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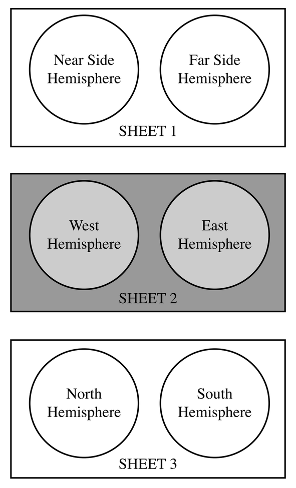
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION



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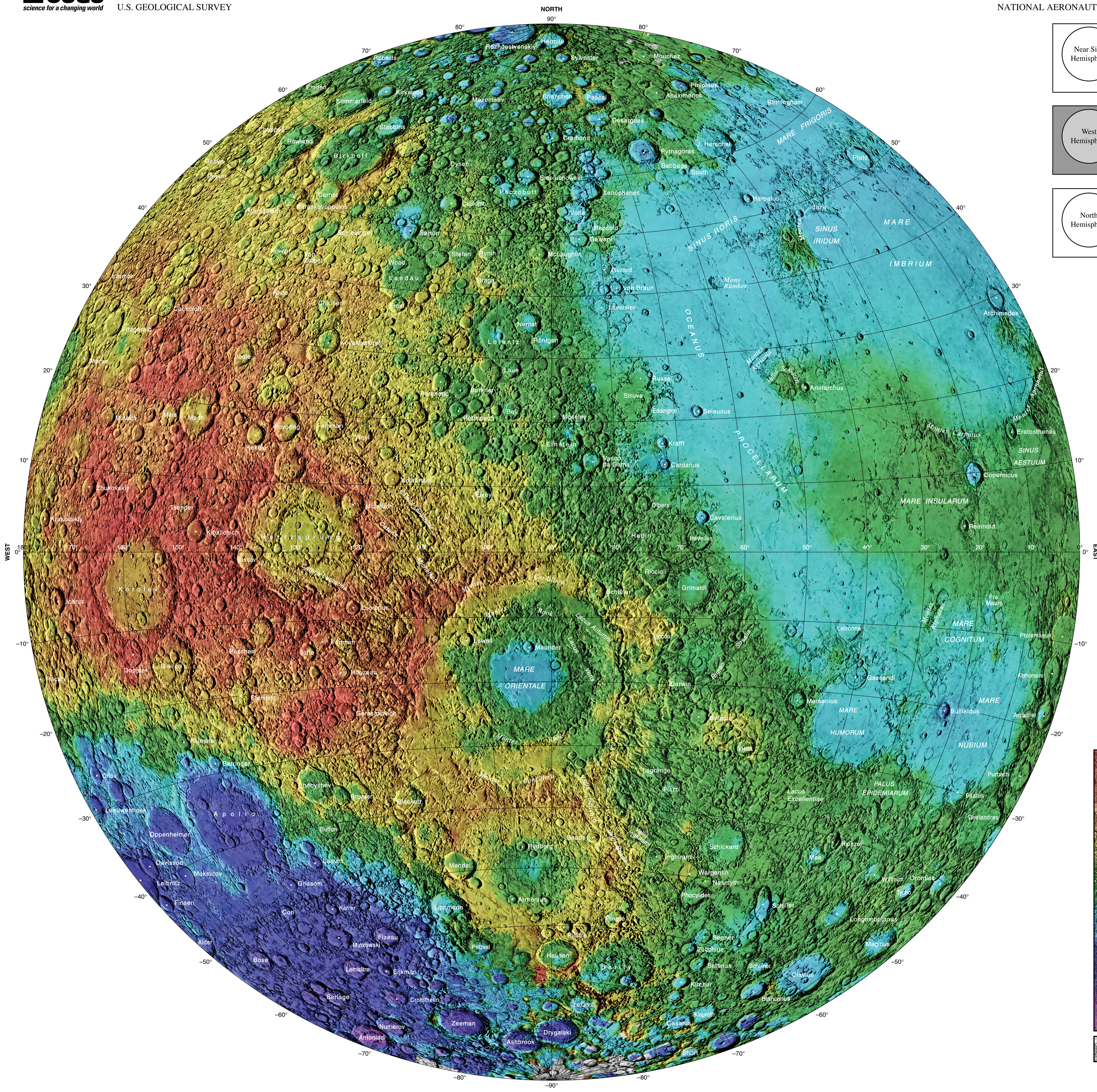
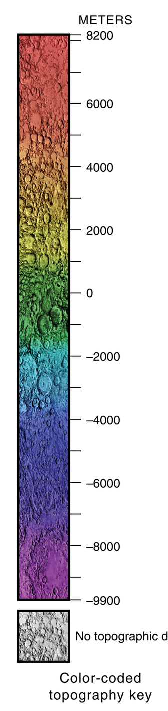
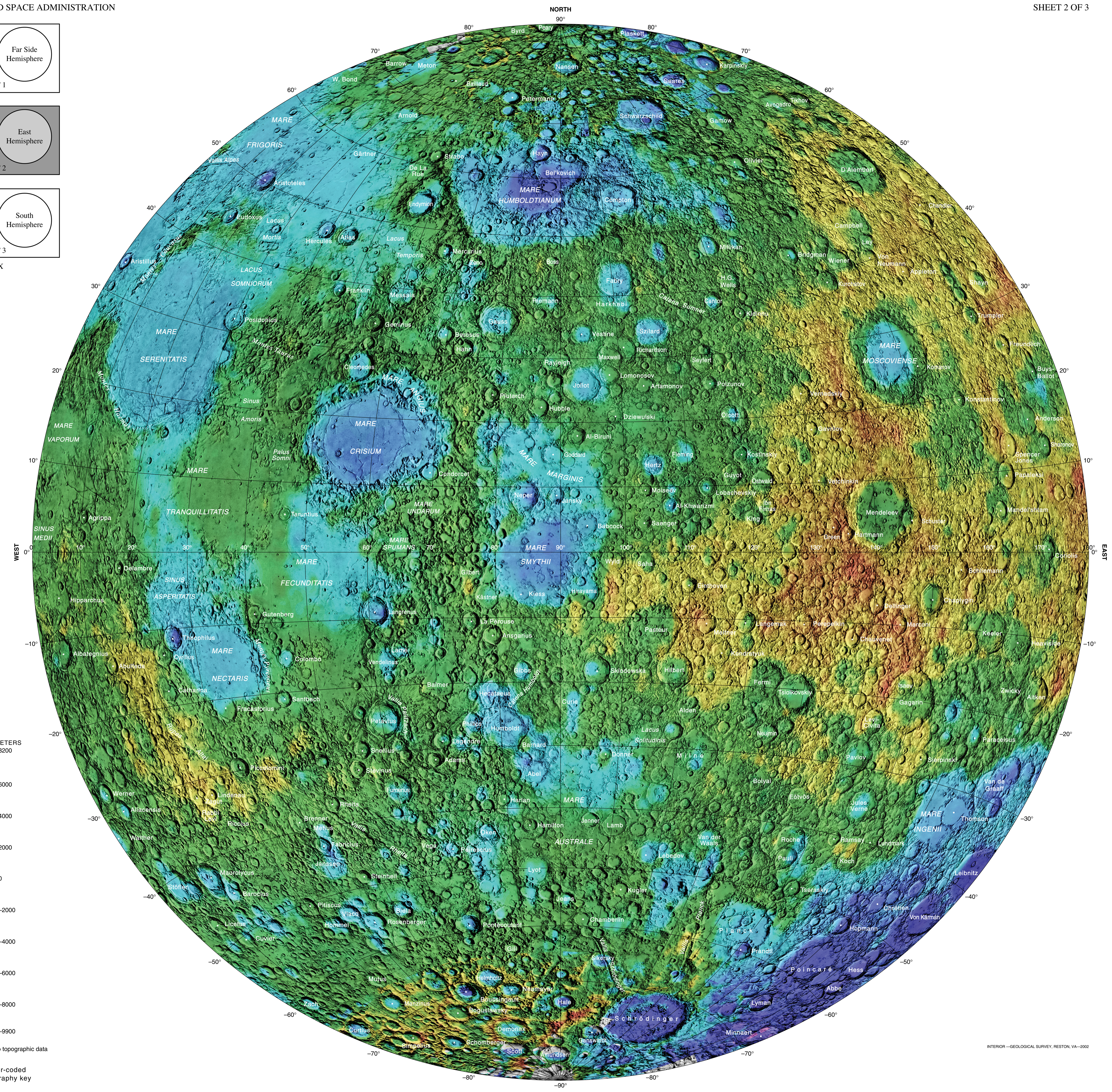


