Laser Altimetry

Reinald Kallenbach

- Measurement Technique
- Instruments
- Planetary Science
- BepiColombo Laser Altimeter Project at MPS
Measurement Technique

28 October 2010

IMPRS lecture
Measurement Technique

- Power Supplies and Thermal Interface
- Diode-pumped Nd:YAG Laser
- Computer and Data Interface
- Ranging and Waveform Electronics
- Detector Filters

Flow: Laser light → Beam Expander → Diode-pumped Nd:YAG Laser → Computer and Data Interface → Ranging and Waveform Electronics → Detector Filters

Trigger signal for timer:

Backscattered light from target surface
Measurement Technique

extra pulse spread:

$$\Delta T_s = \frac{2}{c} \cdot \tan(\Phi + S) \cdot Z \cdot \Delta \Phi$$

c: speed of light

$$\Phi$$: off-nadir pointing angle

S: surface slope

Z: slant range to the surface

$$\Delta \Phi$$: laser divergence angle or uncertainty in pointing angle
**Measurement Technique**

### Link budget (Example BELA)

Number of photoelectrons on detector:

\[
N_r = \left( \frac{E_t \cdot \eta}{h \cdot v} \right) \cdot \left( \frac{A_r}{Z^2} \right) \cdot t_{sys} \cdot t_{atm}^2 \cdot \left( \frac{r_{tar}}{\Omega_{tar}} \right)
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit laser energy</td>
<td>(E_t)</td>
<td>50 mJ</td>
</tr>
<tr>
<td>APD quantum efficiency</td>
<td>(\eta)</td>
<td>0.36</td>
</tr>
<tr>
<td>Photon energy</td>
<td>(h \cdot v)</td>
<td>1.875 \cdot 10^{-19} J</td>
</tr>
<tr>
<td>Receiver telescope area</td>
<td>(A_r)</td>
<td>0.049 m²</td>
</tr>
<tr>
<td>Range to Mercury</td>
<td>(Z)</td>
<td>400 km</td>
</tr>
<tr>
<td>System transmission</td>
<td>(t_{sys})</td>
<td>0.77</td>
</tr>
<tr>
<td>Atmospheric transmission</td>
<td>(t_{atm})</td>
<td>0.9</td>
</tr>
<tr>
<td>Target scattering angle</td>
<td>(\Omega_{tar})</td>
<td>(\pi)</td>
</tr>
<tr>
<td>Target diffuse reflectivity</td>
<td>(r_{tar})</td>
<td>0.25</td>
</tr>
</tbody>
</table>

\[
N_r = 1460 \text{ at } Z = 400 \text{ km to Mercury}
\]
Instruments
Mercury Laser Altimeter (MLA)
Cavanaugh et al. (2007)
Instruments

*MLA orbit (Cavanaugh et al., 2007)*

[Diagram showing the MLA orbit with labels for dawn-dusk orbit, perigees at ~300 km altitude and 60-70°N latitude, noon-midnight orbit, and orbit insertion details.]
**Instruments**

**MLA Transmitter (Cavanaugh et al., 2007)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1.064.5 nm ± 0.2 nm</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>20 mJ ± 2 mJ</td>
</tr>
<tr>
<td>Pulse width</td>
<td>6 ns ± 2 ns</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>8 Hz</td>
</tr>
<tr>
<td>Beam divergence (1/e^2)</td>
<td>less than 80 μrad</td>
</tr>
</tbody>
</table>

### Error source

<table>
<thead>
<tr>
<th>Error source</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading edge timing</td>
<td>0.06 m</td>
</tr>
<tr>
<td>Clock frequency error (0.1 parts per million)</td>
<td>0.20 m</td>
</tr>
<tr>
<td>Measurement quantization (2.5 ns)</td>
<td>0.11 m</td>
</tr>
<tr>
<td>Pointing angle uncertainty (0.13 mrad)</td>
<td>0.68 m</td>
</tr>
<tr>
<td>Spacecraft orbit knowledge error</td>
<td>0.75 m</td>
</tr>
<tr>
<td>Total (root sum squared)</td>
<td>1 m</td>
</tr>
</tbody>
</table>

