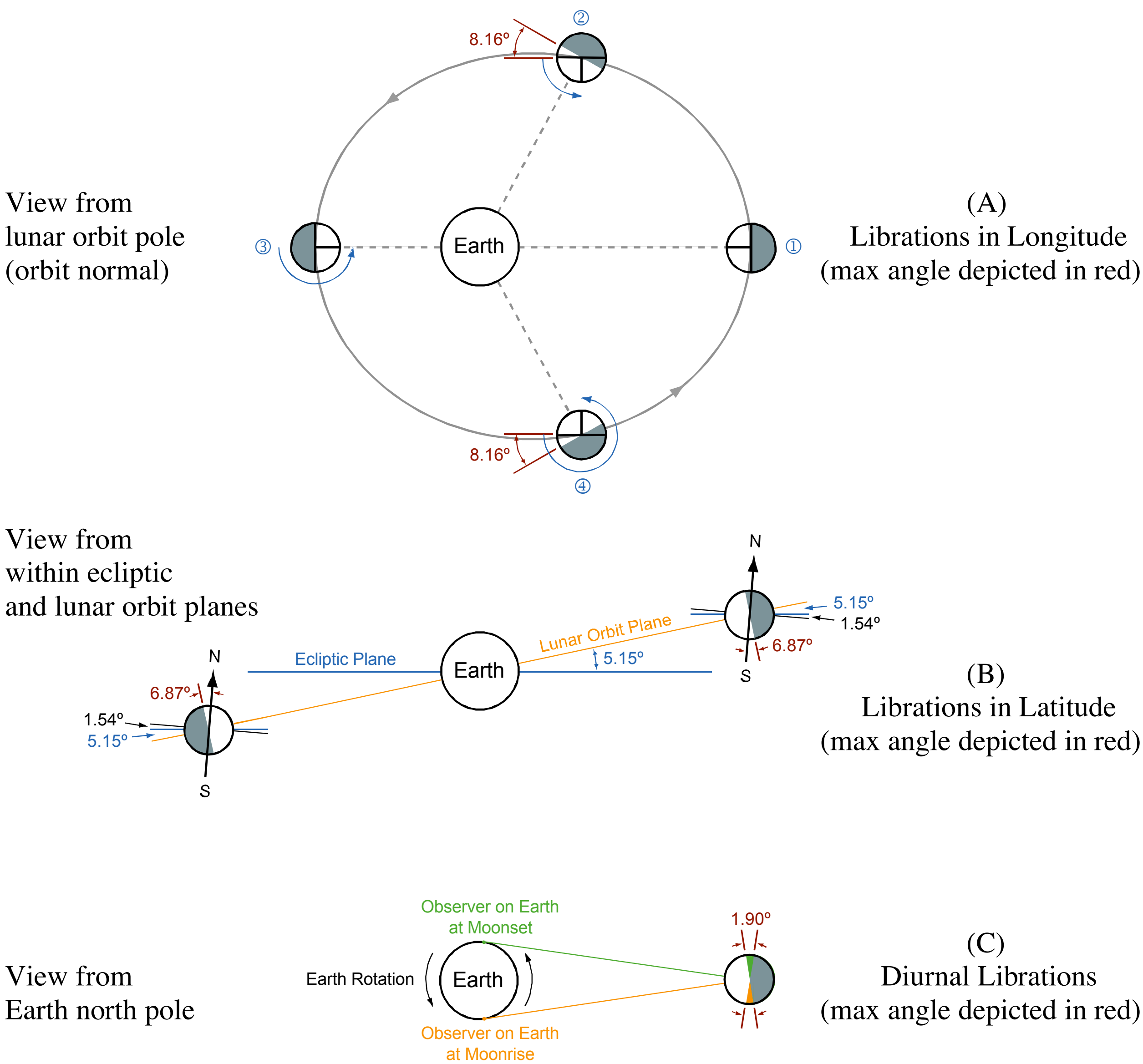


Figure 2-8: Geometric Lunar Librations

2.6 Physical Properties

This section is provided to give the reader some idea of the physical properties of the Moon, particularly those properties or characteristics that can influence the trajectory design and/or navigation development of a lunar mission. Some of the physical properties, however, have little influence on mission design and are provided for informational purposes only.

[Note: The data presented here are not intended to replace or be a substitute for the production of a detailed Environmental Requirements Document necessary for flight system design and test].

2.6.1 Topography

The deviations from the overall spherical shape of the Moon due to local topography can be substantial. The maximum and minimum variations are approximately +8 km/-9 km with both extremes occurring on the far-side of the Moon (relative to a sphere with a radius of 1737.4 km) [14]. (See also Reference 7 for more information). The maximum surface elevations occur in the region surrounding the Korolev crater while the minimum elevations occur in the geographically nearby South Pole-Aitken basin.

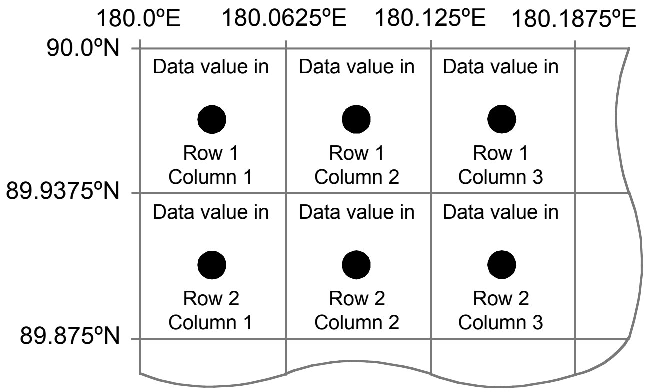
The topography of the Moon is illustrated in Figures 2-9 and 2-10 [14]. Color-coded topography information is overlaid onto shaded relief maps of the near-side and far-side hemispheres of the Moon. The topography data depicted in the maps are based primarily upon range measurements taken by a laser altimeter (LIDAR) on board the 1994 Clementine mission between approximately 70° N and 70° S latitudes. Since there were comparatively few LIDAR measurements taken near the poles, and none taken over the poles, topographic data in the polar regions were collected photogrammatically using nadir and oblique Clementine images [14].

The following United States Geological Survey (USGS) website, ftp://ftpflag.wr.usgs.gov/dist/pigpen/moon/usgs/topo/, provides digital elevation data for the lunar surface. ASCII files containing lunar topography data are located in the folder 'global_ASCII'. The files are listed below.

1) lunarDEM_ASCII_dd_geocentric_v2.asc.gz (includes areas with no elevation data)
2) lunarDEM_ASCII_interp_dd_geocentric.asc.gz (includes interpolated/extrapolated data)

The first file is a compressed file that spans the entire lunar surface, but does include some areas where no topography data exist. (The elevation data are assigned a value of –9999 in these areas). The second file is similar to the first, except that the areas with no elevation data have been filled in with interpolated or extrapolated data values.

The elevation data in the files are expressed in meters and are referenced to a sphere with radius 1737.4 km (the same value quoted in Section 2.3). The data are provided at a resolution of 0.0625° (which is equivalent to 1895.209 m along a great circle of the Moon). The data are stored in a simple cylindrical map projection starting at the North pole. The simple graphic on the next page illustrates the data-file format of the two files.



Each file contains a matrix of data, where an element (or grid cell) within the matrix is an interpolated elevation value for the center (latitude/longitude) of the cell (represented by the black dots in illustration above).

While the elevation data in the files is provided down to the meter level, the uncertainty in the elevation data is considerably larger. The relative uncertainty in the elevation data from point to point (or grid cell to grid cell) is probably on the order of 200-500 m. The absolute uncertainty in the elevation data is probably on the order of 1.0-1.5 km.

For more information, see the '.txt' files (or ReadMe files) in the 'global_ASCII' topography folder. Those files, along with the text in Reference 14, provide a detailed description of the format, limitations, and uncertainty of the topography data.

[Note: The topography data in these files are the same data that are depicted in Figures 2-9 and 2-10. The interpolated values are based on Clementine LIDAR elevation data and point elevations collected in the polar areas that were sampled to form a regular spaced grid of points].

2.6.2 Lunar Control Network

The previous section described the current state of knowledge regarding the "vertical accuracy" of the lunar topography data. While not strictly a physical property of the Moon, this section provides the current state of knowledge regarding the "horizontal accuracy" of the placement of lunar images (i.e. surface features) on to a well-defined lunar coordinate system. This process is known as establishing a "lunar control network" and usually involves taking image data from a variety of sources and selecting "control points" (e.g. craters or imaged spacecraft hardware) for which good position estimates are known and transforming their coordinates into a common coordinate system (usually the mean Earth / rotation system described in Section 2.2). The uncertainty or error in the placement of these images on to the lunar body-fixed coordinate system is often called the "map-tie error". This uncertainty must be accounted for when attempting to land on the Moon or to precisely image a particular spot or feature from lunar orbit.

Reference 15 describes an analysis that produced a Unified Lunar Control Network (ULCN) using images from Apollo, Mariner 10, Galileo, and Earth-based telescopes. The estimated horizontal accuracies of the ULCN range from 100 m to 3 km – with the smaller numbers near the Apollo sites and the larger numbers on the lunar far-side and near the poles. Reference 16 describes an activity in progress (in 2005) to update the ULCN by merging the existing ULCN (developed in 1994) with a control network based on the image data set collected by the Clementine mission.

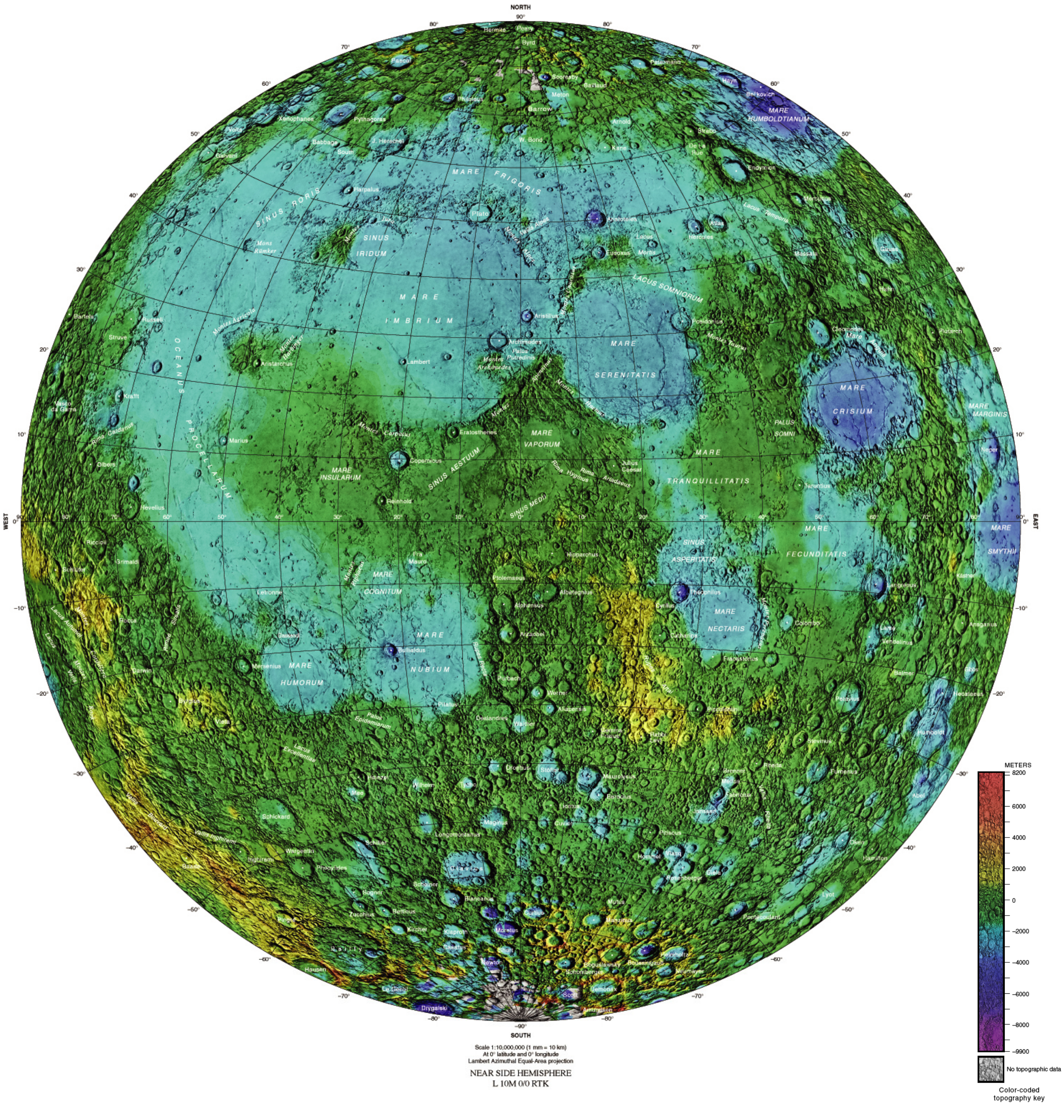


Figure 2-9: Color-Coded Topography and Shaded Relief of Near-Side Hemisphere

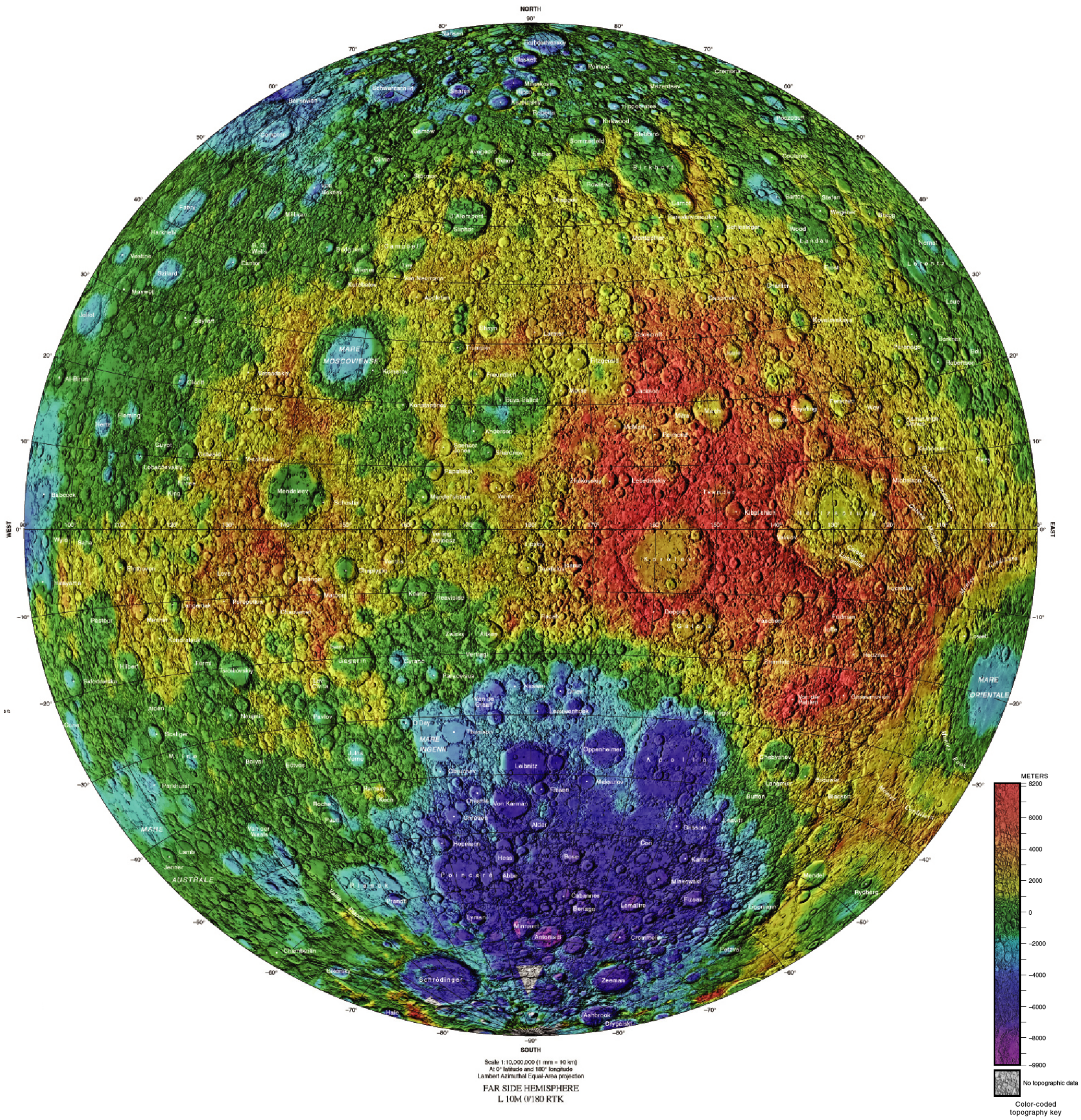


Figure 2-10: Color-Coded Topography and Shaded Relief of Far-Side Hemisphere

2.6.3 Atmosphere

For nearly all intents and purposes the Moon can be considered to have no atmosphere. Certainly from a mission design or navigation perspective no atmospheric drag or heating effects need to be considered when analyzing the trajectory of a spacecraft near the surface of the Moon.

