Expected Improvements in Lunar Gravity and Topographic Models Over the Next 2 Years From the 4 Upcoming Lunar Missions

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Introduction

In the next 2 years we will see a great increase in data that can be used to improve our knowledge of the lunar gravity field and the lunar topography.

- Selene (Kaguya) - already in lunar orbit
- Chang’E-1 - launched today
- Chandraayan - to be launched early next year (2008)
- LRO - to be launched late next year (2008)

- All missions plan to improve the gravity model of the Moon by tracking of a low altitude spacecraft.
- All missions carry laser altimeters for global scale topography.
## Spacecraft Orbits

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Altitude</th>
<th>Inclination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaguya (Japan)</td>
<td>~ 100 km</td>
<td>~ 90 degrees</td>
</tr>
<tr>
<td>Chang’E-1 (China)</td>
<td>~ 100 km</td>
<td>~ 90 degrees</td>
</tr>
<tr>
<td>Chandrayaan (India)</td>
<td>~ 100 km</td>
<td>~ 90 degrees</td>
</tr>
<tr>
<td>LRO (US)</td>
<td>~ 50 km</td>
<td>~ 90 degrees</td>
</tr>
</tbody>
</table>

All spacecraft will be significantly perturbed by the lunar gravity field which will affect coverage in the polar regions.
Ground-tracks and Coverage from 50 and 100 km Over South Polar Region

Patterns very similar, coverage appears more uniform from 100 km altitude

50 km altitude

100 km altitude

88S TO THE POLE
Orbital Perturbations of Near Polar Lunar Orbits

Example: LRO at 50 km; very similar changes at 100 km

- The mascons on the lunar near-side perturb the altitude of the orbit by ±15 km each month. The inclination is also perturbed by the mascons and the Earth’s attraction.
Motion of the Periapse Position of LRO Every 27 Days
Average Height of LRO above Lunar Surface

Spacecraft always higher over the lunar far-side

min 33.9 max 66.2 (km) about a Lunar 1737.4 km radius sphere

56 to 62 km  40 to 44 km  56 to 62 km
Variation in Height over the Lunar Surface (LRO)

Altitude variation over a given location is usually much smaller

min 0.0 max 27.2 (km) about a Lunar 1737.4 km radius sphere
History of Laser Altimetry at the Moon

Apollo and Clementine

- The first laser altimeter measurements of the Moon were made by the Apollo 15, 16, & 17 in the early 70’s.

- The last laser altimeter measurements were by Clementine in 1994.

The Apollo and Clementine altimeter measurements are the basis of today’s knowledge of the shape of the moon.
Lunar Topography Model (USGS)

Radial accuracy is about ~100 meters, 2°x2° square

Lunar topo in km about a 1737.4 km radius sphere
Lunar Gravity Model (Konopoliv et al)

Gravity obtained mainly from Lunar Prospector Tracking Data

mGal

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
Lunar Gravity Model, unconstrained (Konopoliv et al)

Figure shows effect of not being able to track over far-side

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
### Laser Altimetry at the Moon in the Next 2 Years

#### 4 Missions; 4 Laser Altimeters

<table>
<thead>
<tr>
<th>MISSION</th>
<th>MEAN ALTITUDE</th>
<th>RANGE ACCURACY</th>
<th>PULSE RATE</th>
<th>SPOT SIZE</th>
<th>LASER ENERGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>SELENE</td>
<td>100 km</td>
<td>± 5 m</td>
<td>1 to 0.5 Hz</td>
<td>40 m</td>
<td>100 mJ</td>
</tr>
<tr>
<td>CHANDRAYAAN</td>
<td>100 km</td>
<td>± 10 m</td>
<td>10 Hz</td>
<td>10 m</td>
<td>20 mJ</td>
</tr>
<tr>
<td>CHANG’E-1</td>
<td>100 km</td>
<td>± 5 m</td>
<td>1 Hz</td>
<td>200 m</td>
<td>150 mJ</td>
</tr>
<tr>
<td>LRO</td>
<td>50 km</td>
<td>± 0.1 m</td>
<td>28 Hz, 5 spots</td>
<td>5 m</td>
<td>2.7 mJ</td>
</tr>
</tbody>
</table>