Scale 1:10,000,000 (1 mm = 10 km)
At 0° latitude and 90° W longitude
Lambert Azimuthal Equal-Area projection

WEST HEMISPHERE
L 10M 0/–90 RTK



Color-coded topography key



Scale 1:10,000,000 (1 mm = 10 km)
At 0° latitude and 90° E longitude
Lambert Azimuthal Equal-Area projection

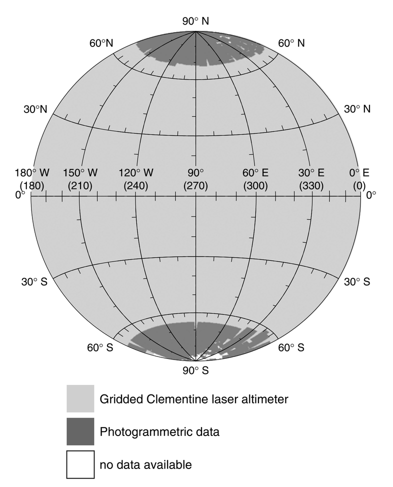
EAST HEMISPHERE
L 10M 0/90 RTK

INTERIOR—GEOLOGICAL SURVEY, RESTON, VA—2002

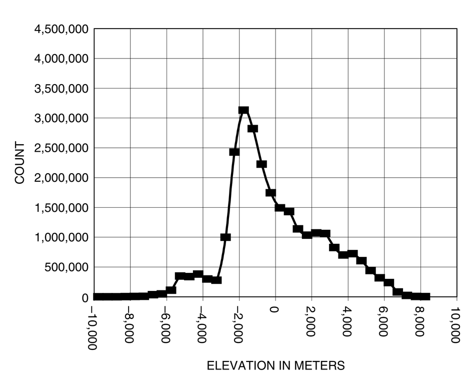
Elevation values for the west hemisphere binned in increments of 500 meters. Count is number of elevation posts within the bin. Percent is count for indicated elevation values divided by total count.

Minimum	Maximum	Count	Percent
−10000	−9500	169	0.00%
−9500	−9000	518	0.00%
−9000	−8500	826	0.00%
−8500	−8000	2,380	0.01%
−8000	−7500	4,147	0.02%
−7500	−7000	7,745	0.03%
−7000	−6500	35,531	0.13%
−6500	−6000	48,612	0.18%
−6000	−5500	110,030	0.42%
−5500	−5000	348,543	1.32%
−5000	−4500	336,699	1.28%
−4500	−4000	380,951	1.44%
−4000	−3500	297,586	1.13%
−3500	−3000	277,757	1.05%
−3000	−2500	998,766	3.78%
−2500	−2000	2,426,804	9.20%
−2000	−1500	3,131,526	11.87%
−1500	−1000	2,819,781	10.69%
−1000	−500	2,223,878	8.43%
−500	0	1,744,190	6.61%
0	500	1,491,147	5.65%
500	1000	1,428,808	5.41%
1000	1500	1,138,869	4.32%
1500	2000	1,034,507	3.92%
2000	2500	1,072,031	4.06%
2500	3000	1,062,262	4.03%
3000	3500	826,748	3.13%
3500	4000	701,355	2.66%
4000	4500	723,026	2.74%
4500	5000	605,993	2.30%
5000	5500	441,706	1.67%
5500	6000	317,694	1.20%
6000	6500	237,941	0.90%
6500	7000	80,408	0.30%
7000	7500	23,217	0.09%
7500	8000	6,233	0.02%
8000	8500	1,459	0.01%
8500	9000		
9000	9500		
9500	10000		