In reality, however, the Moon has a very tenuous atmosphere whose gases are easily lost to space. The atmospheric density on the Moon is about 14 orders of magnitude less dense than the Earth's atmosphere [17]. Although difficult to detect, the primary constituents of the ambient lunar atmosphere are: Neon (^{20}Ne), Helium (He), Hydrogen (H_2), and Argon (^{40}Ar), *roughly* in order of their abundance. Trace amounts of other gases were also detected. The source of the lunar atmosphere is believed to be largely composed of particles from the solar wind and atoms from the surface rocks and soil released by the impacts of comets and meteorites. Argon, by contrast, is produced by the radioactive decay of Potassium (^{40}K) in the lunar interior. (See also *http://www.lpi.usra.edu/expmoon/Apollo17/A17_Experiments_LACE.html*). Reference 17 indicates the interesting trivial fact that the "six Apollo landings delivered six times as much gas to the lunar surface as there is in the ambient atmosphere".

2.6.4 Temperature

The temperatures on the lunar surface vary widely from location to location and are greatly influenced by the diurnal cycle. Near the equator the surface temperatures increase about 280º C from just before lunar dawn to lunar noon. Table 2-3 was taken from Reference 17. It indicates the estimated average surface temperatures and the temperature extremes at various locations on the Moon. The average surface temperature at local noon on the Moon changes by about 6º C between Earth perihelion and aphelion.

Table 2-3: Estimated Lunar Surface Temperatures

	Shadowed Polar Craters	Other Polar Areas	Near-Side Equatorial	Far-Side Equatorial	Limb Equatorial	Typical Mid Latitudes
Average Temp.	-233º C (?)	-53º C	-19º C	-17º C *	-18º C	-53º C < T < -18º C
Monthly Range	None	±10º C †	±140º C	±140º C	±140º C	±110º C

* The far-side of the Moon is closer to the Sun at noon than the near-side is, so it gets ≈1% more solar energy.
† Average temperature has a yearly variation that makes it very cold (T < -73º C) for several weeks.

Figure 2-11, taken from Reference 18, provides an interesting graphical comparison of surface temperatures on the Earth, the Moon, and Mars. The minimum and maximum lunar surface temperatures are average mid-latitude daytime and nighttime temperatures – not the extremes that can be experienced at, for example, the polar regions on the Moon.

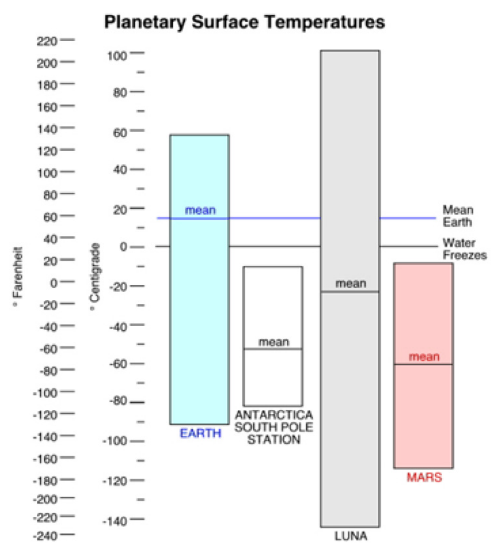


Figure 2-11: Planetary Surface Temperatures

2.6.5 Albedo

Despite appearing from Earth as the brightest object in the sky next to the Sun, the Moon is actually a very dark object. The Moon only reflects about 7-24% of the visible light that reaches its surface. The light-colored rocks of the lunar highlands have generally higher albedos ranging from 11-18%, while the lunar maria have low albedos in the range of 7-10% [17].

[Note: Earth-based albedo measurements are made during the full Moon].

The images in Figure 2-12 represent an albedo map of the Moon indicating the relative brightness of lunar surface features [19]. The Moon is rotated 60 degrees east in longitude between each view.

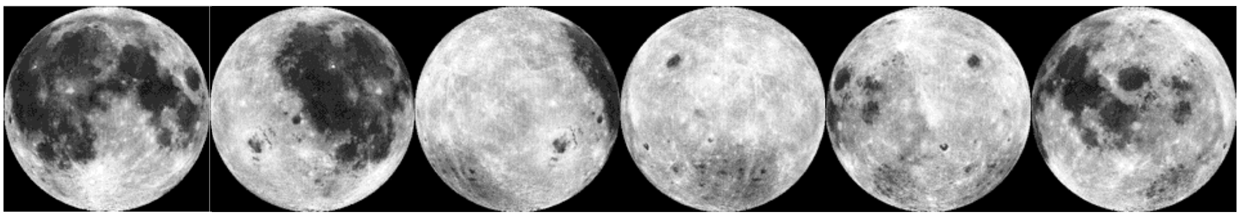


Figure 2-12: Lunar Albedo Map

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3. EARTH DATA

3.1 Earth Gravity Field

The Earth gravity field currently recommended for use is the GRACE (Gravity Recovery and Climate Experiment) gravity model GGM02C. This is a 200th spherical harmonic degree and order model that combines nearly a year of GRACE K-band range-rate, attitude, and accelerometer data with surface gravity and mean sea surface information [20].

[Note: The GGM02C Earth gravity model was released October 29, 2004 and supersedes the three different Earth gravity models recommended in Reference 3].

For the majority of lunar missions, particularly those that don't spend too much time in low-Earth orbit, use of an 8th degree and order subset of the GGM02C gravity field is sufficient. Appendix C lists the normalized coefficients for an 8 x 8 subset of the GGM02C gravity field. In addition, Appendix C indicates where the full GGM02C field can be found.

$R_{Earth\text{-}Ref}$	= 6378.1363 km	(Reference radius, GGM02C)
GM_{Earth}	= 398600.4356 km^3/s^2	(Gravitational parameter, GGM02C, GGM02C value transformed to a solar system barycentric reference frame. See 'Note' below)
$\bar{J}_{2\ Earth}$	= 4.841652160548 x 10^{-4}	(Earth 2nd degree zonal, Normalized, GGM02C)
$J_{2\ Earth}$	= 1.082626335439 x 10^{-3}	(Earth 2nd degree zonal, Un-normalized, GGM02C) (Epoch J2000 , no permanent tide)
$\dot{J}_{2\ Earth}$	= –2.6 x 10^{-11} /year	(Earth 2nd degree zonal rate, Un-normalized, GGM02C)
$D_{SOI\ Earth}$	= 9.25 x 10^5 km	(Earth Sphere of Influence, calculated at 1 AU)
g_{Earth}	≐ 9.80665 m/s^2	(Earth standard acceleration of gravity [21])

[Note: The GM_{Earth} value specified in the GGM02C Earth gravity field is 398600.4415 km^3/s^2. This value differs slightly from the GM_{Earth} value quoted above. The two different values are actually both "equally correct", but they represent the Earth GM in two different reference frames. The GGM02C model was developed assuming a geocentric reference frame. The time system used in the geocentric reference frame, as discussed in Section 4.1.1, is TT (Terrestrial Time, or also called TDT for Terrestrial Dynamical Time). The JPL planetary and satellite ephemerides (including the GMs of the other solar system bodies), on the other hand, were developed using a solar system barycentric based time scale called T_{eph} (see Section 4.1.1). T_{eph} differs slightly from TT due to relativistic effects. Since the units of GM involve time (km^3/s^2), the value of GM_{Earth} is slightly different in the geocentric reference frame vs the solar system barycentric reference frame. Since the DE403 ephemeris and the lunar gravity field presented in this document were developed using the solar system barycentric reference frame, the solar system barycentric value for GM_{Earth} must be used for everything to be consistent. Note also that the GM of the Earth used in the development of DE403 (see Section 5.1) is equivalent to the solar system barycentric value quoted above. For more information on the transformation between the geocentric and solar system barycentric reference frames and how the selection of those frames affect the value of GM_{Earth}, see References 3 and 22].

3.2 Earth Pole and Prime Meridian

The direction of the Earth's north pole and prime meridian can be approximated by the following equations, taken from the IAU/IAG 2000 Report [6]. For precise navigation calculations, the IERS standards should be used [3].

$\alpha_{Earth\text{-}IAU}$	$= 0.00 - 0.641 * T$ deg	(Right ascension of Earth pole in EME2000)
$\delta_{Earth\text{-}IAU}$	$= 90.00 - 0.557 * T$ deg	(Declination of Earth pole in EME2000)
$W_{Earth\text{-}IAU}$	$= 190.147 + \dot{W}_{Earth} * D$ deg	(Prime meridian wrt Earth IAU-Node vector, Earth equinox of J2000 + 90 deg = IAU-Node)
$\dot{W}_{Earth}$	= 360.9856235 deg/day	(Rotational rate of Earth)
T	$= \dfrac{D}{36525}$	(Julian centuries past epoch of J2000)
D	= (Julian Day – J2000)	(Days past epoch of J2000)
J2000	= 2451545.0	(Reference epoch of J2000 in Julian days)
	= Jan. 1, 2000 12:00:00 ET	(Calendar date of J2000 reference epoch. See Section 4.1.1 for a description of ET)

[Note: The equations above were taken from Table I in Reference 6. Table I incorrectly indicates that these equations were developed using the TCB time system. The correct time system reference for Table I (as well as the other tables in Reference 6) should be TDB. See Section 4.1.1 for a brief discussion of dynamical time systems, including TCB and TDB].

3.3 Earth Shape Parameters

The Earth radii that should be used for determining Sun and spacecraft visibility are taken from the IAU/IAG 2000 Report [6].

$R_{Earth\text{-}Equator}$	= 6378.14 km	(Radius of Earth equator from IAU/IAG)
$R_{Earth\text{-}Pole}$	= 6356.75 km	(Radius of Earth pole from IAU/IAG)
f_{Earth}	= 0.00335364228	(Earth flattening factor, derived from IAU/IAG values $((R_{Earth\text{-}Equator} - R_{Earth\text{-}Pole}) / R_{Earth\text{-}Equator})$)

3.4 Atmospheric Entry Interface Radius for Sample Return Trajectories

The radius that defines the atmospheric boundary at the Earth for lunar sample return missions is given below. This is the radius that is used for targeting the entry aimpoint.

[Note: The value indicated below is the same value used for the Genesis and Stardust sample return missions. It was originally defined as 125 km above an Earth equatorial radius of 6378.14 km].

$R_{Atmos\text{-}Interface}$	= 6503.14 km	(Radius at atmospheric entry interface)

4. TIME SYSTEMS

4.1 Types of Time Systems

Reference 9 provides the following broad definitions of the four types of time systems in common use in physics and astronomy. To varying degrees, each of these types of time systems (and the relationships between them) is important to the mission analyst.

a) *Atomic time*, in which the unit of duration corresponds to a defined number of wavelengths of radiation of a specified atomic transition of a chosen isotope.

b) *Universal time*, in which the unit of duration represents the solar day, defined to be as uniform as possible, despite variations in the rotation of the Earth.

c) *Sidereal time*, in which the unit of duration is the period of the Earth's rotation with respect to a point nearly fixed with respect to the stars.

d) *Dynamical time*, in which the unit of duration is based on the orbital motion of the Earth, Moon, and planets.

[Note: It is very difficult to be both succinct and technically correct when defining the different types of time systems that exist. The definitions provided above from Reference 9 generally convey the proper intent, but not all of them are strictly correct. No attempt, however, has been made to modify them since they were intended to simply introduce the subject. In light of the complexity of this topic, in particular for precision navigation applications, this section only summarizes basic definitions].

4.1.1 Dynamical Time (or "Ephemeris Time")

Despite being somewhat misleading (and in a strict sense, incorrect), the words "Ephemeris Time" and the acronym "ET", as used by the present-day mission analyst, generally refers to the independent variable in the equations of motion governing the major bodies of the solar system. This time scale, referred to as T_{eph} in Reference 23, represents a smooth-flowing, coordinate time that is used in the development of the numerically integrated solar system ephemerides produced at JPL and distributed worldwide.

Over the years, a number of different types of dynamical times have been incorrectly assumed to be equivalent to T_{eph}. Reference 23 describes a few of the more common misconceptions and illustrates the differences between T_{eph} and these other time systems. For example:

- As initially defined in the 1960's, Ephemeris Time (ET) was the independent variable of the (then) existing *analytic* planetary and lunar theories. As a result, ET is subject to the inadequacies of those analytical theories and is not exactly equivalent to T_{eph}.
- Later in the 1970's, another pair of dynamical time systems was defined: A geocentric based time scale initially called TDT for Terrestrial Dynamical Time, but later renamed TT for Terrestrial Time and a solar system barycentric based time scale called TDB for Barycentric Dynamical Time. TDB was defined to differ from TT by only periodic terms, but this yields a time scale which is physically impossible [23].

Thus, while T_{eph} is approximately equal to ET and TDB, it is not exactly equal to either one. Reference 23 characterizes T_{eph} as being "what ET and TDB were intended to be".

- Finally, in 1991, in an attempt to clarify relationships between space-time coordinates, the IAU defined another solar system barycentric based time scale called TCB for Barycentric Coordinate Time. IERS 2003 (Reference 3) recommends the use of the TCB time scale.

Reference 23 states that "T_{eph} is mathematically and physically equivalent to the newly-defined TCB, differing from it by only an offset and a constant rate". The TCB time scale, however, is not used at JPL – nor is it used by most astronomers. At least for the present, it should be ignored.

All of the Section 343 software is based upon and internally uses T_{eph}, but unfortunately, due to past history, still uses the label "ET" in all output to refer to the uniform measure of time in the equations of motion (for spacecraft and planetary bodies). As a result, this document will also continue to use the label "ET" despite the fact that it's not technically correct. Strangely enough, this is done to avoid further confusion that would be introduced by changing the name here.

4.1.2 International Atomic Time

Temps Atomique International (TAI) or International Atomic Time is defined as a continuous time scale resulting from a statistical analysis by the Bureau International des Poids et Mesures (BIPM) of a large number of atomic clocks operating around the world. An atomic clock uses the oscillations of an undisturbed cesium atom to measure the passage of time. A specific number of oscillations is used to define the fundamental unit of time (the second) in the SI (Système International) system. The value of TT - TAI was set to a fixed value of 32.184 seconds on January 1, 1958.

[Note: TT – TAI = 32.184 seconds; T_{eph} (often called "ET") = TT + relativistic terms; thus, "ET" – TAI = 32.184 + relativistic terms, where | relativistic terms | < 2 ms].

4.1.3 Universal Time

Universal Time (UT) is a time scale whose unit of duration is based upon the mean solar day.

<u>UT1</u>

UT1 represents the daily rotation of the Earth, independent of the observing location (i.e. including corrections for polar motion on the longitude of the observing site). Since the Earth's rotation rate is somewhat irregular and unpredictable, UT1 is deduced from the combination of a variety of different types of observations (including Very Long Baseline Interferometry (VLBI) measurements of extragalactic radio sources (quasars), lunar laser ranging (LLR), satellite laser ranging (SLR), and global positioning system (GPS) measurements – to name a few).

