THE GRAVITATIONAL FIELD OF THE MOON: GODDARD LUNAR GRAVITY MODEL-1; Frank G. Lemoine[1,2], David E. Smith[2], and Maria T. Zuber[3,2], [1]Astronomy Department, University of Maryland, College Park, MD 20742, [2]Laboratory for Terrestrial Physics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771 and [3]Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, MD 21218.

Summary. Information on planetary gravity fields provides information on the internal structure of the planet, and is essential for accurate navigation by orbiting and landing spacecraft. We have recently re-evaluated the gravity field of the Moon using data obtained from the Clementine mission along with the historic data acquired from the Apollo-15 and Apollo-16 subsatellites, and Lunar Orbiters 1 through 5. In this paper we describe the data used in the model and the techniques employed in the development of the field, and examine the resolution and characteristics of the field. We also characterize spatially the errors associated with the new gravity field solution by evaluating the field in a statistical sense and by examining correlations with visible features over different sections of the planet.

Data. The data sets were velocity perturbations of the various spacecraft as determined from the Doppler shift of the tracking signals. The data include 361,000 S-Band Doppler observations from Clementine, which provides a powerful constraint on the low degree and order field of the Moon, as well as 330,000 observations from the other satellites. The accuracy of the clementine data ranged from 0.3 mm s^{-1} for data collected at Deep Space Network sites (Goldstone, Canberra, Madrid) to 3 mm s^{-1} for data collected from the Navy's Pomonkey tracking site in southern Maryland. The older satellites, which orbited the Moon from 1966 to 1968 in the case of the Lunar Orbiters and from 1971 to 1972 in the case of the Apollo 15 and 16 subsatelites, provide distributed regions of high resolution coverage in region of ±40° of the lunar equator.

Development of the Field. To determine the gravity field first determined the spacecraft orbit with respect to the Moon's center of mass. In both the orbit determination and gravity field recovery procedures we utilized NASA/GSFC's GEODYN programs [1], which numerically integrate the spacecraft cartesian state and force model partial derivatives by employing a high order predictor-corrector model. The force model includes spherical harmonic representations of the lunar and terrestrial gravity fields, as well as point mass representations for the Sun and other planets. We estimated solar radiation pressure, tidal parameters, planetary rotation, measurement and timing biases and tracking station coordinates along with the orbit. Spacecraft jet firings to relieve attitude disturbance torques were accounted for by explicitly estimating them in the orbit determination process or by simply breaking the arc at the time of the maneuver.

In developing the gravity model, we applied an *a priori* power law constraint of the form $15x10^{-5}/l^2$, where l is the spherical harmonic degree [2]. This constraint has the effect of bounding the gravitational power in the wavelengths whose effect on the signal is at or below the noise level. In addition, we judiciously down-weighted some of the low altitude data to avoid inducing spurious signals in the model, commonly manifest as "striping" in the field, at short wavelengths. These techniques, which we have previously applied in models of the gravity fields of Earth, Mars and Venus [3, 4, 5], has the advantage of preserving short wavelength information in the field where it is well-resolved by the tracking data. In the model development we slectively downweighted spurious arcs and avoided construction of arcs that spanned the time of spacecraft maneuvers. We evaluated the field at the surface, rather than at spacecraft altitude, as has been done by previous workers [6, 7, 8].

Details of the Model. We performed a 70th degree and order spherical harmonic expansion (80 km half wavelength spatial resolution) to yield the gravitational field model designated Goddard Lunar Gravity Model-1 (GLGM-1). Because of the Moon's synchronous rotation, spacecraft cannot be directly tracked from Earth over most of the lunar farside, so there is no tracking data from 120o-240o longitude in the ±45° latitude band. Nonetheless, orbiting spacecraft are sensitive to the positions of gravity anomalies even in areas without direct tracking,

LUNAR GRAVITY FIELD: Lemoine, F.G. et al

as evidenced by numerous anomalies that correlate with major impact basins. However, themagnitudes of gravity anomalies in occulted regions are characterized by much larger errors than in regions that directly tracked from Earth. Gravity anomaly errors from GLGM-1 ranged from 27 mGals over the well-tracked nearside at low latitudes to 42 mGals for the high latitude farside.