Elevation (meters)	
Minimum	−9889
Maximum	8192
Mean	1
Standard Deviation	2582



Sources for west hemisphere topographic data
[Coordinates shown in parenthesis are longitude coordinates in 0 to 360 east system]



Histogram of elevation values for west hemisphere

NOTES ON BASE

This sheet is one in a series of topographic maps that presents color-coded topographic data digitally merged with shaded relief data.

ADOPTED FIGURE

The figure for the Moon, used for the computation of the map projection, is a sphere with a radius of 1737.4 km (Seidelmann and others, 2002). Because the Moon has no surface water, and hence no sea level, the datum (the 0 km contour) for elevations is defined as the radius of 1737.4 km. Coordinates are based on the mean Earth/polar axis (M.E.) coordinates system, the z axis is the axis of the Moon's rotation, and the x axis is the mean Earth direction. The center of mass is the origin of the coordinate system (Davies and Colvin, 2000). The equator lies in the x–y plane and the prime meridian lies in the x–z plane with east longitude values being positive.

PROJECTION

The projection is Lambert Azimuthal Equal Area Projection. The scale factor at the central latitude and central longitude point is 1:10,000,000. For the west side hemisphere the central latitude and central longitude point is at 0° and 90° west. For the east side hemisphere the central latitude and central longitude point is at 0° and 90° east.

CONTROL

The original control for the shaded relief maps was based on horizontal control tied to either the Lunar Positional Reference of 1974 (Schimerman, 1975) or the Apollo control system of 1973. Positional discrepancies as large as 25 km at map scale existed in the original shaded relief map. To improve the accuracy, digital shaded relief data were aligned with a mosaic produced from Clementine 750 nm images (Eliason, 1997, Isbell and others, 1997, Eliason and others, 1999). This alignment process consisted of picking features (commonly called match or tie points) that were visible in both the shaded relief data and the Clementine mosaic. To accomplish this, the files were divided into three areas: north pole, equatorial region, and south pole. They were aligned first in the equatorial region and then in the polar regions. Within the equatorial region, an area extending from 60° S. to 60° N., approximately 1000 points were picked. Within the north polar region, an area from 57° N. to 90° N., approximately 1900 points were picked. Within the south polar region, an area from 57° S. to 90° S., approximately 1100 points were picked. These points were used to warp the shaded relief map to match the Clementine mosaic. The Clementine mosaic has a positional accuracy of 500 m (1/60°) (Eliason and others, 1999).

Vertical control is based on measurements from the Clementine laser altimeter that collected data between 79° S. and 81° N. The along-track spacing of these measurements varied: over some smooth mare surfaces an along-track spacing of 20 km was achieved; where the instrument lost lock over rough highland terrain, the spacing degraded to 100 km. The across-track spacing was based on the orbital ground track and is approximately 60 km (2°) at the equator. Elevation values were collected at 72,548 points by the Clementine laser altimeter. The estimated vertical accuracy of points collected by the Clementine laser altimeter is 130 m (Smith and others, 1997).

