TOPOGRAPHIC MAPPING OF THE MOON

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(Received 18 July 1984)

Abstract. Contour maps of the Mooon have been compiled by photogrammetric methods that use stereoscopic combinations of all available metric photographs from the Apollo 15, 16, and 17 missions. The maps utilize the same format as the existing NASA shaded-relief Lunar Planning Charts (LOC-1, -2, -3, and -4), which have a scale of 1:2 750 000. The map contour interval is 500 m. A control net derived from Apollo photographs by Doyle and others was used for the compilation. Contour lines and elevations are referred to the new topographic datum of the Moon, which is defined in terms of spherical harmonics from the lunar gravity field. Compilation of all four LOC charts was completed on analytical plotters from 566 stereo models of Apollo metric photographs that cover approximately 20% of the Moon. This is the first step toward compiling a global topographic map of the Moon at a scale of 1:5 000 000.

1. Introduction

Laser altimeter measurements of the Moon along the tracks of the Apollo spacecraft as well as the results of other lunar studies have shown that the Moon is slightly egg-shaped, with the small end pointing toward the Earth (French, 1977). Its asymmetry is thought to be caused by interaction between the gravity fields of the Earth and Moon. Low mare features cover much more area on the near side than on the rugged terrain of the far side of the Moon. Since its center of mass is displaced about 2 km toward the Earth from its center of figure (Bills and Ferrari, 1977), and thus a spherical figure does not adequately describe the Moon, lunear maps that are based on a spherical figure may not be adequate for detailed studies of the lunar surface. In contrast, a global topographic map that is based on the lunar gravity field will not only represent the general topography and thus provide knowledge of the Moon's overall physical structure, internal strength, geology, and composition, but also will be useful in the planning for future lunar missions. For this reason a global topographic map of the Moon is being compiled from topographic information derived from photographs of the Apollo and Lunar Orbiter missions, from Apollo laser altimetry, and from lunar radar sounder and Earth-based radar observations. The map will be compiled at a scale of 1:5 000 000 and use a contour interval of 500 m (Wu, 1979, 1981a). For this compilation, a new topographic datum for the Moon has been defined that is based on the lunar gravity field (Wu, 1981b).

As an intermediate step, contour maps are being compiled by photogrammetric methods, using stereoscopic combinations of all available metric photographs from the Apollo 15, 16, and 17 missions (Wu, 1981c, 1982). Both the global map and the intermediate maps (see discussion in Section 3 below) use a control net derived by the joint efforts of the National Oceanic and Atmosperhic Administration and the U.S. Geological Survey (NOAA/USGS) (Doyle *et al.*, 1977). Intermediate products will be

Earth, Moon, and Planets **32** (1985) 165–172. 0167–9295/85/0322–0165$01.20.

TABLE I

The fifth-degree and fifth-order gravitational coefficients of the Moon with sixth-degree sectorial terms (Ferrari *et al.*, 1980).

Coefficients (C_{nm})	Value ($\times 10^{-6}$)	Coefficients (S_{nm})	Value ($\times 10^{-6}$)
C20	−202.1510	S20	
C21	− 0.1014	S21	0.0
C22	22.3025	S22	0.0173
C30	− 12.1260	S30	
C31	30.7083	S31	5.6107
C32	4.8884	S32	1.6874
C33	1.4360	S33	−0.3344
C40	0.1454	S40	
C41	− 7.1778	S41	2.9474
C42	− 1.4395	S42	−2.8844
C43	− 0.0855	S43	−0.7890
C44	− 0.1549	S44	0.0564
C50	− 44.6452	S50	
C51	3.2601	S51	6.7327
C52	1.5556	S52	0.5218
C53	− 0.1481	S53	0.1273
C54	0.0598	S54	0.0456
C55	0.0122	S55	0.0137
C66	0.1636×10^{-10}	S66	0.3531×10^{-8}

published as special maps in the format of the existing NASA Lunar Planning Charts, LOC-1, -2, -3, and -4 (NASA, 1971).