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Instruments

Detector: Avalanche Photodiode (APD)

\[
\frac{S}{N} = \frac{I_L^2 \cdot M^2}{2q \cdot (I_L + I_{DG}) \cdot B \cdot M^2 \cdot F(M) + 2q \cdot I_{DS} \cdot B + \frac{4 \cdot k_B \cdot T \cdot B}{R_L}}
\]

where

- \( q \): Charge of the electron
- \( I_L \): Photocurrent at \( M=1 \)
- \( I_{DG} \): Dark current component to be multiplied
- \( I_{DS} \): Dark current component not to be multiplied
- \( B \): Bandwidth
- \( M \): Multiplication ratio (gain)
- \( F \): Excess noise factor
- \( T \): Temperature
- \( k_B \): Boltzmann constant
- \( R_L \): Load resistance
Instruments

**MOLA: Mars Orbiter Laser Altimeter**

NASA – Mars Global Surveyor MGS
Planetary Science

MOLA: Mars Orbiter Laser Altimeter

NASA – Mars Global Surveyor MGS
Planetary Science
Seasonal variations of Mars polar ice caps

MGS/MOLA

Hubble

Viking I

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12
Laplace resonance Io, Europa, and Ganymed in Jupiter system: Europa diurnal tides

- Love number $h_2$: vertical displacement of surface relative to height of tidally perturbed potential surface
  
  \[ \text{depends on presence of subsurface ocean} \]

<table>
<thead>
<tr>
<th></th>
<th>no ocean</th>
<th>ocean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europa</td>
<td>0.1</td>
<td>30 m</td>
</tr>
<tr>
<td>Ganymede</td>
<td>0.5</td>
<td>7 m</td>
</tr>
<tr>
<td>Callisto</td>
<td>0.3</td>
<td>5 m</td>
</tr>
</tbody>
</table>

\[ \text{Moore & Schubert (2000, 2003); Tobie 2003} \]

- Love number $k_2$: additional gravitational potential due to displaced mass, relative to tide generating potential
  
  \[ \text{depends on (Wu et al., 2001) thickness of ice shell, rigidity of mantle, density of ocean (not depth), presence outer/liquid core} \]
• X-band Doppler tracking
  0.09 mm/s range rate error
  Goldstone & Madrid stations
  (degree > 20)
  - static and tidal gravity
  - Jupiter attraction
  - Europa Albedo
  - IR thermal radiation
  - 3.55 day forced libration

• Simulations laser altimetry:
  Koch et al. (2009)

Wu et al. (2001): Error of 0.002 in $h_2/k_2$
corresponds to 1 km thickness of ice shell
Planetary Science

Time-dependent variation of Mercury’s topography due to solar gravitation

3:2 Spin-Orbit Resonance of Mercury

Forced libration

\[
\frac{C_m}{C} = \frac{C_m}{B - A} \times \frac{B - A}{M a^2} \times \frac{M a^2}{C}
\]

Solar tides

\[
\delta r_{\text{tide}} = h_2 F_{\text{nd}}(\psi, R) = h_2 \frac{M_{\text{sun}}}{M_{\text{merc}}} \frac{a^4}{R^3} \left( \frac{3}{2} \cos^2[\psi - \delta] - \frac{1}{2} \right)
\]
Planetary Science

Forced libration of Mercury

![Graph showing the relationship between libration amplitude (arcsec) and core radius (m) with different sulfur concentrations.](image)
Planetary Science
Forced libration of Mercury

![Graph showing the relationship between relative mantle moment of inertia and outer core radius (m) for different sulfur concentrations.](image)
Planetary Science

Tidal amplitude

Love number $h$

outer core radius (m)

0.1 wt% S

14 wt% S

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BELA at MPS
Thesis by C. Koch – Simulations on Instrument performance
• Simulate observations for different, nominal elliptical orbit of MPO (continuous and/or with data gaps):
  resonant: 910.000 MPO orbits within 1 Mercury year
  non-resonant: 909.234 MPO orbits within 1 Mercury year

• Add tidal elevation.

• Add noise (including small-scale topography, orbital and measurement errors).