The Clementine laser altimeter did not collect data over the lunar north or south pole. Therefore, topographic data were collected photogrammetrically to fill in these gaps. The image sources were the oblique and nadir 750 nm images collected by the Clementine UVVIS camera (Rosiek and others, 1998). Vertical control, for the photogrammetric data, was established by using the Clementine laser altimeter data at the outer edge of these circular polar areas, and the imagery was used to bridge control and fill in the central part of the circle (Rosiek and others, 2001). The expected precision of points collected photogrammetrically is 180 m (Rosiek and others, 1998). Further discussion of the photogrammetric topographic data can be found in the topographic data section below.

IMAGE BASE

The shaded relief data were originally published as a series of 1:5 million shaded relief maps. This series included three U.S. Geological Survey maps: I–1218–B, Shaded Relief Map of the Lunar Far Side, 1980; I–1326–A, Shaded Relief Map of the Lunar Polar Regions, 1981; and I–2276, Sheet 2 of 2, Shaded Relief Map of the Lunar Near Side, 1992. These data were digitized and mosaicked into a single digital file. An area of approximately 500,000 km^2 near the south pole was not visible in any pre-Clementine images and is blank on the published map. The digitized relief base was revised based on the Clementine mosaic and recent Earth-based radar imagery (Margot and others, 1999) to show features in this area. Errors that were present in the original interpretations of lunar morphology have not been corrected in the digital version of the warped shaded relief map base. These original errors were caused by scanty data, ambiguities introduced by highly oblique solar incidence angles, and distortions created in generating orthophotographs from oblique images (Rosiek and Aeschliman, 2001).

TOPOGRAPHIC DATA

The Clementine laser altimeter points were interpolated to create a global topographic gridded digital terrain model for the lunar surface. Because the altimeter points were sparser near the poles and non-existent over the poles in this digital terrain model, only data between 75° S. and 75° N. were used in the final digital terrain model. To fill in the polar regions, topographic data were collected photogrammetrically from Clementine 750 nm oblique and nadir images.

For the photogrammetric analysis, horizontal control was established by selecting some of the match points that were used in building the Clementine global mosaic. These points provided estimates for latitude and longitude values, but no estimate for elevation values. Vertical control was established by using the global topographic gridded digital terrain model developed from the Clementine laser altimeter points to estimate elevation values for the Clementine match points. To improve the geometry of the control network for the photogrammetric analysis, the Clementine match points, which were selected to tie two images together in order to build the Clementine global mosaic, were transferred to all images that contained the point. Additional points were selected to have four well-distributed points per image, where possible. Analytical areotriangulation, a weighted least squares process, is used to solve for all the parameters of the photogrammetric project. These parameters include image sensor position and angles; latitude, longitude, and elevation of match points; and image coordinates of match points. Adjusting the weight assigned to a parameter determines whether values with high weight are held to the original estimate or values with low weight are allowed to float and a new value determined for the parameter. The parameters with the most error in their original estimate for their values are the image sensor angles, so they are given a low weight. The latitude and longitude values of Clementine match points are given a high weight so the solution holds to the Clementine global mosaic horizontal coordinates. Weights for the elevation values are varied depending on the horizontal distance to a Clementine laser altimeter point: match points within 2000 m of a Clementine laser altimeter point are given a high weight; match points between 2000 m and 5000 m from a Clementine laser altimeter point are given a medium weight; and match points greater than 5000 m from a Clementine laser altimeter point are given a low weight. This weighting allows the vertical control to be bridged between areas of known vertical control (the area covered by Clementine laser altimeter measurements) and the areas void of control (the area over the poles).

The Clementine mission collected both oblique and vertical images over the polar regions; these images form stereo pairs that can be used photogrammetrically to collect topographic data. In the north pole region (90° N. to 64° N. latitude) data were collected from 640 stereo models. Over the south pole region (90° S. to 63° S. latitude) topographic data were collected from 667 stereo models. Topographic data were collected within each stereo model with an elevation post spacing of 1 km in the x and y directions. This spacing resulted in 1,437,368 points being collected in the north pole region and 1,724,872 points being collected in the south pole region. On average, over the area that data were collected (79° S. and 81° N.), the Clementine laser altimeter collected an elevation value for every 514 km^2; and the photogrammetric data collected an elevation value for every 1.3 km^2 in the north pole and 1.2 km^2 in the south pole. The photogrammetric data were merged and vertically transformed to align with the Clementine laser altimeter data to form the final digital terrain model (Rosiek and others, 2001).