4.1.4 Coordinated Universal Time

Coordinated Universal Time (UTC) is the basis for the worldwide system of civil timekeeping and is available from radio broadcast signals. It is the time system used by flight operations teams and tracking stations. UTC was set equal to TAI in 1958 and is adjusted with leap seconds so that it remains within 0.9 seconds of UT1.

4.1.5 Difference between ET and UTC

"ET", as referred to in Sections 4.1.1 and 4.1.2, is currently 64.184 seconds (excluding periodic relativistic terms) ahead of UTC, as it has been since January 1, 1999. From the previous definitions this difference consists of two parts. ET-TAI = 32.184 seconds (excluding relativistic terms) and currently (in 2005) TAI-UTC = 32.0 (leap) seconds. According to the IERS Bulletin C (current Leap Seconds Announcement) "A positive leap second will be introduced at the end of December 2005". Bulletin C is available at the U. S. Naval Observatory (USNO) internet website (*http://maia.usno.navy.mil/*). It is updated approximately six months in advance of leap second opportunities that occur at the end of June and December.

4.2 Lunar Time Systems

For a spacecraft in orbit about the Moon or on the surface of the Moon, it is often more convenient to keep track of events using a time system associated with the time of day on the Moon rather than the time of day on Earth. Since the word "day" is usually associated with a mean solar day, a day on the Moon – or a mean lunar day – is defined to be the mean interval of time between successive crossings of the Sun on a particular lunar longitude (e.g. the lunar prime meridian). As a result, the period of one mean lunar day is equal to the period of a mean synodic lunar month.

	Duration (Earth days)	Duration (days	hrs	min	sec)
Mean Lunar Day (mean synodic lunar month)	29.53059	29	12	44	03

[Note: Due to the eccentricity of the Earth's orbit and small periodic variations in the Moon's rotation rate, the duration of an actual lunar day (associated with a given location on the Moon) can vary by nearly ± 2 hours from the mean value quoted above over the course of a year].

4.2.1 Local True Solar Time

Local true solar time (LTST) on the Moon is defined as follows:

$$\text{LTST} = \left(\lambda_{P} - \lambda_{TS}\ \text{deg}\right)\frac{24\ \text{hr}}{360\ \text{deg}} + 12\ \text{hr}$$

where, in the simplest case, λ_P is the East longitude of a point P on the surface of the Moon and λ_{TS} is the East longitude of the true Sun (see Figure 4-1). The equation above converts the difference in angles from degrees to true solar hours, with 12 hours representing the time that the true Sun crosses the meridian containing the point P (local noon). The conventional method for computing LTST is to determine λ_{TS} from the planetary ephemeris file.

[Note: The choice of the reference vector within the lunar equatorial plane from which λ_P and λ_{TS} are measured is somewhat arbitrary, since only the angular difference between the point P and the true Sun is important. Thus, while the lunar prime meridian is an obvious (and perhaps the simplest) choice for the reference vector, it is not the only choice. For example, the X-axis in a Moon-centered, IAU-defined coordinate system (i.e. the Moon IAU-Node of Epoch) works equally well. See Note 2 on page 37 in Section 6.1 for a definition of the IAU-defined coordinate system].

[Note: LTST is not a uniform time system. Since LTST is based upon the true motions of the Earth and the Moon, LTST does not progress at a constant rate].

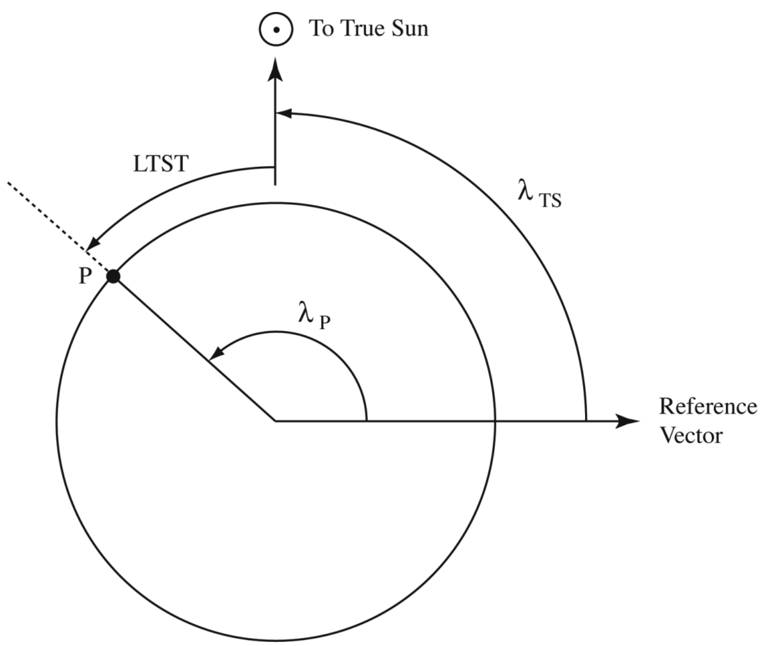

Figure 4-1: Definition of LTST

4.2.2 Orbit Local Solar Time System

During the development and operations of nearly all planetary and satellite orbiting missions, understanding how the geometry of the orbit plane changes relative to the Sun over time is extremely important – from both an engineering and science perspective. A useful way to characterize the orbit geometry, particularly for high inclination orbiters, is to report the local solar time of the ascending or descending node. The convention generally adopted is to report the local time of the orbit node relative to the true Sun.

For an orbit about the Moon that remains essentially inertially fixed in space, the following partial for the change in orbit local solar time (OLST) per unit time can be derived from the mean synodic and sidereal periods of the Moon's orbit.

$$\text{OLST}_{\text{in LTST}} \text{ changes by } -3.94 \frac{\text{minutes}}{\text{Earth day}} = -27.60 \frac{\text{minutes}}{\text{week}} = -1.94 \frac{\text{hours}}{\text{mean lunar day}}$$

[Note: Despite being associated with an orbit about the Moon, the partial quoted above is primarily a function of the rate at which the Earth moves about the Sun. Thus, the partial will change slightly as a function of time due to the eccentricity of the Earth's orbit. For example, each year during the three-year period from 2009-2012, the partial will vary roughly within the following range:

$$\textit{OLST}_{\textit{in LTST}} \textit{ changes by } -4.1 \frac{\text{minutes}}{\text{Earth day}} \textit{ to } -3.8 \frac{\text{minutes}}{\text{Earth day}} \textit{ within 2009-2012]}$$

4.2.3 Surface Local Solar Time System

Due to the basic diurnal nature of mission operations for a surface mission, a landing site or surface local solar time system has to be defined. For lunar surface missions, an appropriate local solar time system to use is LTST.

For an object on the surface of the Moon, the following partial for the change in surface local solar time (SLST) per unit time can be derived from the mean synodic period of the Moon's orbit.

$$\text{SLST}_{\text{in LTST}} \text{ changes by } +48.76 \frac{\text{minutes}}{\text{Earth day}} = +5.69 \frac{\text{hours}}{\text{week}}$$

[Note: The partial quoted above will change slightly as a function of time due to the eccentricity of the Earth's orbit and small periodic variations in the Moon's rotation rate. For example, during the three-year period from 2009-2012, the partial will vary roughly within the following range:

$$\textit{SLST}_{\textit{in LTST}} \textit{ changes by } +48.6 \frac{\text{minutes}}{\text{Earth day}} \textit{ to } +48.9 \frac{\text{minutes}}{\text{Earth day}} \textit{ within 2009-2012}$$

Another point worth noting is the fact that for a given site on the Moon, the time from local noon (i.e. SLST = 12:00:00) to local noon is not exactly equal to the time from new Moon to new Moon. In other words, at each of the new Moon times listed in Table 2-1 in Section 2.4, a slightly different lunar longitude is experiencing local noon].

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5. FUNDAMENTAL CONSTANTS AND PLANETARY / SATELLITE EPHEMERIDES

5.1 Planetary Ephemeris

The planetary ephemeris file that contains the current best lunar ephemeris for general mission and navigation analyses and external export is DE403/LE403 (Developmental Ephemeris 403 / Lunar Ephemeris 403), or more commonly referred to as simply DE403 [24].

[Note: This is not the latest, nor best, ephemeris file to use for the other planets].

The planetary ephemeris file is located on the Section 343 mission design/navigation server ***nexus*** via the path:

/nav/common/import/ephem/de403_2000-2020.nio (.nio format is used with NAV software)
/nav/common/import/ephem/de403_2000-2020.bsp (.bsp format is used with MAS software)

As is indicated in the file name, this particular ephemeris file spans the time period from the year 2000 through the year 2020. Both Linux and Sun versions of the ephemeris files are available. The naming convention for the Sun versions end in the standard "_hp.bsp" or "_hp.nio". The planetary ephemeris file, in all formats, can also be found on afs via the path:

/afs/jpl.nasa.gov/group/mas/ephem/

In afs, the directory identified above has been symbolically linked to /afs/jpl.nasa.gov/group/mas/sec343-data/@sys/ephem such that the proper formatted ephemeris file is accessed using the same filename (i.e. filenames without the "_hp") regardless of which computer platform (e.g. Sun, HP, linux, etc.) is used.

[Note: The DE403 ephemeris file is also available, in its export format, to users outside JPL via the following website: http://ssd/iau-comm4/ . Once at the website, click on "Where to Obtain Ephemerides". Then read the README file in the section titled "Modern High-Accuracy Ephemerides". To construct a DE403 ephemeris file that covers the years from 2000 to 2025, download the ASCII file ascp2000.403 from the ftp site and follow the instructions].

The gravitational parameters of the Sun and planets that are used by DE403 are:

Body	GM (km^3/s^2)	
Sun	132712440017.987	
Mercury	22032.080486	
Venus	324858.598826	
Earth	398600.435608	
Mars*	42828.314258	
Jupiter*	126712767.857796	
Saturn*	37940626.061137	
Uranus*	5794549.007072	
Neptune*	6836534.063879	
Pluto*	981.600888	
Moon	4902.799108	- See Section 2.1 for a discussion on current best estimate of the lunar GM.

- All GMs are consistent with a solar system barycentric reference frame.

* Includes the gravitational parameters of the planet's satellites.

[Note: The JPL planetary ephemerides are developed in a solar system barycentric reference frame].

The following constants were assumed / derived in the development of DE403.

c	≐ 299792.458 km/s	(Speed of light, defined quantity)
AU	= 149597870.691 km	(Astronomical Unit, solved for quantity in the development of DE403)

5.2 Satellite Ephemeris

Since the lunar ephemeris is contained within the DE403 planetary ephemeris file, no separate satellite ephemeris file is needed.

5.3 Solar Constant

The total solar irradiance at 1 AU, which is used for computing the solar radiation force on a spacecraft, is specified in Reference 25.

$F1_{AU}$ = 1366.1 W/m^2 (Solar constant; total solar irradiance at 1 AU)

6. COORDINATE SYSTEMS

6.1 Coordinate Systems

This section contains a description of a few of the more common coordinate systems used in lunar mission analysis to convey or communicate states from one user or application to another. The descriptions are largely based upon the terminology and conventions used in the Mission Analysis Software Library (MASL) (and, in particular, in the QUICK program) developed at JPL over the past several decades. The first portion of the text is a brief review of the relevant nomenclature, and more importantly, how some of the basic terms will be used or interpreted in this section.

Coordinate System Attributes

In general, three fundamental (and independent) attributes are needed to fully specify a "coordinate system" (as used by the mission analyst to describe a trajectory state and relate points in three dimensional space). They are:

- a coordinate frame (e.g. EME2000),
- a coordinate center (e.g. Earth-centered), and
- a coordinate type (e.g. a 6-vector representation of a trajectory state, such as a cartesian state vector).

(Note that for this discussion, the specification of the epoch of the coordinate frame and the epoch of the state vector is included as part of the specification of the above quantities).

Of the three attributes of listed above, the coordinate frame is usually the one that requires the most effort to precisely define. As a result, the primary purpose of this section, despite being titled "Coordinate Systems", is really to provide a detailed description of a number of different coordinate frames. Throughout this section, the description of a particular coordinate system includes a reasonable selection of the coordinate center and coordinate type, but those selections are mainly to facilitate a description of the coordinate frame and should not be interpreted as the only possible choices.

The coordinate system descriptions in this section include the standard MASL IORB flag designations – which uniquely represents a coordinate frame and a coordinate system type, but not a coordinate system center. Similarly, another descriptive term used in this section, the "coordinate system label", specifies the coordinate frame and coordinate center, but not the coordinate system type.

[Note: For a detailed description of MASL IORB flags see the following website http://eis.jpl.nasa.gov/mas/GROUP/software/misc/iorb.html .

For a detailed description of the coordinate frames used in MASL see the following website http://eis.jpl.nasa.gov/afs/jpl.nasa.gov/group/mas/documents/masl/coords.html

The MASL body numbers for the Sun, the Earth, and the Moon are 0, 3, and 103 respectively].

Inertial vs Non-Rotating

In a strict sense, the word "inertial", when used to describe a coordinate system, means that that coordinate system is unaccelerated. Thus, the only truly unaccelerated coordinate system in our solar system is a non-rotating coordinate frame centered at the solar system barycenter. For a variety of reasons, however, the words "inertial coordinate system" are often used to describe what is technically just a "non-rotating coordinate system". Thus, as a (perhaps unpleasant) compromise to technical accuracy, but without totally ignoring the conventions used by most readers, this document will label the non-rotating coordinate frames, wherever they are centered, as "non-rotating / "inertial" " (with the word inertial in quotes).

MASL/QUICK Conventions

While there are approximately 85 different coordinate frames automatically defined and available within MASL (and within the QUICK program), all of them, by necessity, are either rotating or non-rotating coordinate frames. The non-rotating (or "inertial") coordinate frames are defined by taking a "snapshot" of the orientation of a particular set of orthogonal axes at a specific epoch or time. In other words, the non-rotating coordinate frame, however it is defined, is frozen or fixed at a specific time – for all time. In MASL, these non-rotating coordinate frames are referred to as "*of Epoch*" or "*of Instant*" (or just "inertial") coordinate frames.

The snapshot taken to define the orientation of a set of axes for the "*of Epoch*" frame is taken at the initial epoch (or time), while the snapshot taken to define the "*of Instant*" frame is taken at a "delta-time" from the initial epoch – the delta-time being specified by the user. Thus, for an "*of Instant*" frame, if any parameter or set of parameters (e.g. a state vector) is computed at a delta-time from the initial epoch, then the snapshot to define the orientation of the non-rotating coordinate frame is taken at that time.

For rotating coordinate frames, the same concept of a "snapshot" taken at a specific time is used to define the orientation of a set of axes, but in this case the frame rotates about the instantaneous spin axis of the coordinate frame at a rate consistent with the definition of the rotating frame. Thus, at any time specified by the user (implemented in MASL as the same "delta-time from initial epoch" as described above), the orientation of the frame, orientation of the spin vector, and rotation rate of the frame are re-evaluated. The rotating coordinate frames are referred to as "*Body-fixed*" or "*Rotating*" – depending on the particular coordinate frame.

Coordinate System Label	MASL IORB Flag	Coordinate System Description
E-EME2000	152	Earth-Centered, Earth Mean Equator and Equinox of J2000 (cartesian) (non-rotating / "inertial") (see Figure 6-1)

[Note: The celestial reference frame used for the development of the DE403 ephemeris is the International Celestial Reference Frame (ICRF) maintained by the International Earth Rotation and Reference Systems Service (IERS). The EME2000 coordinate frame is often assumed to be identical to the ICRF, however, Reference 26 indicates that the pole of the EME2000 frame differs from the ICRF pole by ~18 milliarcseconds (mas) and the right ascension of the EME2000 X-axis differs from the right ascension of ICRF X-axis by 78 mas].

