Lunar Prospector: Gravity Mapping

A.S. Konopliv

Jet Propulsion Laboratory, California Institute of Technology, Pasadena

Abstract. Lunar Prospector, the third mission of the NASA Discovery series, is scheduled to launch Oct. 24, 1997. One of the objectives of the mission is to map the gravity field of the Moon using radiometric Doppler tracking data from JPL's Deep Space Network, Below we access the expected improvement in the lunar gravity field from this mission and identify the products that will be made available to the scientific community. In summary, Lunar Prospector will provide dramatic improvement in the nearside higher latitude and polar regions and improvement in the nearside mid-latitude regions., allowing for better internal modeling of the Moon.

Introduction

In April 1966 the Russian's Luna 10 spacecraft's orbiting the Moon provided the first dynamical proof that the Moon's oblateness was far larger than what would be predicted from hydrostatic conditions. These results were produced by Akim [1966] when he evaluated the secular motion of the spacecraft's orbital state element in the ascending node. His results for J_2 and C_{22} are fairly close to our present day best estimates.

During that same year in August of 1966 the first U.S. Lunar Orbiter was launched and four more were placed in orbit by August of 1967. Many investigators analyzed these data for detailed structure in the gravity field. Lorell [1968] and colleagues at JPL produced spherical harmonics fields up to degree 8. Muller and Sjogren [1968], using a rather novel technique of differentiating the Doppler residuals, produced a frontside gravity map that displayed very large positive gravity anomalies within the large circular maria basins. This result was completely opposite of any geophysical model at that time and started the development of new models of the Moon's interior.

The features were called Mascons, which was a contraction for mass concentrations. The Apollo missions had orbits that were at very low altitudes over the basins and their detailed Doppler profiles revealed that the Mascons are near surface anomalies rather than deep buried structures.

Further analyses into the 1970s were continued by Ferrari [1977] and Bills and Ferrari [1980] to at most degree and order 16. Konopliv et al [1993] extended the resolution to degree and order 60 using all the available historic data, More recently, Lemoine et al [1997] included the Clementine tracking data with the same historic Lunar Orbiter and Apollo data and he showed that the Clementine data, from an elliptical orbit with a higher periapse altitude of 400 km, provided improvement in the low degree (n=2,3) and sectoral terms (to degree 20) of the gravity field.

Gravity Data Coverage

Lunar Prospector (LP) will be placed in a polar (within 1/2 degree) initially circular orbit around the Moon with an altitude of 100 km (see Binder [1997]). The gravity field of the Moon, in particular the zonal coefficients, will cause reduction of the periapse altitude because of long term increase in the orbit eccentricity. The Apollo 16 subsatellite, which had no propulsive system, impacted the lunar surface in 35 days after release from a circular 100 km altitude. The rate decrease for the periapse altitude is a function of the inclination of the orbit with respect to the Lunar equator. The rate of LP has a large uncertainty since there has not previously been a low polar circular orbiter. To maintain an altitude of at least 75 km, orbit maintenance maneuvers are expected roughly every month.

The measurements used for the Lunar gravity field determination will be two-way coherent Doppler tracking of the LP spacecraft acquired at the Deep Space Network complexes at Goldstone, California; Madrid, Spain; and Canberra, Australia. The LP tracking data will consist of S-band (22 Ghz) uplink and downlink, compressed to 5 second intervals. This is equal to the spin period of LP and will minimize the spin effects in the Doppler data since the Doppler data is essentially difference range at the sample interval end times. The orbital velocity of 1.6 km/s allows for 3 to 4 measurements for 1 degree on the lunar surface (3O km). The expected precision of the S-band measurements is 0.3 mm/s for 1 minute compression times (as was obtained by Clementine, Zuber et al [1994]; LP will be carrying the same make Near-Earth Loral transponder as Clementine).

The current high resolution gravity data coverage from the Lunar Orbiters I-V, Apollo subsatellites, and Clementine is limited to the nearside (visible from Earth) equatorial region between 30” N and S latitude. Figure 1 shows the current resolution in spherical harmonic degree and order for all the existing data (see Konopliv and Sjogren [1995] and [1996] for how this degree strength map is calculated). The highest resolution is the equatorial nearside at degree and order 90. The high latitude regions and lunar farside (for which there is no direct Doppler tracking) shows a resolution of at most degree and order 30.

Prospector will be tracked nearly continuously by the DSN because of data downlink requirements. Since it is in a 2-hour circular orbit, a global data set will be nearly complete after 14 days with a 1.1 degree spacing between orbits. Tracking data for gap fills and finer resolution with differing altitudes will follow for the remaining months of the one-year nominal mission. In the planned extended mission, periapse altitude will be lowered to 10 km for very high resolution gravity mapping,

Expected Gravity Results

Prospector will improve the resolution for the entire nearside of the Moon to about degree and order 90 (i.e., 2* or 60 km surface resolution). This is a dramatic improvement for the nearside mid-latitude and polar regions. Although there is no direct tracking of the lunar farside, LP will improve the long wavelength gravity information for especially the higher latitudes of the farside. High resolution mapping of the lunar farside will have to wait for a future mission with direct observation using two spacecraft or on-board gradiometers.