Merging the topographic data required an iterative process to reduce the error between the photogrammetric data and the topographic data derived from the Clementine laser altimeter data. At first the photogrammetric topographic data exhibited a systematic stair-step error, in that stereo models closer to the poles had a systematic bias to be higher than stereo models farther from the poles. When this bias was removed, the resulting digital terrain model had a bowl-shape appearance with a low spot near the pole. Each stereo model was tilted to remove the bowl shape: for stereo models in the north pole area this was 800 m per degree and for stereo models in the south pole area this was 1 km per degree. To fit the stereo models to the Clementine laser altimeter data, an initial set of stereo models that overlaid the Clementine laser altimeter data was adjusted to vertically align with the Clementine laser altimeter data. Stereo models that overlaid the previously adjusted stereo models were adjusted further, this process continued until all stereo models were adjusted to align vertically.

In analyzing the photogrammetric data for the north pole region, 1,189,935 points (83% of the data) occur on two or more stereo models. For 90% of those points, the standard deviation in elevation is between 24 and 409 m, with a mean of 184 m. In the south pole region, 1,262,349 points (73% of the data) occur on two or more stereo models. For 90% of those points, the standard deviation in elevation is between 13 and 395 m, with a mean of 160 m.

In the north pole region 1,276 Clementine laser altimeter points are in the area where photogrammetric topographic data were collected. Comparing the photogrammetric topographic data with the Clementine laser altimeter points shows that for the north pole region the stereo topographic data is an average of 46 m higher than the Clementine laser altimeter points, with a standard deviation of 719 m. In the south pole region, 1,379 Clementine laser altimeter points are in the area where photogrammetric topographic data were collected. For the south pole region the stereo topographic data is an average of 163 m lower than the Clementine laser altimeter points, with a standard deviation of 1005 m.

The merged topographic data were color-coded and combined with the shaded relief data. Areas where no topographic data were collected are not color-coded, and the shaded relief image is shown as gray scale.

NOMENCLATURE

The number, size, and placement of text annotations were chosen to provide a general orientation of conspicuous features on a 1:10,000,000-scale map. Features are labeled with names approved by the International Astronomical Union (for a complete list of lunar nomenclature, see http://planetarynames.wr.usgs.gov).

L 10M 0/±90 RTK: Abbreviation for Moon; 1:10,000,000 series; center of maps: 0° latitude and 90° west longitude for west side hemisphere, and 0° latitude and 90° east longitude for east side hemisphere; shaded relief (R) with topographic data and nomenclature (T) and color-coded topographic data (K) (Greeley and Batson, 1990).

OTHER SOURCES OF LUNAR ELEVATION DATA

Two other recent sources of lunar elevation data are from work done by Dr. Tony Cook of the National Air and Space Museum and by Dr. Jean-Luc Margot while at Cornell University. The elevation data collected by Dr. Cook is derived from overlapping Clementine images from the same orbit. This method provides a larger set of images to use in collecting topographic data. Elevation values that are collected are relative to each other and are not known in an absolute sense relative to some datum. To provide an estimate of the absolute height, the elevation values are matched to the Clementine altimetry data and to elevation values previously collected where Clementine altimetry does not exist. Traditional photogrammetric solutions employ a least squares method to distribute the error throughout the model, whereas the method employed by Dr. Cook aligns the derived data with the Clementine altimetry data where it exists and in areas where there is no data the relative elevation measurements are aligned with previous aligned data until the area is connected back with Clementine data. The error in unknown areas is unconstrained, but the method does close back to an area with known elevation values, which constrains the error at the starting and ending spots (Cook and others 2000).