2. Topographic Datum

The new lunar topographic datum has been defined from the lunar gravity field in terms of spherical harmonics of fifth-degree and fifth-order with sixth-degree sectorial terms (Wu, 1979, 1981b). Gravity coefficients that were used to define the datum were derived by Sjogren (cf. Ferrari *et al.*, 1980) using Lunar Orbiter IV tracking and laser-ranging data; they are listed in Table I as C_{nm} and S_{nm}. The gravitational potential of the Moon is shown in Figure 1. The J_2 term is not included in the map. By use of a mean radius (R_m) value of 1738 km, the rotational velocity of the Moon, ω as $0.266\,17 \times 10^{-5}$ rad sec^{-1}, and a value of 4902.799 km^3 sec^{-2} for μ, the topographic datum of the Moon, R_D, is computed by the equation

$$R_D = R_m + \Delta R_m, \tag{1}$$

where

$$\Delta R_m = \Delta r + \tfrac{1}{2}\omega^2 \frac{R_m^4}{\mu} \cos^2 \phi \tag{2}$$

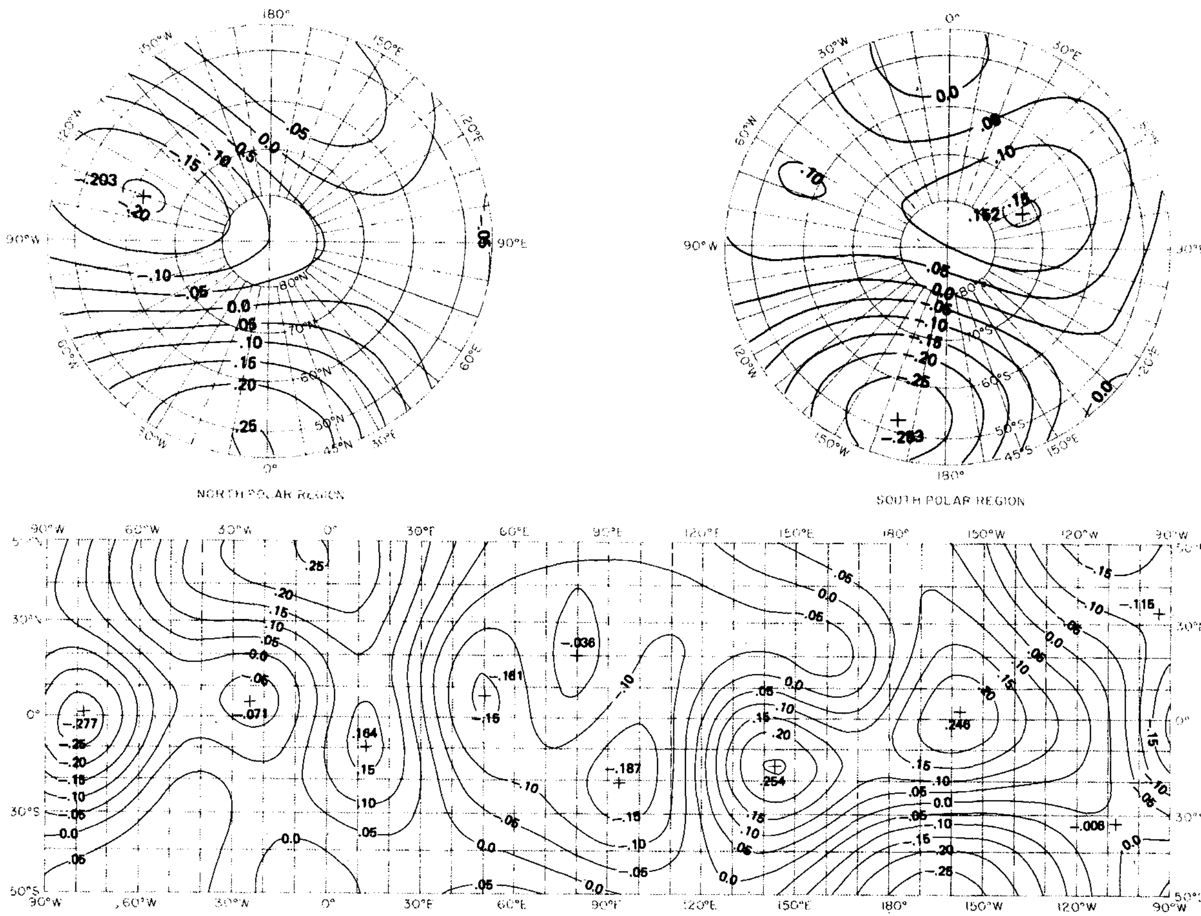

Fig. 1. Contour map of gravitational potential of the Moon, fifth-degree and fifth-order spherical harmonics, with sixth-degree sectorial terms. J_2 is set equal to zero. Contour interval 0.05 km. Mercator projection shows latitudes + 50° to − 50° and polar stereographic projections show latitudes higher than 45°.

and

$$\Delta r = R_m \sum_{n=1}^{N} \sum_{m=0}^{n} P_{nm} (\sin \phi) [C_{nm} \cos m\lambda + S_{nm} \sin m\lambda], \tag{3}$$

where r is the radial distance of the orbiter from the Moon, and P_{nm} denotes the associated Legendre polynomials; ϕ and λ are latitude and longitude of the Moon, respectively.