Together with topography, the gravity field allows one to probe the interior structure of the Moon, although non-uniquely. With additional constraints this can lead to an understanding of Lunar tectonic and thermal evolution. The Clementine mission, with the Laser altimeter, provided dramatic improvement in the topography information for the Moon (Zuber, et al [1994], Smith et al [1996]). The improved Lunar gravity field which will result from LP data will allow, in conjunction with Clementine topography, for better selenophysical modeling of the Moon. Studies which will benefit from the better gravity models include crustal thickness investigations (Neumann et al [1996], which are important when addressing such issues as nearside-farside Lunar dichotomy, as well as long-wavelength compensation studies. The higher resolution of the gravity field will be useful in short wavelength studies of lithospheric support as well as studies involving Lunar Mascons. As a complement to the Clementine topography set, occultation times from Lunar Prospector when it goes behind the Moon will be collected. This will provide topography of the Lunar limb to the several hundred meter level and provide an independent constraint on the center of figure offset.

Since LP is a simple spin stabilized spacecraft with minimal propulsive maneuvers, it will be a valuable data set for investigating long term effects of the gravity field for mission planning and for science. As a precursor it will determine the fuel costs for any following lunar mission such as the proposed European MORO and Japanese SELENE missions.

The normalized polar moment of inertia (C/MR^2) or homogeneity constant for the Moon depends on the lunar libration parameters y and β (determined from the Lunar Laser Ranging or LLR, Dickey et al [1994], Williams et al [1996]) and the second order gravity harmonics $.1_2$ and C_{22}. A

C/MR^2 value of 0.4 indicates a homogeneous Moon and a value less than 0.4 indicates increasing density with depth. The current value of $C/MR^2 = 0.3929 \pm 0.0009$ (Williams [1996]) indicates a maximum core size of 220 to 350 km [Dickey et at, [1994], see Fig. 5). Improvement in the polar moment of inertia comes from improvement in the third degree harmonics for the LLR libration solution and in the second degree coefficients J_2 and C_{22}.

Table 1 lists the uncertainties in the second degree harmonics J_2 and C_{22} and the third degree harmonics for a solution based upon all the historical data (as in Konopliv et al [1993], as well as the Clementine data) and from the historical data plus 14 days of LP simulated data (using two 7 day arcs). The uncertainties of the historical solution (denoted CLEM75A by the author) listed in Table 1 are the formal uncertainties scaled up by a factor of 10 to reflect more realistic uncertainties. This scale factor is determined in the same fashion as Williams et al [1996] knowing that the coefficients C_{21}, S_{21}, and S_{22} are near zero. Such a large scale factor for these coefficients is required mostly because of unknown nonconservative forces on the spacecraft (mostly the attitude control system) that degrade the lower degree harmonics. With Lunar Prospector, the improvement in the coefficients range from factors of 2.5 to 6.1. So we expect a factor of two to three improvement in the polar moment of inertia and thus a finer constraint on the lunar core.

Also of interest is the tidal effect or Love number of the Moon. The Love number has been accurately determined from LLR data (0.0302 ± 0.0012), but Dickey et al [1994] points out that the LLR cannot separate out the contribution from ellipticity in the core-mantle boundary. The uncertainty in the Love number with the LP data is perhaps too large (0.012) to determine this effect, but may be improved with longer data arcs and additional months of data. The inherent accuracy of the Love number in the LP data set may have to wait until direct measurement of the gravity on the lunar farside is made to remove errors from medium to high degree gravity terms.

All the historical Doppler tracking data (including Clementine) will be combined with the LP data into a global spherical harmonic solution of at least degree and order 60, This solution will be made available to the scientific community one month after launch. The coefficients, full covariance, and corresponding maps will be archived at the Geosciences Node of the Planetary Data System in St. Louis, MO (see http://wwwpds.wustl.com). The maps include the geoid, freeair, and Bouguer (theoretical gravity from topography minus observed gravity) anomalies and their corresponding errors. Generation of line-of-sight accelerations relative to the spherical harmonic solution and their archival will be proposed through a follow-on data analysis program.

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A.S. Konopliv, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA, 91109.

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Table 1: Unnormalized second and third degree harmonic coefficients. (1) values from solution author's solution CLEM75A, (2) realistic uncertainties from CLEM75A, (3) uncertainties with 14 days of LP added, and (4) factor of improvement with LP.