Apollo: 1 Hz, 50 m range accuracy, ? ? ? spot  
Clementine: 0.5 Hz, 40 m accuracy, 200 m spot
<table>
<thead>
<tr>
<th>LOLA Measurement Accuracy/Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range to surface:</strong></td>
</tr>
<tr>
<td><strong>Surface Roughness:</strong></td>
</tr>
<tr>
<td><strong>Albedo (1064 nm):</strong></td>
</tr>
<tr>
<td><strong>Slopes, 2 directions:</strong></td>
</tr>
<tr>
<td><strong>Orbital altitude:</strong></td>
</tr>
<tr>
<td><strong>Along track position</strong></td>
</tr>
</tbody>
</table>
Cross-Calibration of Altimeters

Kaguya, Chang’E-1, Chandrayaan, LRO

• No single mission will observe the complete moon in one or two years

• Combining data across missions will require calibration of each altimeter on orbit - the floor of a small flat crater could be a calibration target

• Differing spot sizes will make comparison more difficult

• Orbital knowledge and accuracy will vary from mission to mission

Objective should be to obtain agreement at the 1 meter level for the radius of the moon at a specific location
Gravity Methods

Kaguya will employ a second spacecraft as its principal approach for gravity

The problem: We cannot track spacecraft over the lunar farside from Earth without a second s/c

LRO will use the LOLA laser altimeter, orbital cross-overs, and laser ranging from Earth
Laser Ranging to LRO

LR: 10 cm range precision
28 Hz, 532 nm

LOLA: 10 cm range accuracy
28 Hz, 1064 nm

LRO Precision Tracking

From a combination of LR, altimeter, and S-band tracking we estimate positional accuracies of ~25 m along track and ~0.5 m radially (CoM) after improvement of the lunar gravity field.
Laser Altimeters Can Use Orbital Cross-Overs

Earth Tracking

Cross-overs - 1 month

Cross-overs occur about every 1 km in longitude and 3 deg in latitude at equator

Cross-overs - 1 year

2 degs in longitude
Position Error after Gravity Model Improvement

LRO simulation suggests significant improvement

Average RSS Position Error

221 m Approx. orbital accuracy with present gravity field.

23 m Altimetry+Laser Ranging+S-band
Power Spectrum of New Models

Kagua will make the largest improvement in the lunar gravity
Significant Improvements in Lunar Shape Model

Better Instrumentation, New Approaches

• Better altimeter instrumentation
• Longer missions than Apollo and Clementine
• Tracking on the lunar far-side
• Use of orbital cross-overs approach
  - altimetry
  - surface slopes
  - surface roughness
  - very large number of cross-over locations. all latitudes
  - but, computationally complex
Significant Improvements in Lunar Gravity Model

- Tracking over the lunar far-side

- Use of orbital cross-overs approach for orbit and gravity
  - altimetry, surface slope, surface roughness

- Tracking with VLBI, X-band, for improved spacecraft positioning, multiple satellites

- Greater gravity resolution - approx 2 degrees on the lunar surface (50 to 60 km) - limited by spacecraft altitude
Potential Lunar Gravity and Shape Accuracies

- **Topography & Shape**
  Positional knowledge of surface features … ~ 50m
  Radial knowledge of surface… ~ 1m

- **Gravity Field and Geoid**
  Lunar near-side: limited improvement
  Lunar far-side: major improvement, equal to lunar near-side
  - **Accuracy:** ~ 10 mGals 2x2 degree square.
Summary

- The new missions will permit significant improvements in both lunar shape & topography, and gravity models.
- A full geodetic coordinate system in both body fixed and inertial coordinates will be derivable from these datasets.
- We can expect to know distances and locations of lunar features to 25 to 50 meters horizontally (~50 to 70 meters from LRO) and 1 meter radially, in a center of mass system.
- We could know the Moon almost as well as many areas on Earth (~10 meters)!

Gravity could be adequate for landing at identified locations to within ± 50 meters.