Coordinate System Label	MASL IORB Flag	Coordinate System Description
M-MEIAUE	-172	Moon-Centered, Moon Mean Equator and IAU-Node of Epoch (cartesian)[1,2] (non-rotating / "inertial") (see Figure 6-2)
M-MEIAUE	-1040073 (incoming) -1140073 (outgoing)	Moon-Centered, Moon Mean Equator and IAU-Node of Epoch (hyperbolic asymptote)[1,2] (non-rotating / "inertial") The six elements of the hyperbolic state vector expressed relative to the B-plane coordinate system are: 1. Radius (km) of spacecraft from the center of the Moon 2. B-plane angle θ (deg) with respect to the Moon equator 3. Inertial flight path angle (deg) 4. V_∞ magnitude (km/s) 5. Declination of the V_∞ vector (deg) with respect to the Moon equator 6. Right ascension of the V_∞ vector (deg) with respect to the Moon IAU-Node of Epoch The B-plane coordinate system is illustrated in Figure 6-3. *[Note: The use of the B-plane is generally not valid at Earth for missions returning to Earth from the Moon, since the return trajectories are generally not hyperbolic].*

Notes:

1) The use of the phrase "Moon Mean Equator" in the Moon-centered coordinate system descriptions is not technically accurate, since there really isn't a "mean" equator for the Moon, but it is used here to be consistent with the terminology used in the MASL software. However, the "M" for "mean" is left out of the coordinate system label.

2) Following IAU/IAG conventions, the reference X-axis in an IAU-Node of Epoch coordinate system is defined as the cross product of the Earth's mean rotational pole of J2000 with the body's (in this case, the Moon's) rotational north pole at the desired time (i.e. "of Epoch").

   [Note: It's important to realize that, as defined above, the orientation of the IAU/IAG defined coordinate frame changes slowly over time. This is due to the fact that the Moon's north pole rotates on a cone (with a half cone-angle of about 1.54 degrees) about the ecliptic north pole with a period of 18.6 years. Note also that to a very high degree of accuracy the lunar orbit pole, the ecliptic north pole, and the Moon's physical north pole always lie in the same plane. This attribute or characteristic is referred to as Cassini's Third Law.

   From a MASL perspective, as described earlier, Moon Mean Equator and IAU-Node of Epoch coordinate frame is a non-rotating ("inertial") coordinate frame. This just means that a "snapshot" of this coordinate frame taken at one time will be oriented in space differently than a snapshot taken at another time].

There are three slightly different Moon-centered, prime meridian-based coordinate systems that may be of interest – two are non-rotating ("inertial") coordinate systems and one is a body-fixed, rotating coordinate system. In all cases, the X-axis of the coordinate frame is pointed in the direction of the Moon's prime meridian and the Z-axis is pointed in the direction of the Moon's north pole. The prime meridian is defined with respect to the Moon IAU-Node by the relationship in Section 2.2 (see Figure 6-4). The type of coordinate frame follows the MASL conventions described earlier (i.e. "*of Epoch*", "*of Instant*", or "*Body-fixed*"). The coordinate systems have slightly different IORB flags.

Coordinate System Label	MASL IORB Flag	Coordinate System Description
M-MEPME	132	Moon-Centered, Moon Mean Equator and Prime Meridian *of Epoch* (cartesian) (non-rotating / "inertial")
M-MEPMI	100000132	Moon-Centered, Moon Mean Equator and Prime Meridian *of Instant* (cartesian) (non-rotating / "inertial")
M-MEPMD	142	Moon-Centered, Moon Mean Equator and Prime Meridian *Body-fixed* (previously referred to as *of Date*) (cartesian) (rotating)

The Moon-centered coordinate systems indicated previously are primarily used when operating in close proximity to the Moon. There are, however, a few additional coordinate systems that are also useful when analyzing trajectories in the vicinity of the Earth-Moon system. They are rotating coordinate systems associated with two different three-body systems: the Sun-Earth-spacecraft system and the Earth-Moon-spacecraft system. (See Section 2.4.1 for a discussion of the Lagrange points associated with these two three-body systems).

The Sun-Earth and Earth-Moon rotating coordinate systems are defined as follows. The pole vector or Z-axis of the coordinate frame is set equal to the instantaneous orbit normal of the secondary (smaller) body about the primary (larger) body and the X-axis is set equal to the vector from the primary body to the secondary body. The X-axis rotates at a rate equal to the rotation of the secondary body about the primary body.

The Sun-Earth and Earth-Moon rotating coordinate systems are available in the MASL software via the selection of a particular IORB flag in conjunction with an earlier call to a routine (BTRGRF) that sets the primary (reference) and secondary (target) bodies of the rotating system. This means that the same IORB flag is used to refer to either the Sun-Earth or Earth-Moon rotating coordinate system, depending on which bodies are set as the primary and secondary bodies of the rotating system.

Coordinate System Label	MASL IORB Flag	Coordinate System Description
(Non-unique: e.g. SE-ROT, EM-ROT)	600000172	Target body orbit plane and position vector with respect to reference body (cartesian) (rotating) Examples are Sun-Earth rotating and Earth-Moon rotating

[Note: Either of these two rotating coordinate systems (i.e. the Sun-Earth or Earth-Moon rotating coordinate system) can be used independent of the current central body of an input spacecraft trajectory (e.g. a Moon-centered state can be expressed in a Sun-Earth rotating coordinate frame)].

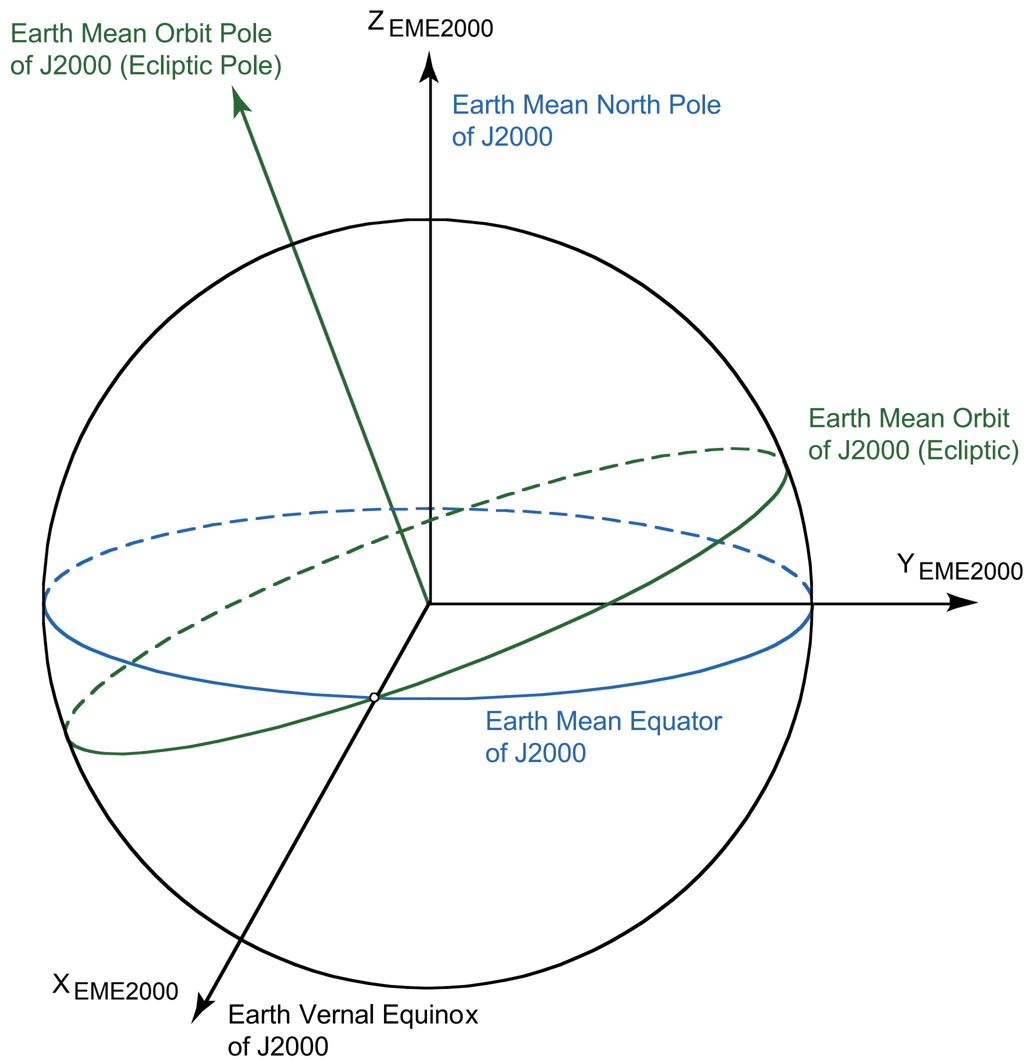


Figure 6-1: Earth-Centered, Earth Mean Equator and Equinox of J2000 (E-EME2000) (Non-Rotating / "Inertial")

[Note: Specification of the coordinate center is not needed to define the EME2000 coordinate frame].

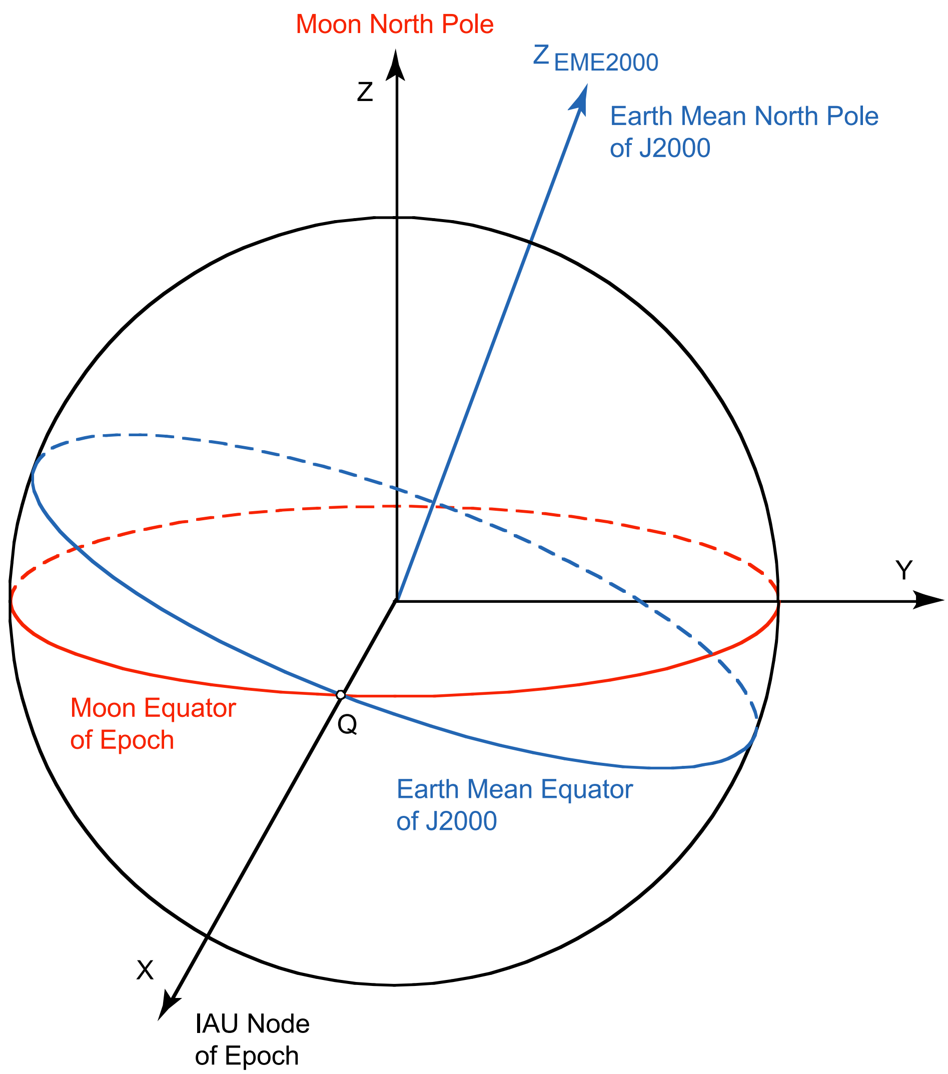
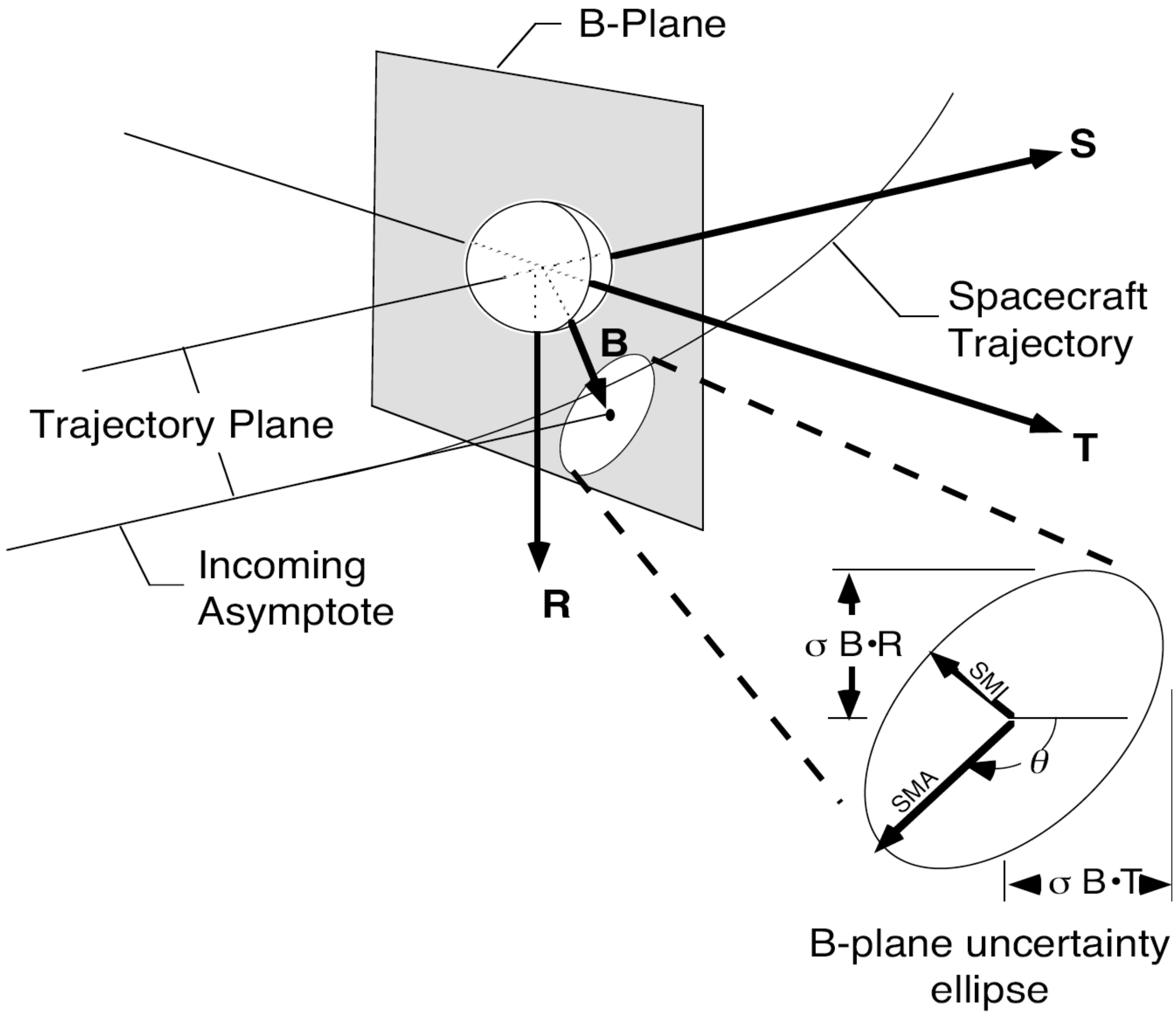


Figure 6-2: Moon-Centered, Moon Mean Equator and IAU-Node of Epoch (M-MEIAUE) (Non-Rotating / "Inertial" – see Note 2 on page 37)

[Note: Specification of the coordinate center is not needed to define the MEIAUE coordinate frame].