The elevation data collected by Dr. Margot is derived from radar interferometry using the Goldstone radar. Over the polar region, five images were collected and mosaicked together. To collect elevation information, the radar signal is sent from one antenna and is received by at least two antennas. The phase difference in the received signal from the two radar sites provides information about the elevation. The elevation information derived from radar interferometry is relative and requires the use of the Clementine altimetry points to provide absolute elevation information relative to a datum (Margot and others 1999, 2000).

REFERENCES

Cook, A., Watters, T.R., Robinson, M.S., Spudis, P.D., and Bussey, D.B.J., 2000, Lunar polar topography derived from Clementine stereoimages: Journal of Geophysical Research, v. 105, no. E5, p. 12,023–12,033.

Davies, M.E., and Colvin, T.R., 2000, Lunar coordinates in the regions of the Apollo Landers: Journal of Geophysical Research, v. 105, no. E8, p. 20,277–20,280.

Eliason, E.M., 1997, Production of Digital Image Models using the ISIS system [abs.], *in* Lunar and Planetary Science Conference XXVIII: Houston, Lunar and Planetary Institute, p. 331–332.

Eliason, E.M., McEwen, A.S., Robinson, M.S., Lee, E.M., Becker, T.L., Gaddis, L.R., Weller, L.A., Isbell, C.E., Shinaman, J.R., Duxbury, T., Malaret, E., 1999, Digital processing for a global multispectral map of the Moon from the Clementine UVVIS imaging instrument [abs.], *in* Lunar and Planetary Science Conference XXX: Houston, Lunar and Planetary Institute, abstract no. 1933 [CD-ROM].

Margot, J.L., Campbell, D.B., Jurgens, R.F., Slade, M.A., 1999, Topography of the lunar poles from radar interferometry: A survey of cold trap locations: Science, v. 284, p. 1658–1660.

———2000, Digital elevation models of the Moon from Earth-based radar interferometry: IEEE Transactions on Geoscience and Remote Sensing, v. 38, no. 2, p. 1122–1133.

Isbell, C.E., Eliason, E.M., Becker, T.L., Lee, E.M., McEwen, A.S., and Robinson, M.S., 1997, The Clementine Mission—An archive of a Digital Image Model of the Moon [abs.], *in* Lunar and Planetary Science Conference XXVIII: Houston, Lunar and Planetary Institute, p. 623–624.

Greeley, R., and Batson, R.M., 1990, Planetary mapping: New York, Cambridge University Press, p. 261–276.

Rosiek, M.R., Kirk, R.L., and Howington-Kraus, E.T., 1998, Lunar topographic maps derived from Clementine imagery [abs.], *in* Lunar and Planetary Science Conference XXX: Houston, Lunar and Planetary Institute, abstract no. 1853 [CD-ROM].

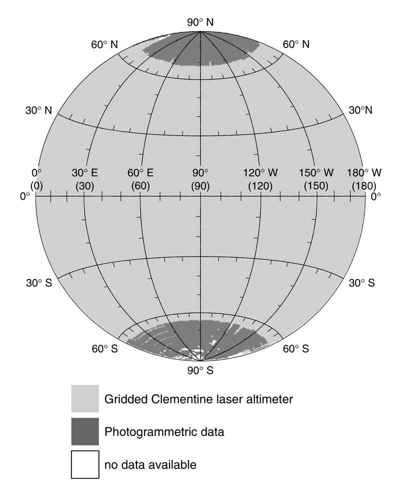
Rosiek, M.R, and Aeschliman, R.A., 2001, Lunar shaded relief map updated with Clementine data [abs.], *in* Lunar and Planetary Science Conference XXXII: Houston, Lunar and Planetary Institute, abstract no. 1943 [CD-ROM].