Equation (3) is derived from the spherical harmonics expansion used to represent the lunar gravity field potential as

$$U = \frac{GM_p}{r} \left[1 - \sum_{n=2}^{\infty} J_n \left(\frac{A}{r}\right)^n P_{no} \sin \phi + \sum_{n=2}^{\infty} \sum_{m=1}^{n} P_{nm} \left(\frac{A}{r}\right)^n \sin \phi \, (C_{nm} \cos m\lambda + S_{nm} \sin m\lambda) \right], \tag{4}$$

where G is the constant of gravitation, M is the mass ($\mu = GM$), and A is the equatorial radius.

The topographic datum of the Moon is a mathematical surface and can also be represented graphically as a contour map as shown in Figure 2. The values of R_D for a 5° increment in both longitude and latitude are also computed and have been published (Wu, 1981b).

Geometrically, the lunar topographic datum can be approximated by a triaxial ellipsoid as: $A = 1738.299$ km, $B = 1738.182$ km, $C = 1737.649$ km, and $f = 0.0003$.

3. Selenographic Control and Coordinate System

Analytical photogrammetric methods, based on the known positions and orientations of camera stations provided by Earth-based tracking, orbital ephemerides, laser altimeter data, and stellar cameras, are considered the best means of establishing ground-control networks for extraterrestrial bodies. From 1244 metric photographs takine within 24 paths of the Apollo 15, 16, and 17 missions, the Defense Mapping Agency (DMA) and the National Oceanic and Atmospheric Administration (NOAA) in cooperation with the U.S. Geological Survey (USGS) have each established a single integrated selenocentric control network of the Moon (Schimerman, 1973; Doyle *et al.*, 1977). Materials and data used to generate the two networks were essentially the same; the approaches taken, however, were fundamentally different: DMA used the orbital constraints to force a best fit between tracking and photogrammetry and to fit Apollo 16 and 17 to 15 results, whereas NOAA/USGS performed a purely photogrammetric solution that obtained a simultaneous adjustment of 23 436 unknown parameters in the data of all three missions. The results of the NOAA/USGS network, which produced 5324 terrain control points, are considered to be superior because 70% of the adjusted points have positional accuracy of better than 30 m and 74% of the elevation values are accurate to 30 m (Doyle *et al.*,