$\hat{S} \equiv$ Parallel to incoming asymptote, $\hat{V}_\infty$

$\hat{T} = \hat{V}_\infty \times POLE_{ME} \equiv$ Parallel to Moon equatorial plane

$\hat{R} = \hat{S} \times \hat{T}$

Figure 6-3: B-Plane Coordinate System

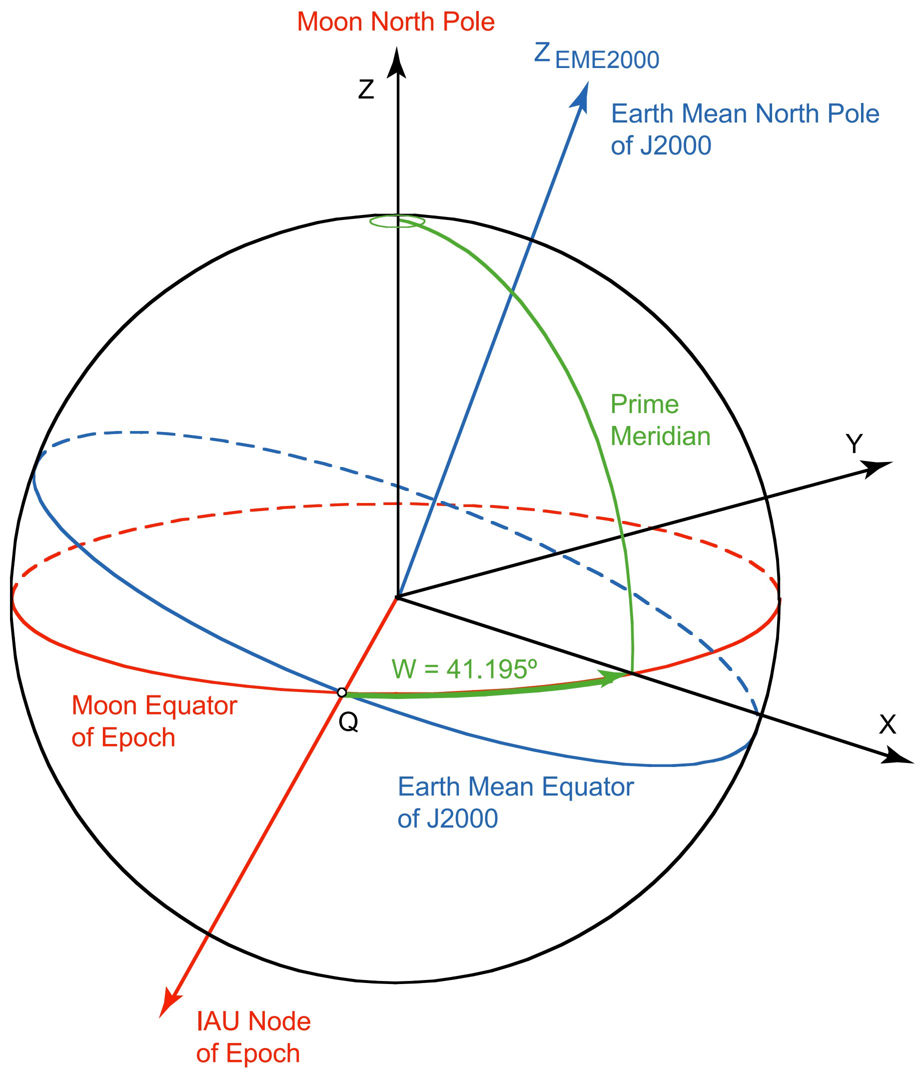


Figure 6-4: Moon-Centered, Moon Mean Equator and Prime Meridian (shown at J2000 Epoch)

Three possible versions: *of Epoch* (M-MEPME) (Non-Rotating / "Inertial")
***of Instant* (M-MEPMI) (Non-Rotating / "Inertial")**
***Body-fixed* (previously *of Date*) (M-MEPMD) (Rotating)**

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APPENDIX A. LUNAR MAPS

A.1 Global Lunar Maps

Many different types of global lunar maps have been produced over the past 30-40 years. The following represent just a few of the maps that one might find useful.

A.1.1 Lunar Near-Side

Miscellaneous Investigations Series, Map I-2276, Scale 1:5M, Published in 1992 by USGS

- Sheet 1: Shaded Relief and Surface Markings Map of the Lunar Near Side
- Sheet 2: Shaded Relief Map of the Lunar Near Side
  (Mercator map projections)

Copies of these maps were provided by the Lunar and Planetary Institute (LPI) in Houston, Texas. The maps are located on the Section 343 mission design/navigation server ***nexus*** via the path:

/nav/common/import/maps/Moon/

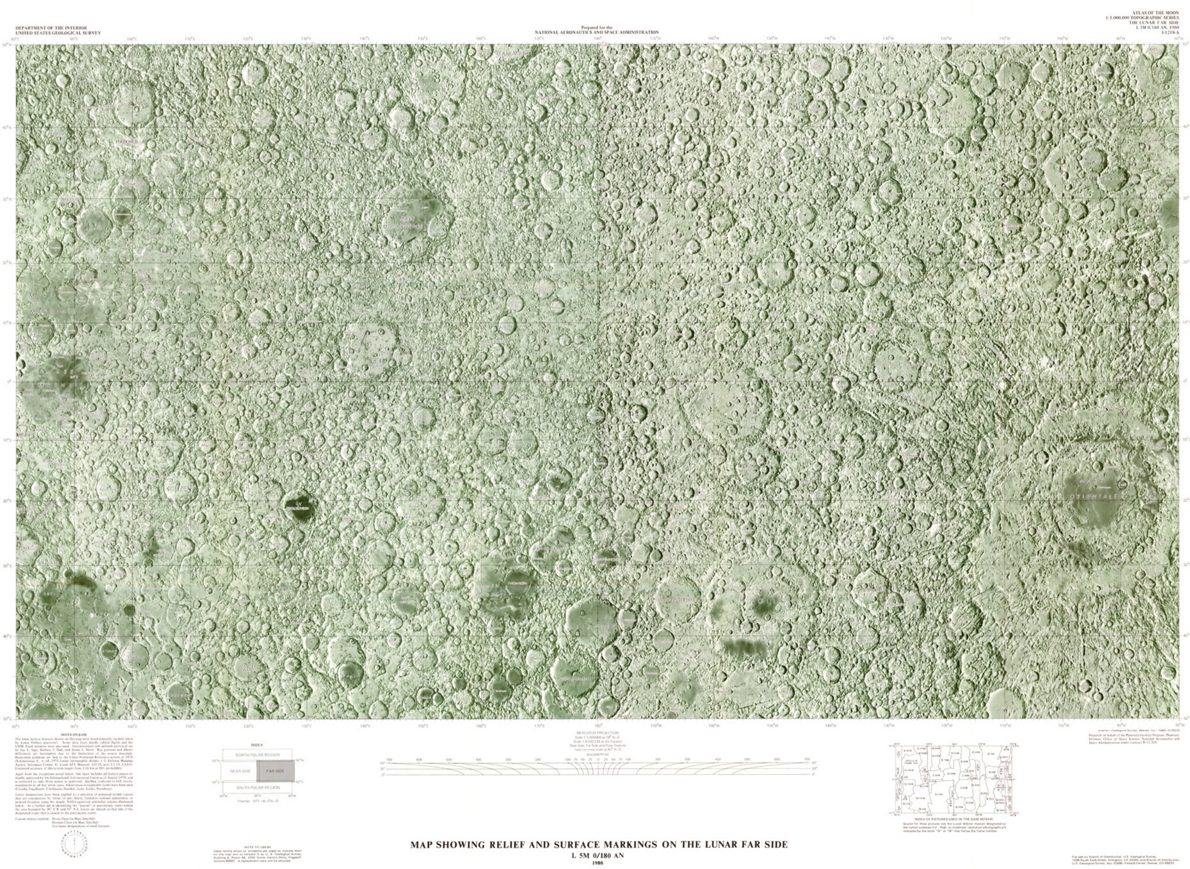
A.1.2 Lunar Far-Side

Miscellaneous Investigations Series, Map I-1218, Scale 1:5M, Published in 1980 by USGS

- I-1218A: Shaded Relief and Surface Markings Map of the Lunar Far Side
- I-1218B: Shaded Relief Map of the Lunar Far Side
  (Mercator map projections)

Copies of these maps were provided by the Lunar and Planetary Institute (LPI) in Houston, Texas. The maps are located on the Section 343 mission design/navigation server ***nexus*** via the path:

/nav/common/import/maps/Moon/



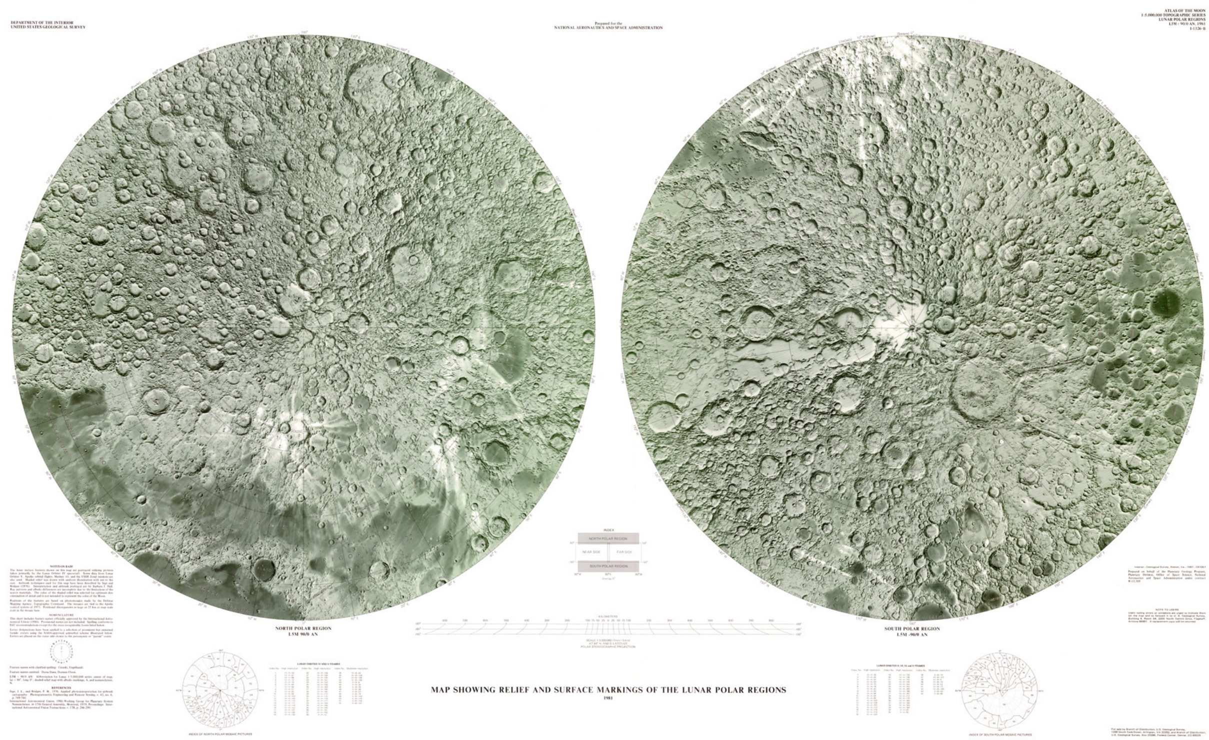
A.1.3 Lunar Polar Regions

Miscellaneous Investigations Series, Map I-1326, Scale 1:5M, Published in 1981 by USGS

- I-1326A: Shaded Relief Map of the Lunar Polar Regions
- I-1326B: Shaded Relief and Surface Markings Map of the Lunar Polar Regions
  (Polar Stereographic map projections)

Copies of these maps were provided by the Lunar and Planetary Institute (LPI) in Houston, Texas. The maps are located on the Section 343 mission design/navigation server ***nexus*** via the path:

/nav/common/import/maps/Moon/



A.1.4 Color-Coded Topography and Shaded Relief Maps of the Lunar Hemispheres

Geologic Investigations Series I-2769, Scale 1:10M, Published by the USGS in 2002

- Sheet 1: Lunar Near Side and Far Side Hemispheres – (see Figures 2-9 and 2-10)
- Sheet 2: Lunar East and West Hemispheres
- Sheet 3: Lunar North and South Hemispheres
  (Lambert-Azimuthal Equal Area map projections)

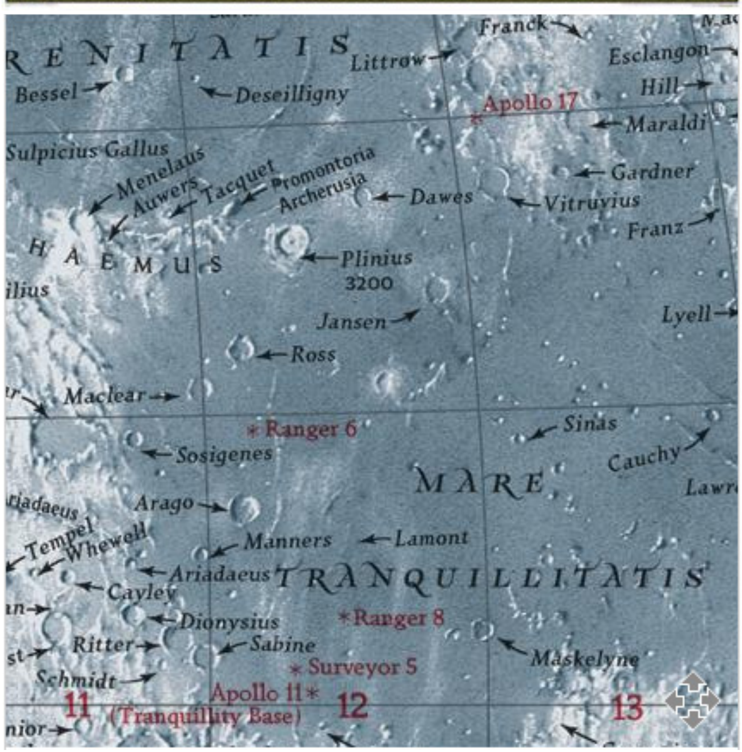
The maps can be found at the following website: http://geopubs.wr.usgs.gov/i-map/i2769/

The maps are also located on the Section 343 mission design/navigation server ***nexus*** via the path:

/nav/common/import/maps/Moon/

A.1.5 Online Lunar Map Wall Poster

Many commercial companies have marketed the sale of lunar maps in the form of wall posters. While not endorsing the purchase of any particular map, one lunar map wall poster, produced by The National Geographic Society (NGS), is worth mentioning since the map is essentially available online. The NGS map is copyright-protected, but a "browse-able" version of the map can be found at the following NGS website: http://www.ngmapstore.com/shopping/product/zoom.jsp?iProductID=111 . With "zoom" and "scroll" capability, the entire map can be viewed at a high resolution. The map is a shaded relief map with surface markings and is depicted using a Lambert-Azimuthal Equal Area projection. The map also indicates the landing site locations of many lunar missions. The following images are example "screen shots" from the National Geographic Society website.



APPENDIX B. LUNAR EXPLORATION

B.1 Lunar Exploration Mission Summary *(for missions that have reached the lunar surface)*

The majority of the data presented in this section were extracted from the Lunar Exploration Timeline compiled by the NASA National Space Science Data Center (NSSDC) [27]. The list of missions summarized in Appendix B only includes those missions that are known to have (or possibly have) deposited terrestrial material (whether intended or not) onto the surface of the Moon. This includes lunar orbiters whose orbit lifetimes have (or are believed to have) expired (i.e. the orbiters crashed into the surface of the Moon). Some of the data and descriptive text presented in this section were augmented by data and text from References 28 and 29.