The model clearly shows the gravity highs or "mascons" that correlate with the major nearside basins. The mascons, which were first recognized from Lunar Orbiter tracking data [9], are believed to be a consequence of the gravitational attraction of lava fill in mare basins [10] and of uplifted mantle beneath the basins [11, 12]. The improved short wavelength control in our representation of the field, however, reveals that many of the mascons are ringed by negative anomalies outside the basins that suggest flexure of the lunar lithosphere in response to loading by the fill of mare lavas and crustal thinning accompanying the impact process [13]. Our model also shows gravitational signatures of several farside basins that have not previously been resolved or well-resolved, including: Hertzprung, Korolev, Freundlich-Sharonov, Moscoviense, and Tsiolkovsky.

GLGM-1 shows that, as in previous lunar gravity models, the highland terrains are gravitationally smooth, indicating a state of isostatic compensationIn contrast to the highlands, lunar basins display a broad range of isostatic compensation states. Nearside mascon basins, which display large free-air positive anomalies, are distinctly uncompensated. The gravitational signature indicates that surface topography is supported flexurally and demonstrates that in the vicinity of these impact structures the lunar lithosphere, *i.e.* rigid outer shell, displayed considerable strength at times since basin infilling by mare basalts [14, 15]. In contrast, the South Pole-Aitken basin on the lunar far side has a modest free-air anomaly for its depth, and is in fact approximately 90% compensated. Our field resolves South Pole Aitken as 2-3 separate lows with a magnitude of -100 to -125 mGals. The 5-km deep Mendel-Rydberg basin shows a very small 25 mGal free-air anomaly and so is almost fully compensated.

The model reveals a marked asymmetry in the free-air gravitational signature of Mare Orientale, the youngest major impact basin on the Moon (age ~3.9 BY)[16]. This basin exhibits a comparatively modest 125 mGal mascon at basin center that is surrounded by a horseshoe-shaped gravity low with a maximum amplitude of -225 mGals centered on the inner and outer Rook rings. In contrast to the nearside basins that are encircled by negative anomalies outside the basins, the discontinuous negative is inside the Orientale basin and the basin is bounded by a gravity high centered on the Cordillera ring. Earlier studies have recognized a "bullseye" appearance of Orientale's gravity signature [7, 8, 17], but careful consideration of low altitude orbital passes shows that the asymmetry is a characteristic feature of the basin. Regional modeling of the structure of individual basins is underway [13, 18].

References. [1] McCarthy J.J. et al. (1994) *NASA /GSFC and Hughes/STX Contractor Report.* [2] Kaula W.M. (1966) *Theory of Satellite Geodesy.* (Blaisdell, Waltham). [3] Marsh J.G. et al. (1990) *J. Geophys. Res., 95,* 22,043. [4] Smith D.E. et al. (1993) *J. Geophys. Res., 98*, 20,871. [5] Nerem R.S. et al. (1993) *Geophys. Res. Lett., 20,* 599. [6] Sjogren W.L. et al. (1975*) J. Geophys. Res., 80*, 2899. [7] Bratt S. R. et al (1985) *J. Geophys. Res., 90,* 3049. [8] Konopliv A.S. et al. (1993) AIAA Astrodynamics Specialist Conference Victoria, B.C., Canada), vol. *AAS 93-622.* [9] Muller P.M. et al. (1968) *Science, 161,* 680. [10] Phillips R.J (1972) *J. Geophys. Res., 77,* 7106. [11] Kaula W.M. (1969) *Phys. Earth Planet. Int., 2,* 123. [12] Wise D.U. and Yates M.Y.s (1970*) J. Geophys. Res., 75,* 261. [13] Williams, K.K. et al. (1995) *LPSC, XXVI*, this volume. [14] Solomon S.C. and Head J.W. (1979) *J. Geophys. Res., 84,* 1667. [15] Solomon S.C. and Head J.W. (1980) *Rev. Geophys., 18,* 107. [16] Wilhelms D.E. (1987) The Geologic History of the Moon. *U.S. Geol. Survey Prof. Paper 1348* (US Govt. Printing Office, Washingotn, DC). [17] Sjogren W.L. et al. (1976) *Proc. Lunar Sci. Conf., 3rd,* 2639-2648. [18] Neumann G.A. et al. (1995) *LPSC, XXVI*, this volume.