• Add offset in longitude due to libration.
BELA at MPS
Assumptions on
Mercury Topography

Martian (Aharonson et al., 2001) & lunar topographic spectral density as reference
Take „topographic measurements“ $T_k$ at a constant frequency:

$$T_k = T(\theta_k, \lambda_k + \Delta \lambda_{\text{libr}}) + \delta r_{tide}(\psi_k) + N_k$$

Deterministic topog. Tidal elevation Noise

$$\Delta \lambda_{\text{libr}} = \phi_0 (\sin M + a_2 \sin 2M + \ldots) = \phi_0 f(M)$$

$$\sum w_k \left[ T_k - h_2 F_{tide}(\psi_k) - \sum_{\ell=0}^{\ell_{\text{max}}} \sum_{m=0}^{l_{\ell,m}} p_{\ell,m}^m (\cos \theta_k) \{C_{\ell,m} \cos (m \dot{\lambda}_k) + S_{\ell,m} \sin (m \dot{\lambda}_k)\} \right]^2 \rightarrow \text{Min}$$

$$\sum w_k \left[ T_k - h_2 F_{tide}(\Psi_k) - \sum_{l,m=0}^{l_{\text{max}},l_{\text{max}}} P_{l,m}^l (\cos \theta_k) \{C_{l,m} \cos m \dot{\lambda} + S_{l,m} \sin m \dot{\lambda}\} \right]^2 \rightarrow \text{Min}$$

$$w_k \Delta \Phi_{\text{lib}} f_{\text{lib}} (M) \sum_{l,m=0}^{l_{\text{max}},l_{\text{max}}} P_{l,m}^l (\cos \theta_k) \{\hat{C}_{l,m} \cos m \dot{\lambda} + \hat{S}_{l,m} \sin m \dot{\lambda}\}^2 \rightarrow \text{Min}$$
BELA at MPS
Simulation results C. Koch

\[ \Delta h_2 \propto l_{\text{inv}}^{-2/3} \]

\[ \Delta \Phi_{\text{lib}} \propto l_{\text{inv}}^{-2/3} \]
BELA at MPS
Crossing point analysis

- Large number of crossing points close to the Poles due to MPO’s orbit.
- Amplitude of the tidal Love number approximately 30 cm at the Poles.
- 455/910 tracks are crossing each other within 2/4 Mercury years.
BELA at MPS
Crossing point analysis
BELA at MPS
GALA – Ganymede Laser Altimeter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value JEO</th>
<th>Value JGO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi major axis</td>
<td>$a$</td>
<td>1769 km</td>
<td>2834 km</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>$e$</td>
<td>0.00001</td>
<td></td>
</tr>
<tr>
<td>Relative orbital period</td>
<td>$T_{\text{JEO/JGO}}$</td>
<td>3819.216 s</td>
<td>7744.294 s</td>
</tr>
<tr>
<td>Inclination</td>
<td>$i$</td>
<td>89.9 deg</td>
<td></td>
</tr>
</tbody>
</table>

Near-polar orbit of JEO/JGO, 10 Hz repetition rate, 8 km ground track spacing in longitude 1536 x 3072 grid, decomposition spatial and time-dependent topography
Ganymede: dynamo?

- Magnetoconvection
- Remanent magnetization due to Jupiter’s magnetic field
- Internal active dynamo
- Remanent magnetization due to an internal dynamo which is no longer active

„Micro“ Laser I

- Several devices jointly developed by NASA/GSFC and MIT/Lincoln Lab (SLR2000)
- Power:
  - >1 Watt @1064 nm
  - Repetition Rate: up to 16 kHz
- Energy: up to 250 µJ/pulse
- Pulsewidths: 300 to 2200 psec
- Pumped by single GaAs diode laser array at 808 nm (< 20W)
- Passively Q-switched
- Monolithic Structure
  - Thermally bonded Nd³⁺:YAG, Cr⁴⁺:YAG and undoped YAG
  - Coatings applied to crystals
  - Laser resonator < 11 mm in length
  - Can’t misalign
„Micro“ Laser II

BELA heritage

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BELA MPS Zeiss Laser
BELA MPS Laser ZeO Subcons

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Beratung und EDV-gestützte Dienstleistungen im Bereich des thermischen und strukturmechanischen Engineering für die Luft- und Raumfahrt und für andere hochtechnologische Sektoren.
BELA MPS Laser SCD test activities
GENERAL BF

BEFORE CYCLING

AFTER CYCLING