B.1.1 Soviet Luna Probes

The Luna series of unmanned probes included the first to fly by the Moon and photograph the far-side of the Moon, the first to impact the Moon, the first to soft land and return photographs, the first robotic sample return (which occurred after the manned Apollo 11 and Apollo 12 had already returned their lunar samples), and the first to deploy a remotely-controlled rover.

Mission	Mission Type	Launch Date	Remarks
Luna 2	Impact	12 Sep 1959	First spacecraft to reach another celestial body.
Luna 5	Lander	9 May 1965	First soft landing attempt. Lost attitude 40 km from the Moon.
Luna 7	Lander	4 Oct 1965	Lost attitude prior to retrorocket ignition – ignition aborted.
Luna 8	Lander	3 Dec 1965	Entered uncontrolled spin – retrorocket burn prematurely terminated.
Luna 9	Lander	31 Jan 1966	First successful soft landing.
Luna 10	Orbiter	31 Mar 1966	First orbiter. Initial period 178.05 min, Inclination 21.9 deg, Eccentricity 0.14, Operated for 460 orbits.
Luna 11	Orbiter	24 Aug 1966	Initial period 178 min, Inclination 27 deg, Eccentricity 0.22, Operated for 277 orbits.
Luna 12	Orbiter	22 Oct 1966	Initial period 205 min, Inclination 4 deg, Eccentricity 0.31, Operated for 602 orbits.
Luna 13	Lander	21 Dec 1966	Transmitted panoramic views of lunar landscape.
Luna 14	Orbiter	7 Apr 1968	Initial period 160 min, Inclination 42 deg, Eccentricity 0.16 .
Luna 15	Sample Return	13 Jul 1969	First sample return attempt. Completed 52 orbits. Lost signal upon impact after descent burn – while Apollo 11 Lunar Module (Eagle) was on the surface.
Luna 16	Sample Return	12 Sep 1970	First successful robotic lunar sample return. Landed in darkness. 101 g returned to Earth on 24 Sep 1970.
Luna 17	Rover	10 Nov 1970	Lunokhod 1 rover traveled 10.5 km and survived 11 months.
Luna 18	Lander	2 Sep 1971	Completed 54 orbits. Lost signal upon impact after descent burn.
Luna 19	Orbiter	28 Sep 1971	Initial period 121.13 min, Inclination 40.6 deg, Eccentricity 0.18 .
Luna 20	Sample Return	14 Feb 1972	Landed approximately 120 km from where Luna 16 landed. 30 g of lunar material returned to Earth on 25 Feb 1972.
Luna 21	Rover	8 Jan 1973	Lunokhod 2 rover traveled 37 km and survived about 4 months.
Luna 22	Orbiter	29 May 1974	Period 192 min, Inclination 21 deg, Eccentricity 0.279 (final orbit).
Luna 23	Sample Return	28 Oct 1974	Spacecraft damaged during landing. Survived 3 days. No samples returned.
Luna 24	Sample Return	9 Aug 1976	Landed a few hundred meters from Luna 23. 170 g of lunar material returned to Earth on 22 Aug 1976.

B.1.2 U.S. Ranger Probes

The Ranger series included both probes which impacted the Moon at high velocity, returning images with increasing resolution up to the moment of impact, and "hard landers" which fired a braking motor at the last moment, dropping an instrument package protected by a balsa wood spherical shock absorber. The early Ranger missions were plagued by problems – the first successful mission was Ranger 7 in 1964. None of the hard landers succeeded. The three successful missions were all imaging impact probes. Ranger 8 flew a direct-in trajectory toward Mare Tranquillitatis, the Sea of Tranquility, providing the first close-up views which indicated the surface was smooth enough for the Apollo Lunar Module to land there.

Mission	Mission Type	Launch Date	Remarks
Ranger 4	Impact	23 Apr 1962	Computer failure, no telemetry received. Impacted far-side of Moon.
Ranger 6	Impact/Photo	30 Jan 1964	Camera system failure. No images returned.
Ranger 7	Impact/Photo	28 Jul 1964	Transmitted 4,308 photographs over the final 17 minutes of flight.
Ranger 8	Impact/Photo	17 Feb 1965	Transmitted 7,137 photographs over the final 23 minutes of flight.
Ranger 9	Impact/Photo	21 Mar 1965	Transmitted 5,814 photographs over the final 19 minutes of flight.

B.1.3 U.S. Surveyor Landers

The Surveyor soft landers proved the lunar surface was sufficiently flat and strong to allow the Apollo Lunar Module to land. (Prior to the soft landings by Luna 9 and Surveyor 1 in 1966, some believed that the Moon was covered by a deep sea of dust which would be unable to support the weight of a lander – i.e. any landed vehicle would sink beneath the surface.) The Surveyor probes were equipped with steerable cameras which provided panoramic views of their landing sites. Later Surveyors carried a robotic scoop which could excavate soil, move rocks, and deposit soil into instruments for analysis, which provided the first in-situ data about the composition of the lunar regolith.

Mission	Mission Type	Launch Date	Remarks
Surveyor 1	Lander	30 May 1966	Operated until 7 Jul 1966. No operation during lunar night.
Surveyor 2	Lander	20 Sep 1966	One of three vernier engines failed to ignite during a mid-course maneuver. Impacted the Moon.
Surveyor 3	Lander	17 Apr 1967	Vernier engines continued to fire during landing - spacecraft lifted off the surface twice before engines finally shut down.
Surveyor 4	Lander	14 Jul 1967	Lost contact approximately 2.5 minutes before touchdown. Landing could have been successful.
Surveyor 5	Lander	8 Sep 1967	First in-situ chemical soil analysis. Operated until 17 Dec 1967. No operation during lunar night.
Surveyor 6	Lander	7 Nov 1967	Spacecraft engines were restarted after landing lifting the vehicle about 4 m off the ground and coming down about 2.4 m from the original landing site.
Surveyor 7	Lander	7 Jan 1968	Operated 80 hours past sunset on first lunar day. Operated until 21 Feb 1968.

B.1.4 U.S. Lunar Orbiters

The Lunar Orbiter program consisted of five Lunar Orbiters which returned photography over 99% of the lunar surface (near and far-side) with a resolution, in some images, down to 1 meter. All together the Orbiters returned 2180 high resolution and 882 medium resolution frames. The micrometeoroid experiments recorded 22 impacts showing the average micrometeoroid flux near the Moon was about two orders of magnitude greater than in interplanetary space but slightly less than the near-Earth environment. The radiation experiments confirmed that the design of Apollo hardware would protect the astronauts from average and greater-than-average short-term exposure to solar particle events. The Lunar Orbiters were all eventually commanded to crash on the Moon before their attitude control gas ran out so they would not present navigational or communications hazards to later Apollo flights.

Mission	Mission Type	Launch Date	Remarks
Lunar Orb 1	Orbiter	10 Aug 1966	Initial period 208.1 min, Inclination 12 deg, Eccentricity 0.33 .
Lunar Orb 2	Orbiter	6 Nov 1966	Initial period 208.07 min, Inclination 11.9 deg, Eccentricity 0.35 .
Lunar Orb 3	Orbiter	5 Feb 1967	Initial period 208.1 min, Inclination 20.9 deg, Eccentricity 0.33 .
Lunar Orb 4	Orbiter	4 May 1967	Initial period 721 min, Inclination 85.5 deg, Eccentricity 0.28 .
Lunar Orb 5	Orbiter	1 Aug 1967	Initial period 510.08 min, Inclination 85 deg, Eccentricity 0.26 .

B.1.5 U.S. Apollo Manned Lunar Landings

The Apollo manned lunar landings returned more than 380 kilograms of samples from a variety of lunar terrain types and emplaced instrument packages which performed measurements long after the astronauts had left. Seismometers allowed studying the lunar interior, both from response to natural moonquakes and impacts from spent Saturn IV-B stages (that boosted the Apollo spacecraft to the Moon) and Lunar Module ascent stages (jettisoned in lunar orbit) that were deliberately crashed into the Moon. Laser retroreflectors left by Apollo missions remain in use today, providing data for research in topics ranging from dynamics of the Earth-Moon system to tests of general relativity.

Mission	Mission Type	Launch Date	Remarks
Apollo 11	Manned/Lander	16 Jul 1969	First humans to step foot onto another celestial body. EVA 2.53 hrs. Traverse distance 250 m. Sample return 21.7 kg.
Apollo 12	Manned/Lander	14 Nov 1969	Apollo 12 landed within walking distance of Surveyor 3. The Ascent Stage of the Lunar Module was intentionally crashed into the Moon creating the first recorded artificial moonquake. EVA 7.75 hrs. Traverse distance 1.35 km. Sample return 34.4 kg.
Apollo 14	Manned/Lander	31 Jan 1971	EVA 9.38 hrs. Traverse distance 3.45 km. Sample return 42.9 kg.
Apollo 15	Manned/Lander	26 Jul 1971	The Lunar Roving Vehicle explored regions within 5 km of the landing site. A scientific sub-satellite was deployed from the Service Module in lunar orbit. EVA 19.13 hrs. Traverse distance 27.9 km. Sample return 76.8 kg.
Apollo 16	Manned/Lander	16 Apr 1972	The Lunar Roving Vehicle explored regions within 4.5 km of the landing site. A scientific sub-satellite was deployed from the Service Module into an elliptical orbit with an estimated lifetime of one month. EVA 20.23 hrs. Traverse distance 27 km. Sample return 94.7 kg.
Apollo 17	Manned/Lander	7 Dec 1972	Last mission to carry humans to the Moon. The Lunar Roving Vehicle explored regions within 7.5 km of the landing site. EVA 22.07 hrs. Traverse distance 35 km. Sample return 110.5 kg.

B.1.6 Other Lunar Orbiting Missions

Mission	Mission Type	Launch Date	Remarks
Explorer 35	Orbiter	19 July 1967	U.S. spacecraft also known as IMP-6 for the sixth spacecraft in the Interplanetary Monitoring Platform series.
Explorer 49	Orbiter	4 July 1968	U.S. spacecraft also known as RAE-2 (or RAE-B) for the second spacecraft in the Radio Astronomy Explorer series.
Hiten	Orbiter	24 Jan 1990	Japanese Earth orbiting satellite originally called MUSES-A (MU rocket Space Engineering Satellite) designed primarily to test and verify technologies for future lunar and planetary missions. Included 10 lunar flybys before going into lunar orbit.
Hagoromo	Orbiter		Sub-satellite deployed from Hiten on 18 March 1990.
Lunar Prospector	Orbiter	7 Jan 1998	U.S. spacecraft to study the Moon – the third mission in NASA's Discovery program.

B.2 Terrestrial Objects on the Moon

Table B-1 indicates the impact and landing sites of all of the missions that are known to have deposited terrestrial material on to the surface the Moon. The list includes staged or jettisoned spacecraft hardware (referred to as "mission elements"). Table B-2 provides the locations of the major Apollo mission elements on the surface of the Moon including those deployed by the Apollo astronauts. Table B-3 indicates the locations of the Apollo mission elements that were directed to impact the Moon from either a trans-lunar trajectory or from lunar orbit. This list includes those mission elements left in lunar orbit, but whose orbits are believed to have decayed to the point of impact with the lunar surface. Finally, Table B-4 provides a listing of those missions (and mission elements) known to have been in orbit about the Moon when contact was lost with the spacecraft. The orbits of most (but perhaps not all) of these spacecraft have decayed to the point of impact with the surface of the Moon.

As one might imagine, finding the definitive source for the impact / landing site locations for all of these missions (and mission elements) is extremely difficult – and in some cases, is just impossible. An attempt has been made in each of the tables in this section to indicate the source of the site location information. The majority of data were extracted from References 27 and 29-32. Additional sources were also consulted for comparison and corroboration, but only those sources that were used are listed. Unless another source was deemed superior, the default source for the data in this section was the NASA National Space Science Data Center (NSSDC) website [27].

Table B-1: Impact / Landing Sites for Lunar Missions (and Mission Elements)

Mission Msn Element	Impact / Landing Date (UTC)	Latitude (deg)	East Long. (deg)	Impact / Landing Site Location	Source (Ref. No.)
Luna 2	13 Sep 1959	29.1 [1]	0.0 [1]	Palus Putredinis – Near Autolycus crater	27
Launch vehicle 3rd stage – impact 30 min after Luna 2				Assume same location as Luna 2	27
Ranger 4	26 Apr 1962	-15.5	229.3	Far side of the Moon – Near Ioffe crater	27
Ranger 6	2 Feb 1964	9.33	21.52	Mare Tranquillitatis (Sea of Tranquility)	27
Ranger 7	31 Jul 1964	-10.70	339.33	Near Mare Cognitum (Sea that has become known)	27
Ranger 8	20 Feb 1965	2.71	24.81	Mare Tranquillitatis (Sea of Tranquility)	27
Ranger 9	24 Mar 1965	-12.91	357.62	Alphonsus crater	27
Luna 5	12 May 1965	-31 [2]	352 [2]	Mare Nubium (Sea of Clouds)	29
Luna 7	7 Oct 1965	9	311	Oceanus Procellarum (Ocean of Storms)	29
Two auxiliary modules jettisoned before retrorocket ignition				Assume same location as Luna 7	29
Luna 8	6 Dec 1965	9.13	296.7	Oceanus Procellarum (Ocean of Storms)	29
Two auxiliary modules jettisoned before retrorocket ignition				Assume same location as Luna 8	29
Luna 9	3 Feb 1966	7.13	295.63	Oceanus Procellarum (Ocean of Storms)	29
Two auxiliary modules jettisoned before retrorocket ignition				Assume same location as Luna 9	29
Retrorocket				Assume same location as Luna 9	29
Surveyor 1	02 Jun 1966	-2.44	316.66	Oceanus Procellarum (Ocean of Storms)	32
Retrorocket				Assume same location as Surveyor 1	29
Surveyor 2	23 Sep 1966	5.5	348	Southeast of Copernicus crater	29
Lunar Orb 1	29 Oct 1966	6.7	162	Far-side of the Moon – Mandel'shtam crater	29
Luna 13	24 Dec 1966	18.87	297.95	Oceanus Procellarum (Ocean of Storms)	27
Two auxiliary modules jettisoned before retrorocket ignition				Assume same location as Luna 13	29
Retrorocket				Assume same location as Luna 13	29
Surveyor 3	20 Apr 1967	-3.0159 [3]	336.5822 [3]	Near Oceanus Procellarum (Ocean of Storms)	33
Retrorocket				Assume same location as Surveyor 3	29
Surveyor 4	17 Jul 1967	0.4	358.67	Sinus Medii (Bay of the Center or Central Bay)	29

Table B-1: Impact / Landing Sites for Lunar Missions (and Mission Elements) (continued)

Mission Msn Element	Impact / Landing Date (UTC)	Latitude (deg)	East Long. (deg)	Impact / Landing Site Location	Source (Ref. No.)
Surveyor 5	11 Sep 1967	1.49	23.20	Mare Tranquillitatus (Sea of Tranquility)	32
Retrorocket				Assume same location as Surveyor 5	29
Lunar Orb 3	9 Oct 1967	14.6 [4]	268.3 [4]	Far-side of the Moon – Near Einstein crater	29
Lunar Orb 2	11 Oct 1967	-4 [5]	98 [5]	Far-side of the Moon – South of Wyld crater	29
Lunar Orb 4	~31 Oct 1967	-	330 - 338	*Natural Orbit Decay - Impact Site Unknown*	27
Surveyor 6	10 Nov 1967	0.42	358.62	Sinus Medii (Bay of the Center or Central Bay)	32
Retrorocket				Assume same location as Surveyor 6	29
Surveyor 7	10 Jan 1968	-41.01	348.59	Outer rim of Tycho crater	32
Retrorocket				Assume same location as Surveyor 7	29
Lunar Orb 5	31 Jan 1968	-2.79	277	West of Oceanus Procellarum	27
Apollo 10				*Natural Orbit Decay - Impact Site Unknown* §	29
Apollo 11	20 Jul 1969	0.67	23.47	Mare Tranquillitatus (Sea of Tranquility) §	30
Luna 15	21 Jul 1969	17	60	Mare Crisium (Sea of Crises)	29
Apollo 12	19 Nov 1969	-3.01	336.58	Near Oceanus Procellarum (Ocean of Storms) §	30
Luna 16	20 Sep 1970	-0.68	56.30	Mare Fecunditatis – West of Webb crater	29
Luna 17	17 Nov 1970	38.213 [6]	324.803 [6]	Mare Imbrium (Sea of Showers or Sea of Rains)	34,35
Lunokhod 1 Rover		38.287 [6]	324.810 [6]	See footnote below	34,35
Apollo 14	5 Feb 1971	-3.65	342.53	Near Fra Mauro crater §	30
Apollo 15	30 Jul 1971	26.13	3.63	Palus Putredinis (Marsh of Decay) - Hadley Rille §	30
Luna 18	11 Sep 1971	3.57	56.50	Near Mare Fecunditatis (Sea of Fertility)	27
Luna 20	21 Feb 1972	3.53	56.55	Near Mare Fecunditatis (Sea of Fertility)	29
Apollo 16	21 Apr 1972	-8.97	15.50	Descartes highland region §	30
Apollo 17	11 Dec 1972	20.19	30.77	Near Mare Serenitatis - Taurus Littrow §	30
Luna 21	15 Jan 1973	25.85	30.45	Near Mare Serenitatis (Sea of Serenity)	27
Lunokhod 2 Rover		25.83	30.92	See also Table B-2	30
Luna 23	06 Nov 1974	13	62	Mare Crisium (Sea of Crises)	29
Luna 24	18 Aug 1976	12.75	62.20	Mare Crisium (Sea of Crises)	29
Hiten	10 Apr 1993	-34.3 [7]	55.6 [7]	Near Stevinus crater	27
Lunar Prospector	31 Jul 1999	-87.7	42.0	Crater near South Pole	29

Notes:

- In all cases where retrorockets and additional mission elements (e.g. auxiliary modules) were jettisoned prior to landing, the impact site location of those elements is assumed to be the same as the landing site of the primary mission element (e.g. the lander). This assumption, of course, is not correct, but at the moment no better information is available. For example, the impact site of the Surveyor 3 retrorocket was not seen by the Apollo 12 astronauts when they visited the Surveyor 3 landing site, yet the impact site of the retrorocket is indicated in Table B-1 as having the same landing site coordinates as the Surveyor 3 lander.