Rosiek, M.R., Kirk, R.L., and Howington-Kraus, E.T, 2001, Combining lunar photogrammetric topographic data with Clementine Lidar data [abs.], *in* Planetary Mapping 2001, International Society for Photogrammetry and Remote Sensing, Working Group IV/9: Flagstaff, Arizona, web publication http://wwwflag.wr.usgs.gov/USGSFlag/Space/Isprs/flagstaff2001/index.html.

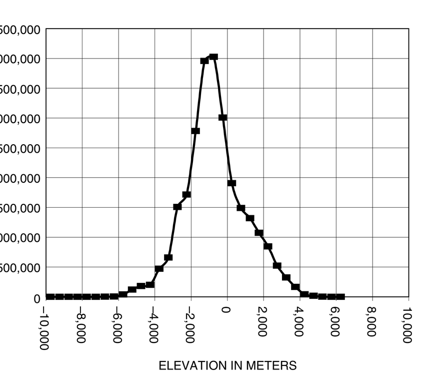
Schimerman, L.A. ed., 1975, Lunar cartographic dossier: U.S. Defense Mapping Agency Aerospace Center, St. Louis, Missouri, v. 1, sections 3.1.10 and 3.4.63.

Seidelmann, P.K., Abalakin, V.K., Bursa, M., Davies, M.E., de Bergh, C., Lieske, J.H., Oberst, J., Simon, J.L., Standish, E.M., Stooke, P., and Thomas, P.C., 2002, Report of the IAU/IAG Working Group on Cartographic and Rotational Elements of the Planets and Satellites—2000: Celestial Mechanics and Dynamical Astronomy, v. 82, p. 83–110.

Smith, D.E., Zuber, M.T., Neumann, G.A., and Lemoine, F.G., 1997, Topography of the Moon from the Clementine Lidar: Journal of Geophysical Research, v. 102, no. E1, p. 1591–1611.



Sources for east hemisphere topographic data
[Coordinates shown in parenthesis are longitude coordinates in 0 to 360 east system]



Histogram of elevation values for east hemisphere

Elevation values for the east hemisphere binned in increments of 500 meters. Count is number of elevation posts within the bin. Percent is count for indicated elevation values divided by total count.

Minimum	Maximum	Count	Percent
−10000	−9500	119	0.00%
−9500	−9000	238	0.00%
−9000	−8500	635	0.00%
−8500	−8000	473	0.00%
−8000	−7500	372	0.00%
−7500	−7000	1,054	0.00%
−7000	−6500	2,913	0.01%
−6500	−6000	5,157	0.02%
−6000	−5500	40,190	0.15%
−5500	−5000	122,138	0.46%
−5000	−4500	179,836	0.68%
−4500	−4000	201,306	0.76%
−4000	−3500	472,307	1.79%
−3500	−3000	659,066	2.50%
−3000	−2500	1,507,604	5.71%
−2500	−2000	1,716,181	6.50%
−2000	−1500	2,782,187	10.54%
−1500	−1000	3,956,635	14.99%
−1000	−500	4,027,048	15.26%
−500	0	3,006,987	11.39%
0	500	1,907,225	7.23%
500	1000	1,489,551	5.64%
1000	1500	1,319,180	5.00%
1500	2000	1,073,012	4.07%
2000	2500	845,010	3.20%
2500	3000	522,506	1.98%
3000	3500	325,416	1.23%
3500	4000	165,767	0.63%
4000	4500	43,277	0.16%
4500	5000	16,225	0.06%
5000	5500	3,231	0.01%
5500	6000	1,113	0.00%
6000	6500	524	0.00%
6500	7000		
7000	7500		
7500	8000		
8000	8500		
8500	9000		
9000	9500		
9500	10000		

Elevation (meters)	
Minimum	−9726
Maximum	6421
Mean	−869
Standard Deviation	1658

COLOR-CODED TOPOGRAPHY AND SHADED RELIEF MAP OF THE LUNAR WEST AND EAST HEMISPHERES

L 10M 0/± 90 RTK

2002

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