Coeff (x10^6)	values[1]	Error[2]	LP Error[3]	Factor[4]
k_2	—	0.034	0.012	2.8
J_2	203.77	0.286	0.069	4.1
C**	22.39	0.074	0.029	2.5
J_3	7.69	0.312	0.069	4.5
C_{31}	28.66	0.87	0023	3.9
S_{31}	S.76	0.111	0.018	6.1
C_{32}	4.87	0.043	0.011	3.9
S_{32}	1.64	0.040	0.011	3.6
C_{33}	1.73	0.012	0.004	3.3
S_{33}	-0.25	0.011	0.004	2.8

Fig. 1 Spherical harmonic degree strength map for the existing lunar gravity data (LO, Apollo, Clementine). The contour lines represent the degree at which the amplitude of the gravity signal equals the noise form the solution covariance. Beyond this, the noise is greater than the signal.

Degree Strength for Lun90a

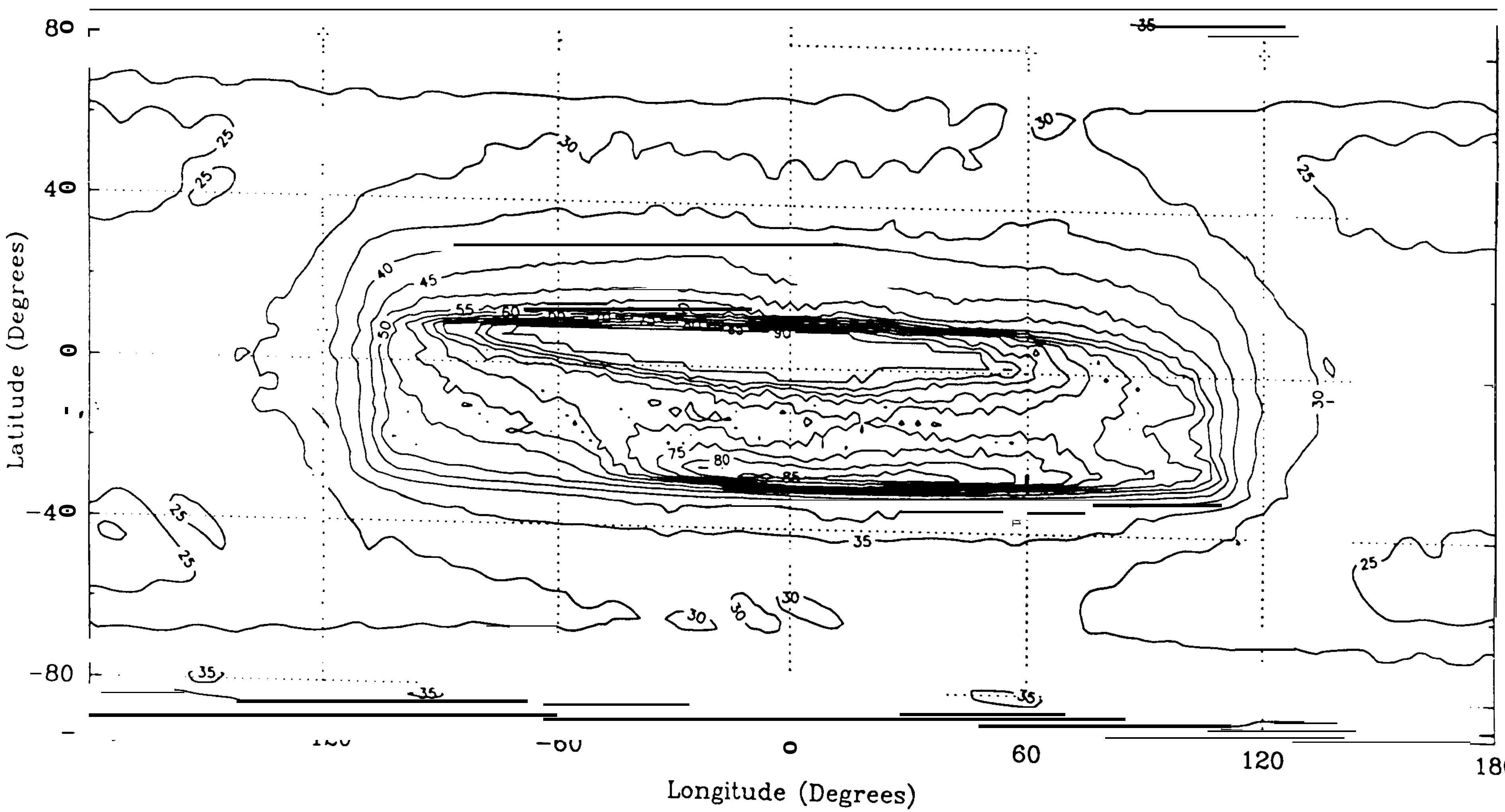

Figure 1