1 The impact site of Luna 2 is often quoted within the range 29º-31º in latitude and 359ºE-1ºE in longitude.

2 A few references place the impact site of Luna 5 in Mare Cognitum – near Lansberg crater at –2º, 335ºE.

3 Reference 33 indicates that the Surveyor 3 lander is located 155 m (Az 133º) from the Apollo 12 LM. The location of Surveyor 3 was computed using the Apollo 12 LM coordinates listed in Table B-2.

4 Some references place the impact site of Lunar Orbiter 3 at 14.3º, 262.3ºE.

5 Some references place the impact site of Lunar Orbiter 2 at 3º, 119.1ºE.

6 The landing site coordinates usually quoted for Luna 17 are 38.28º, 325ºE [27]. Reference 34, however, proposes alternate (but unconfirmed) coordinates for Luna 17 and Lunokhod 1 based upon Apollo 15 and Lunokhod 1 images. Reference 35 includes an estimate of the traverse path of the Lunokhod 1 rover relative to the Luna 17 lander. The combination of data in References 34 and 35 produced the locations indicated above.

7 Some references place the impact site of the Hiten orbiter at -34.0º, 55.3ºE.

§ See also Tables B-2 and B-3 for the locations of other Apollo mission elements.

Table B-2: Site Coordinates of Apollo Surface Mission Elements and Lunokhod 2 Rover

Mission / Mission Element	Latitude (deg)	East Longitude (deg)	Radius (km)	Comments	Source (Ref. No.)
Apollo 11					
LRRR	0.67337	23.47293	1735.472		30
PSEP	0.67322	23.47299		Deployed ~5 m SSE of LRRR	27
LM (Eagle)	0.67408	23.47297			30
Apollo 12					
ALSEP	-3.00942	336.57542	1736.014		30
LM (Intrepid)	-3.01239	336.57843			30
Apollo 14					
LRRR	-3.64421	342.52120	1736.335		30
ALSEP	-3.64398	342.52252	1736.343		30
LM (Antares)	-3.64530	342.52864			30
MET	-3.64530	342.52864		Assume same location as LM - photos	
Apollo 15					
LRRR	26.13333	3.62837	1735.476		30
ALSEP	26.13407	3.62981	1735.477		30
LM (Falcon)	26.13222	3.63386			30
LRV	26.13110	3.63972		163 m (102° Az) from LM	37
Apollo 16					
ALSEP	-8.97537	15.49812	1737.453		30
LM (Orion)	-8.97301	15.50019			30
LRV	-8.97292	15.50279		78 m (88° Az) from LM	37
Apollo 17					
ALSEP	20.19209	30.76492	1734.814		30
LM (Challenger)	20.19080	30.77168			30
LRV	20.19043	30.77726		159 m (94° Az) from LM	37
Luna 21 – Lunokhod 2 Rover					
LRRR	25.83223	30.92201	1734.638		30

Notes:

- In this table the list of Apollo artifacts left on the surface of the Moon only includes the major surface mission elements and does not include things like American flags, seismic mortars, discarded items, and personal artifacts (e.g. pictures, plaques, Alan's Shepard's golf balls, etc.).
- Site coordinates are expressed in the IAU/IAG mean Earth / rotation system. See Section 2.2.
- Acronyms

  LRRR: Lunar laser Ranging RetroReflector, PSEP: Passive Seismic Experiment Package

  [Note: The combination of the Apollo 11 LRRR and PSEP were referred to as the EASEP – Early Apollo Scientific Experiment Package].

  LM: Lunar Module (Descent Stage), ALSEP: Apollo Lunar Surface Experiment Package

  MET: Modularized Equipment Transporter, LRV: Lunar Roving Vehicle
- The ALSEP locations in this table really just indicate the location of the antenna on the ALSEP central station. The layout or configuration of ALSEP components on the surface of the Moon differed substantially for each Apollo mission (as did many of the components themselves). For example, the Radioisotope Thermoelectric Generators (RTGs) that powered the ALSEP investigations were generally located only about 3 m from the central station, but the placement of some of the seismic sensors (geophones), for a few of the Apollo missions, extended out to a range of approximately 90 m from the ALSEP central station. For more information on the deployment configuration of the Apollo ALSEP investigations see Reference 36.
- Reference 37 indicates the results of an analysis performed by E. M. Jones using photographs taken by the Apollo 15, 16, and 17 astronauts of the LMs from the LRVs in their final, parked positions and photographs of the parked LRVs taken from the LMs to estimate the final positions of the LRVs relative to the LMs.

Table B-3. Impact Site Coordinates of Apollo Orbital Mission Elements

Mission Element	Impact Date (UTC)	Latitude (deg)	East Long. (deg)	Impact Site Location
Apollo 10 LM-DS	*Natural Orbit Decay*			*Impact Site Unknown*
Apollo 11 LM-AS	*Natural Orbit Decay*			*Impact Site Unknown*
Apollo 12 LM-AS	20 Nov 1969	-3.94	338.80	73 km (112° Az) from Apollo 12 ALSEP
Apollo 13 S-IVB	15 Apr 1970	-2.75	332.14	135 km (274° Az) from Apollo 12 ALSEP
Apollo 14 S-IVB	4 Feb 1971	-8.09	333.98	172 km (207° Az) from Apollo 12 ALSEP
Apollo 14 LM-AS	7 Feb 1971	-3.42	340.33	67 km (276° Az) from Apollo 14 ALSEP
Apollo 15 S-IVB	29 Jul 1971	-1.51	348.19	184 km (69° Az) from Apollo 14 ALSEP
Apollo 15 LM-AS	3 Aug 1971	26.36	0.25	93 km (276° Az) from Apollo 15 ALSEP
Apollo 15 Sub-Satellite	*Natural Orbit Decay*			*Impact Site Unknown*
Apollo 16 S-IVB	19 Apr 1972	1.3	336.2	132 km (355° Az) from Apollo 12 ALSEP
Apollo 16 LM-AS	*Natural Orbit Decay*			*Impact Site Unknown*
Apollo 16 MS	*Natural Orbit Decay*			*Impact Site Unknown*
Apollo 16 Sub-Satellite	29 May 1972	10.16	111.94	Far-side of the Moon, near Lobachevskij crater
Apollo 17 S-IVB	10 Dec 1972	-4.21	347.69	157 km (96° Az) from Apollo 14 ALSEP
Apollo 17 LM-AS	15 Dec 1972	19.96	30.50	770 km (98° Az) from Apollo 15 ALSEP

Notes:

- The impact site location data for all mission elements except the Apollo 16 sub-satellite were taken from Reference 31. The impact location of the Apollo 16 sub-satellite was taken from Reference 29.
- Site coordinates from Reference 31 are “derived from the manned space flight network Apollo tracking data”. These coordinates are believed to be consistent with the IAU/IAG mean Earth / rotation system. See Section 2.2.
- Acronyms
  - LM-DS: Lunar Module-Descent Stage
  - LM-AS: Lunar Module-Ascent Stage
  - ALSEP: Apollo Lunar Surface Experiment Package
  - S-IVB: Saturn IV-B (third stage of Saturn V rocket)
  - Sub-Satellite: Also known as the Particles and Fields Sub-Satellite (P&FS or PFS)
  - MS: Mass Spectrometer

Apollo 10

- The S-IVB was injected into a heliocentric orbit.
- The LM-DS was jettisoned in lunar orbit approximately 15 km above the lunar surface over the southwest corner of Mare Tranquillitatus (Sea of Tranquility).
- The LM-AS was injected into a heliocentric orbit.

Apollo 11

- The S-IVB was injected into a heliocentric orbit.
- The LM-AS was jettisoned into lunar orbit.

Apollo 12

- The S-IVB was supposed to have been injected into a heliocentric orbit, but observations of a near-Earth object in late 2002 and early 2003 seem to indicate that the Apollo 12 S-IVB was probably injected into a distant Earth orbit, escaped the Earth-Moon system in 1971, was temporarily captured in early 2002, and escaped again in early 2003.

Apollo 13

- The LM re-entered the Earth’s atmosphere on 17 April 1970.

Apollo 15

- The sub-satellite was deployed into lunar orbit.

Notes (from Table B-3 continued):

Apollo 16

- A malfunction resulted in the premature loss of tracking data for the Apollo 16 S-IVB. Location estimates are based on interpretation of seismic data. Uncertainty in the impact location is approximately 0.7° in latitude and 0.3° in longitude. The impact location estimated based on tracking prior to signal loss is 2.24°, 335.51°E [31].
- A malfunction prevented executing a LM-AS de-orbit maneuver. The estimated orbital lifetime of the LM-AS was approximately one year.
- A malfunction prevented the retraction of a 7.3 m long MS boom deployed from the Scientific Instrument Module (SIM) bay while in lunar orbit. As a result, the MS boom was jettisoned from the Service Module (SM) in lunar orbit prior to the trans-Earth injection burn.
- Due to the fact that an orbital shaping maneuver was cancelled prior to ejection, the sub-satellite was deployed into an elliptical lunar orbit with a limited lifetime – estimated to be approximately one month.

B.3 Spacecraft Orbiting the Moon When Contact was Lost (including Mission Elements Jettisoned into Lunar Orbit)

Table B-4: Spacecraft / Mission Elements that Probably Have Impacted the Moon (due to Natural Orbit Decay)

Mission Msn Element	Orbit Insertion Date (UTC)	Last Contact Date	Comments	Source (Ref. No.)
Luna 10	3 Apr 1966	30 May 1966		27
Retrorocket			Retrorocket and cruise stage were jettisoned together	29
Luna 11	28 Aug 1966	1 Oct 1966		27
Luna 12	25 Oct 1966	19 Jan 1967		27
Explorer 35 †	21 Jul 1967	24 Jun 1973		29
Retrorocket				29
Luna 14	10 Apr 1968	April 1968		27
Luna 15-Tanks	17 Jul 1969		Two auxiliary “pods” (4 tanks) jettisoned prior to descent	29
Luna 16-Tanks	17 Sep 1970		Two auxiliary “pods” (4 tanks) jettisoned prior to descent	29
Luna 17-Tanks	15 Nov 1970		Two auxiliary “pods” (4 tanks) jettisoned prior to descent	29
Luna 18-Tanks	7 Sep 1971		Two auxiliary “pods” (4 tanks) jettisoned prior to descent	29
Luna 19	3 Oct 1971	Oct 1972		29
Luna 20-Tanks	18 Feb 1972		Two auxiliary “pods” (4 tanks) jettisoned prior to descent	29
Luna 21-Tanks	12 Jan 1973		Two auxiliary “pods” (4 tanks) jettisoned prior to descent	29
Explorer 49 ‡	15 Jun 1973	Aug 1977		29
Retrorocket				29
Luna 22	2 Jun 1974	Nov 1974		27
Luna 23-Tanks	2 Nov 1974		Two auxiliary “pods” (4 tanks) jettisoned prior to descent	29
Luna 24-Tanks	13 Aug 1976		Two auxiliary “pods” (4 tanks) jettisoned prior to descent	29
Hagoromo	18 Mar 1990	18 Mar 1990	Ignition of retrorocket confirmed by Earth observations	27

† Also known as IMP-6 for the sixth spacecraft in the Interplanetary Monitoring Platform series.

‡ Also known as RAE-2 (or RAE-B) for the second spacecraft in the Radio Astronomy Explorer series.

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APPENDIX C. GRAVITY FIELD INFORMATION

C.1 LP150Q Lunar Gravity Field

C.1.1 File Locations

The normalized gravity field coefficients for the LP150Q field are available on the Section 343 mission design/navigation server ***nexus*** via the path:

/nav/common/import/gravity/lp150q_odp.grv (format used with legacy NAV software)
/nav/common/import/gravity/lp150q_monte_grv.py (format used with next-gen NAV software)

The LP150Q gravity field is also available at the NASA Planetary Data System (PDS) website at http://pds-geosciences.wustl.edu/geodata/lp-l-rss-5-gravity-v1/lp_1001/sha/ .

[Note: The PDS website also includes a number of previously developed (now outdated) lunar gravity fields].