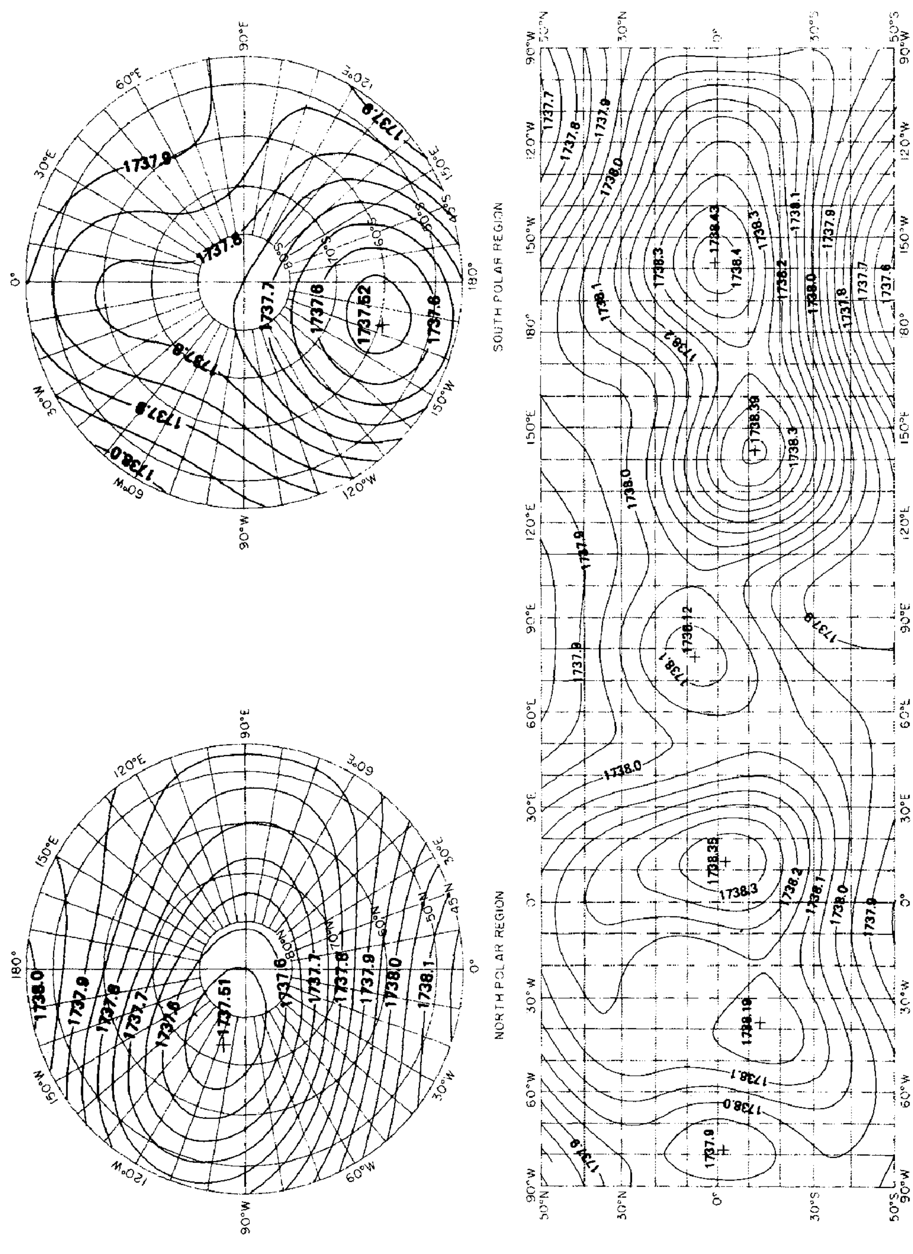

Fig. 2. Contour map of the topographic datum of the Moon. This figure is derived from the lunar gravity field in terms of fifth-degree and fifth-order with sixth-degree sectorial terms spherical harmonics with respect to a mean radius of 1738.0 km. Contour interval 0.05 km.