C.1.2 8 x 8 Subset of LP150Q Gravity Field (Including Zonals up to Degree 50, Normalized, No Permanent Tide)

GM = 4902.801076 km^3/s^2 R_{Ref} = 1738.0 km

J(1) =	0.000000000000D+00,	J(26) =	-0.924403243020D-08,
J(2) =	0.909010949481D-04,	J(27) =	0.776646019845D-06,
J(3) =	0.320307167959D-05,	J(28) =	-0.928771487846D-06,
J(4) =	-0.321409545028D-05,	J(29) =	0.627814558687D-06,
J(5) =	0.221009876393D-06,	J(30) =	-0.169625724228D-06,
J(6) =	-0.376479064475D-05,	J(31) =	-0.615811103571D-06,
J(7) =	-0.561330656403D-05,	J(32) =	0.324113765082D-06,
J(8) =	-0.231953905520D-05,	J(33) =	-0.995925930600D-07,
J(9) =	0.354241582136D-05,	J(34) =	-0.797167560251D-07,
J(10) =	0.933036285877D-06,	J(35) =	-0.177393818401D-06,
J(11) =	0.960353139804D-06,	J(36) =	-0.612788905278D-08,
J(12) =	0.188692162540D-05,	J(37) =	-0.225693717039D-06,
J(13) =	-0.258650494877D-06,	J(38) =	-0.449830332452D-08,
J(14) =	-0.326300330782D-06,	J(39) =	0.311259412103D-06,
J(15) =	0.972530852999D-07,	J(40) =	-0.652544567689D-07,
J(16) =	-0.318446040132D-06,	J(41) =	-0.173282860391D-06,
J(17) =	0.103822696054D-05,	J(42) =	-0.215218698890D-06,
J(18) =	0.372937482506D-06,	J(43) =	0.945325046231D-07,
J(19) =	-0.555446218485D-07,	J(44) =	0.849348275934D-07,
J(20) =	-0.647952861685D-06,	J(45) =	-0.185440783353D-06,
J(21) =	0.971099122315D-07,	J(46) =	0.213600262245D-06,
J(22) =	0.122392450387D-06,	J(47) =	-0.174907671686D-06,
J(23) =	0.196589333948D-06,	J(48) =	0.840684422498D-07,
J(24) =	0.277798576353D-06,	J(49) =	-0.401931394977D-07,
J(25) =	0.162944553469D-06,	J(50) =	-0.168369827480D-07,

C.1.2 8 x 8 Subset of LP150Q Gravity Field (continued) (Including Zonals up to Degree 50, Normalized, No Permanent Tide)

C(1, 1) = 0.000000000000D+00,	S(1, 1) = 0.000000000000D+00,
C(2, 1) = -0.186273608184D-08,	S(2, 1) = -0.142453894610D-08,
C(2, 2) = 0.346376274208D-04,	S(2, 2) = 0.144063503540D-07,
C(3, 1) = 0.263418358622D-04,	S(3, 1) = 0.546307860882D-05,
C(3, 2) = 0.141853316786D-04,	S(3, 2) = 0.488913911795D-05,
C(3, 3) = 0.122862645044D-04,	S(3, 3) = -0.178246270720D-05,
C(4, 1) = -0.600061939740D-05,	S(4, 1) = 0.165955644727D-05,
C(4, 2) = -0.709370101544D-05,	S(4, 2) = -0.678562735558D-05,
C(4, 3) = -0.135880466594D-05,	S(4, 3) = -0.134332571737D-04,
C(4, 4) = -0.602939150193D-05,	S(4, 4) = 0.393525694440D-05,
C(5, 1) = -0.103560812630D-05,	S(5, 1) = -0.411585726681D-05,
C(5, 2) = 0.438127609376D-05,	S(5, 2) = 0.109502526551D-05,
C(5, 3) = 0.454694228437D-06,	S(5, 3) = 0.870152146591D-05,
C(5, 4) = 0.277279104390D-05,	S(5, 4) = 0.307793712297D-07,
C(5, 5) = 0.312687726844D-05,	S(5, 5) = -0.275386200669D-05,
C(6, 1) = 0.153429993945D-05,	S(6, 1) = -0.257237276906D-05,
C(6, 2) = -0.434494761436D-05,	S(6, 2) = -0.217950819643D-05,
C(6, 3) = -0.328182654012D-05,	S(6, 3) = -0.349862907452D-05,
C(6, 4) = 0.371921281230D-06,	S(6, 4) = -0.405761602001D-05,
C(6, 5) = 0.142835081872D-05,	S(6, 5) = -0.102833744711D-04,
C(6, 6) = -0.471022454058D-05,	S(6, 6) = 0.722662556338D-05,
C(7, 1) = 0.753347997634D-05,	S(7, 1) = -0.131539563288D-06,
C(7, 2) = -0.660779046120D-06,	S(7, 2) = 0.237864383691D-05,
C(7, 3) = 0.574652315024D-06,	S(7, 3) = 0.236446570289D-05,
C(7, 4) = -0.899605382165D-06,	S(7, 4) = 0.843758330286D-06,
C(7, 5) = -0.279193000638D-06,	S(7, 5) = 0.108913355675D-05,
C(7, 6) = -0.103476355233D-05,	S(7, 6) = 0.103172986529D-05,
C(7, 7) = -0.178499996340D-05,	S(7, 7) = -0.160311972598D-05,
C(8, 1) = -0.398659493146D-07,	S(8, 1) = 0.111757157884D-05,
C(8, 2) = 0.301238176996D-05,	S(8, 2) = 0.194296603146D-05,
C(8, 3) = -0.188460320268D-05,	S(8, 3) = 0.953692588674D-06,
C(8, 4) = 0.338733082124D-05,	S(8, 4) = -0.502575576501D-06,
C(8, 5) = -0.117868237022D-05,	S(8, 5) = 0.284167245453D-05,
C(8, 6) = -0.153768837893D-05,	S(8, 6) = -0.217660584641D-05,
C(8, 7) = -0.153454236110D-05,	S(8, 7) = 0.332054075243D-05,
C(8, 8) = -0.252624025278D-05,	S(8, 8) = 0.212716792161D-05,

C.2 GGM02C Earth Gravity Field

C.2.1 File Locations

The normalized gravity field coefficients for the GGM02C field are available on the Section 343 mission design/navigation server ***nexus*** via the path:

/nav/common/import/gravity/ggm02c_odp.grv (format used with legacy NAV software)
/nav/common/import/gravity/ggm02c_monte_grv.py (format used with next-gen NAV software)

The GGM02C gravity field is also available at the following website at *http://www.csr.utexas.edu/grace/gravity/* .

C.2.2 8 x 8 Subset of GGM02C Gravity Field (Normalized, No Permanent Tide, Epoch = J2000, Normalized Rates / Year: $\dot{J}_2$ = –1.162755 x 10^{-11} $\dot{\bar{C}}_{21}$ = –0.337 x 10^{-11} $\dot{\bar{S}}_{21}$ = +1.606 x 10^{-11})

[Note: The Earth GM value indicated below has been scaled from its value in the geocentric reference frame to its value in the solar system barycentric reference frame (see 'Note' in Section 3.1)]. If the gravity field is downloaded from the external website, the Earth GM value will not have been scaled to the solar system barycentric value. In addition, the C_{20} ($-J_2$) value from the external website includes the effects of permanent tides].

GM = 398600.4356 km^3/s^2 R_{Ref} = 6378.1363 km

J(1) = 0.0000000000000D+00,	J(5) = -6.8715981001179D-08,
J(2) = 4.8416521605481D-04,	J(6) = 1.4994011973125D-07,
J(3) = -9.5718508415439D-07,	J(7) = -9.0504630229132D-08,
J(4) = -5.3999143526074D-07,	J(8) = -4.9481334104780D-08,

C(1, 1) = 0.0000000000000D+00,	S(1, 1) = 0.0000000000000D+00
C(2, 1) = -2.0458338184745D-10,	S(2, 1) = 1.3968195379551D-09
C(2, 2) = 2.4393233001191D-06,	S(2, 2) = -1.4002662003867D-06
C(3, 1) = 2.0304752656064D-06,	S(3, 1) = 2.4817416903031D-07
C(3, 2) = 9.0480066975068D-07,	S(3, 2) = -6.1900441427103D-07
C(3, 3) = 7.2128924247650D-07,	S(3, 3) = 1.4143556434052D-06
C(4, 1) = -5.3617583789434D-07,	S(4, 1) = -4.7356802287476D-07
C(4, 2) = 3.5051159931087D-07,	S(4, 2) = 6.6243944849186D-07
C(4, 3) = 9.9085503541734D-07,	S(4, 3) = -2.0097529442342D-07
C(4, 4) = -1.8846750474516D-07,	S(4, 4) = 3.0882228278756D-07
C(5, 1) = -6.2904051380481D-08,	S(5, 1) = -9.4373263356928D-08
C(5, 2) = 6.5210393080303D-07,	S(5, 2) = -3.2334838450788D-07
C(5, 3) = -4.5187965449909D-07,	S(5, 3) = -2.1500140801223D-07
C(5, 4) = -2.9533633996919D-07,	S(5, 4) = 4.9817834613976D-08
C(5, 5) = 1.7479367861529D-07,	S(5, 5) = -6.6937444851133D-07

C.2.2 8 x 8 Subset of GGM02C Gravity Field (continued) (Normalized, No Permanent Tide, Epoch = J2000, Normalized Rates / Year: $\dot{\bar{J}}_2 = -1.162755 \times 10^{-11}$ $\dot{\bar{C}}_{21} = -0.337 \times 10^{-11}$ $\dot{\bar{S}}_{21} = +1.606 \times 10^{-11}$)

C(6, 1) = -7.5903534713091D-08,	S(6, 1) = 2.6516969820404D-08
C(6, 2) = 4.8671477410889D-08,	S(6, 2) = -3.7379063632786D-07
C(6, 3) = 5.7235251140830D-08,	S(6, 3) = 8.9355908317172D-09
C(6, 4) = -8.6024306020762D-08,	S(6, 4) = -4.7142492778928D-07
C(6, 5) = -2.6717044535375D-07,	S(6, 5) = -5.3648870593762D-07
C(6, 6) = 9.4667858117668D-09,	S(6, 6) = -2.3740563878695D-07
C(7, 1) = 2.8088898145081D-07,	S(7, 1) = 9.5119644062781D-08
C(7, 2) = 3.3041560746535D-07,	S(7, 2) = 9.2985239787248D-08
C(7, 3) = 2.5045166263142D-07,	S(7, 3) = -2.1714748211003D-07
C(7, 4) = -2.7498938059553D-07,	S(7, 4) = -1.2406704411494D-07
C(7, 5) = 1.6601317328580D-09,	S(7, 5) = 1.7933888039325D-08
C(7, 6) = -3.5880775879961D-07,	S(7, 6) = 1.5179454735699D-07
C(7, 7) = 1.5062884219099D-09,	S(7, 7) = 2.4116259277940D-08
C(8, 1) = 2.3159979727734D-08,	S(8, 1) = 5.8896665124862D-08
C(8, 2) = 8.0015152191272D-08,	S(8, 2) = 6.5278835020898D-08
C(8, 3) = -1.9378833774969D-08,	S(8, 3) = -8.5977473175173D-08
C(8, 4) = -2.4436744168468D-07,	S(8, 4) = 6.9808169573661D-08
C(8, 5) = -2.5695381020603D-08,	S(8, 5) = 8.9195503483206D-08
C(8, 6) = -6.5962471839471D-08,	S(8, 6) = 3.0894479673499D-07
C(8, 7) = 6.7261439849585D-08,	S(8, 7) = 7.4875670873080D-08
C(8, 8) = -1.2403873503204D-07,	S(8, 8) = 1.2055330686769D-07

C.3 Conversion from Normalized to Un-normalized Gravity Field Coefficients

$$S_{nm} = \frac{\bar{S}_{nm}}{\Pi_{nm}} \qquad C_{nm} = \frac{\bar{C}_{nm}}{\Pi_{nm}} \qquad J_n = \frac{\bar{J}_n}{\Pi_{n0}}$$

where $\bar{S}, \bar{C}, \bar{J}$ are the normalized gravity field coefficients and S, C, J are the un-normalized coefficients. The conversion factor Π is given by the formula:

$$\Pi_{nm} = \sqrt{\frac{(n+m)!}{(n-m)!\; k\; (2n+1)}}$$

$k = 1$ if $m = 0$

$k = 2$ if $m \neq 0$

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   [Note: The latest lunar gravity field, LP150Q, is considered the best available lunar gravity field by A. S. Konopliv. It represents an improvement over the gravity fields presented in Reference 1. A published reference for LP150Q is not yet available].

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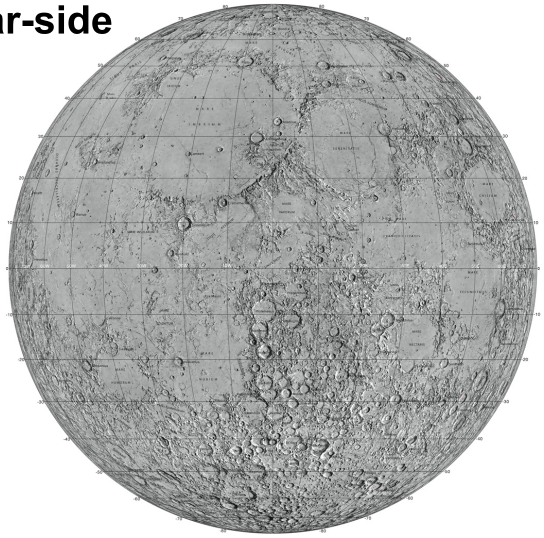

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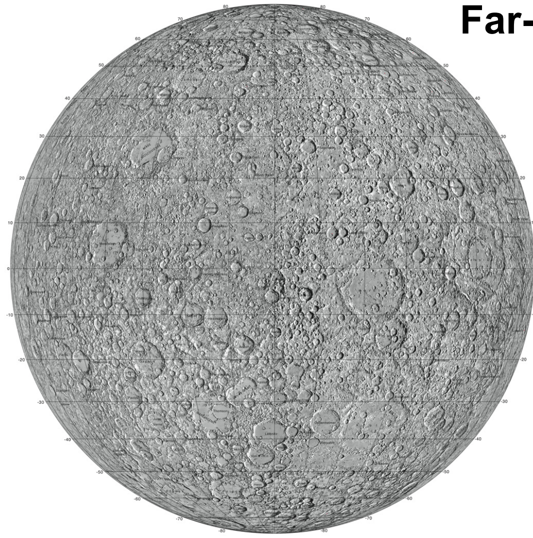

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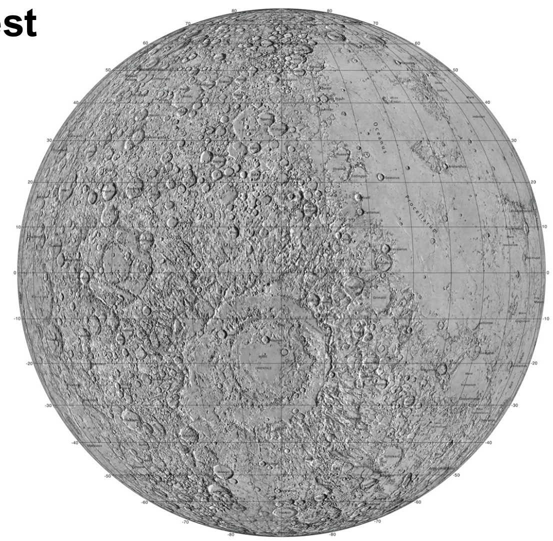

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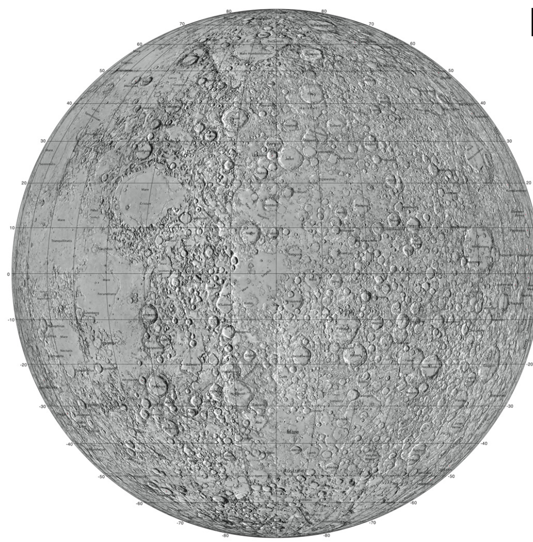

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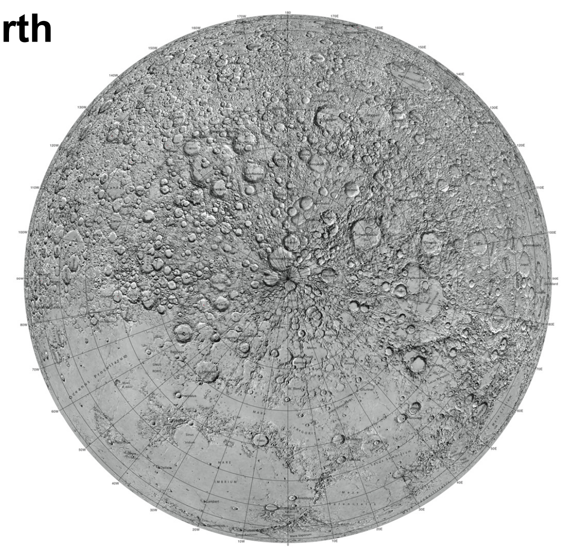

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