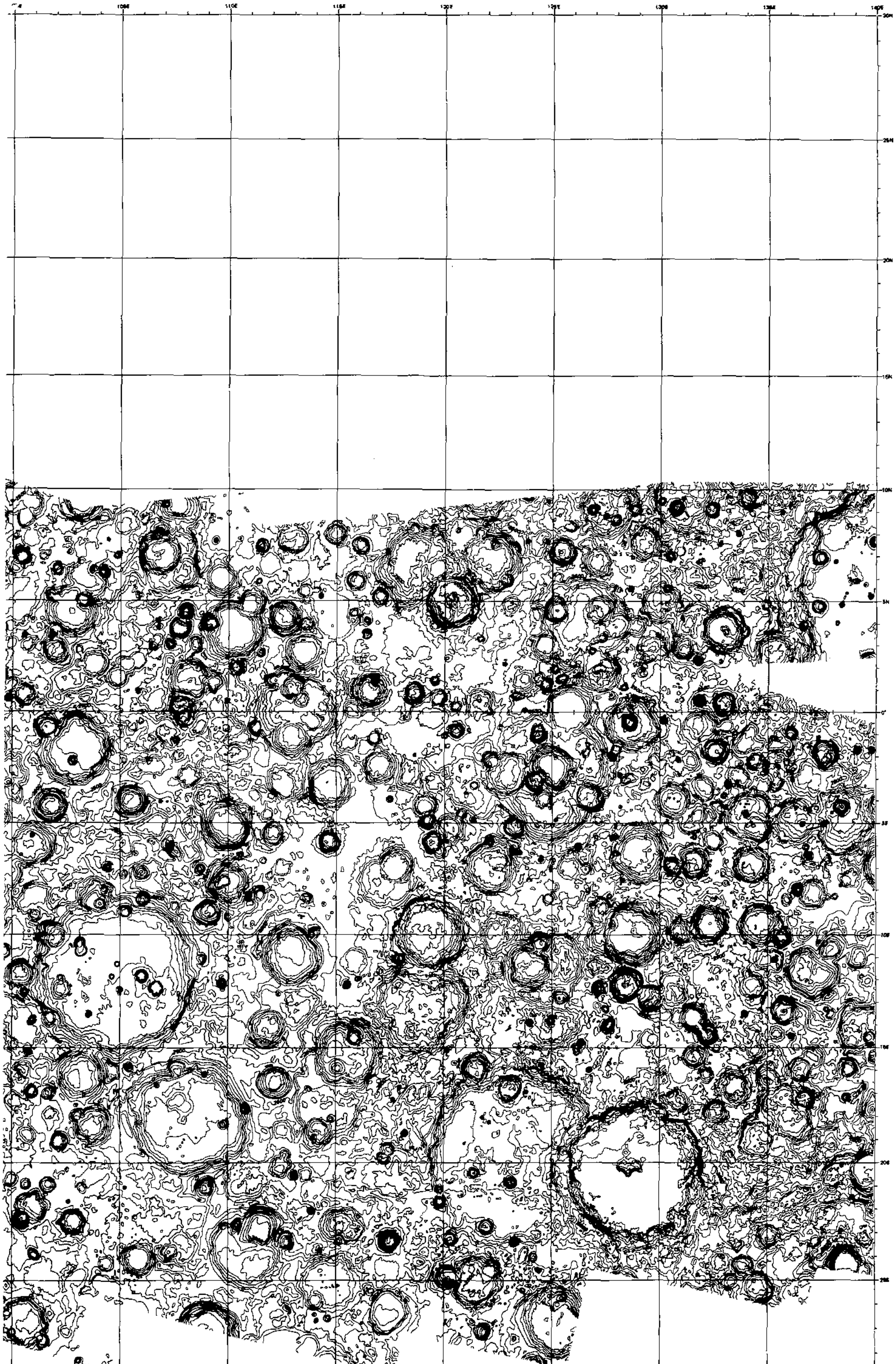

Fig. 3. A portion of LOC-3 contour map of the Moon. Map is compiled by photogrammetric methods using Apollo metric photographs. Contour interval is 500 m.

1977). Therefore, the NOAA/USGS selenocentric geodetic control network has been adopted for the compilation of the global topographic map of the Moon (Wu, 1979). Since the NOAA/USGS network used the Eckhardt Libration Model of the Moon (Doyle *et al.*, 1977; Eckhardt, 1973; Williams *et al.*, 1973), the new global topographic map will be in the same selenographic coordinate system as the Eckhardt Libration Model.

4. Contour Mapping

Data sources used to obtain topographic information for the global map of the Moon include: (1) photographs obtained during the Apollo and the Lunar Orbiter missions (Dietrich and Clanton, 1972a, b; McEwen and Clanton, 1973), (2) laser altimeter data (Roberson and Kaula, 1972; Wollenhaupt and Sjogren, 1972; Wollenhaupt *et al.*, 1973), (3) lunar radar sounder data (Phillips *et al.*, 1973), and (4) Earth-based observations (Arthur and Bates, 1968; Kopal, 1961; Meyer, 1980). Contour maps were compiled as an intermediate step and are being published as special maps that utilize the existing NASA Lunar Planning Charts LOC-1, LOC-2, LOC-3, and LOC-4 (scale 1:2 750 000). As an example, Figure 3 shows contour lines of a portion of LOC-3, covering a region from 100° E to 140° E of longitudes. Maps have a contour interval of 500 m. Contours were compiled on the AP/C, AS11-A, and an upgraded AS11-AM analytical plotters using a total of 566 stereo models (Wu, 1982). Elevation values have a precision of better than 100 m. A Mercator projection is used for these maps. Maps will be available at the Branch of Astrogeology, U. S. Geological Survey, Flagstaff, AZ.

5. Further Work

The ultimate goal of lunar mapping is to complete the compilation of a global topographic map of the Moon at a scale of 1:5 000 000. After a 1.8182 reduction, these maps from stereoscopic compilation will be a part of the final global map (about 20 percent of the lunar surface). The rest of the lunar surface coverage will be compiled by the synthesis of topographic information to be derived from various data sources available.

Acknowledgements

The author wishes to express his gratitude to colleagues in the U.S. Geological Survey including Raymond Jordan, Francis Schafer, Michelle Kerrick, Anni-Elpis Howington, Patricia Garcia, Colleen Maurer, Carol Hildeman, Sherri Bergstrom, and Susan Roeming, who compiled the maps on the analytical plotters; the author also thanks Loretta Barcus and Robert Gurule for their computer programming. Maps were prepared on behalf of the Planetary Geology Program, Office of Space Science, National Aeronautics and Space Administration under contracts W-13, 709 and W-14, 421.

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