EART163 Planetary Surfaces

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Course Overview

• How did the planetary surfaces we see form and evolve? What processes are/were operating?

• Techniques to answer these questions:
  – Images
  – Modelling/Quantitative analysis
  – Comparative analysis and analogues

• Case studies – examples from this Solar System
Course Outline

• Week 1 – Introduction, planetary shapes
• Week 2 – Strength and rheology
• Week 3 – Tectonics
• Week 4 – Volcanism and cryovolcanism
• Week 5 – Midterm; Impacts
• Week 6 – Impacts (cont’d)
• Week 7 – Slopes and mass movement
• Week 8 – Wind
• Week 9 – Water & Ice
• Week 10 – Ice cont’d; Recap; Final
Recent spacecraft missions (2018-19)

JAXA landed on an asteroid (Ryugu)

ESA landed on a comet (C-G)

CNSA landed on the lunar farside

NASA flew by a Kuiper Belt Object (MU69)
Logistics

- Website: http://www.es.ucsc.edu/~fnimmo/eart163
- Prerequisites – 160; some knowledge of calculus
- Grading – based on weekly homeworks (~30%), midterm (~20%), final (~50%).
- Homeworks due on Tuesdays
- Location/Timing – TuTh 1:30-3:05pm D258 E&MS
- Office hours – MoTh 3:05-4:05pm (A219 E&MS) or by appointment (email: fnimmo@es.ucsc.edu)
- Questions/feedback? - Yes please!
Expectations

- Homework typically consists of 3 questions
- Grad students will have one extra question (harder)
- If it’s taking you more than 1 hour per question on average, you’ve got a problem – come and see me
- Midterm/finals consist of short (compulsory) and long (pick from a list) questions
- In both the midterm and the final you will receive a formula sheet
- *Showing up* and *asking questions* are usually routes to a good grade
- Plagiarism – see website for policy.
- Disability issues – see website for policy.
This Week – Shapes, geoid, topography

• How do we measure shape/topography?
• What is topography referenced to?
  – The geoid (an equipotential)
• What controls the global shape of a planet/satellite? What does that shape tell us?
  – Moment of inertia – not covered in this class (see EART162)
• What does shorter-wavelength topography tell us?
How high are you?

• What is the elevation measured relative to?
  – Mean Sea Level (Earth)
  – Constant Radius Sphere (Mercury, Venus)
  – Geoid at 6.1 mbar (Mars)
  – Center of Mass (Asteroids)

• Geoid (see later)
  – Equipotential Surface
  – Would be sea level if there was a sea
How is elevation measured?

- **GPS**
  - Measure time of radio signals from multiple satellites

- **Altimetry**
  - Time-of-flight of LASER or RADAR pulses

- **Stereo**
  - Pairs of slightly mis-aligned images

- **Photoclinometry**
  - Simultaneous solution of slopes and albedos from brightness variations

- **Limb Profiles**
  - Single image of the edge of a body (1D profile)

- **Shadow measurements**
  - Uses known illumination conditions
Altimetry

- RADAR or LIDAR
- Fire a pulse at the ground from a spacecraft, time the return

- **Pro:**
  - Extremely accurate (cm)
  - Long distance (Mercury)

- **Con:**
  - High power usage
  - Poor coverage

For which bodies do we have altimetric measurements?
Stereo

• Pair of images of an area at slightly different angles.
• Infer topography from parallax
• Your eyes use this method
• Pro:
  – Great coverage, high resolution (few pixels)
• Con:
  – Stereo pairs require similar viewing geometries, illumination angles, resolutions
LOLA 128 ppd versus Kaguya Terrain Camera Stereo Data (7 m/px)

Image courtesy Caleb Fassett
Shape from Shading

- Photoclinometry
- Use brightness variations in single image to estimate the shape.

- Pro:
  - Only need one image

- Con:
  - Can’t decouple color variation from shading
  - Errors accumulate (long-wavelengths unreliable – why?)

Jankowski & Squyres (1991)
Stereophotoclinometry

- Brightness variations in many images used to determine topography and albedo.

**Pro:**
- Great coverage
- Resolution comparable to best images
- Can use almost any images containing landmark

**Con:**
- Computationally intensive
- Operator input
Limb Profiles

Dermott and Thomas 1988

~0.1 pixel accuracy

Pappalardo et al. 1997

• “Poor man’s altimeter”
• Works best on small bodies
• Occultations (point measurements) can also be useful
• Prior to *New Horizons*, occultations were only way of measuring Pluto’s radius
Shadow measurements

- Illumination geometry used to derive relative heights

- **Pro**
  - Only requires single image
  - Doesn’t require brightness assumptions

- **Con**
  - Very limited information
  - Has generally been superseded

$h = w \tan i$
Lighting Angles

The phase angle often determines the appearance of the subject. E.g. small particles are only visible at high phase (forward scattering) – why?

The incidence angle controls how much topography affects the appearance.
Shadows

• High incidence angle
  – Longer shadows
  – Easier to see topography

• Low incidence angle
  – Topo washed out
  – See inherent brightness (albedo) variations
Geoid

- The height of an equipotential surface above some reference shape (often an ellipsoid)
- Mean sea level on Earth
- In general, the surface a canal would follow
- Pick an arbitrary equipotential on other planets
- Measured in length units
Geoid of the Earth
Gravitational Potential $V$

- Gravitational potential is the work done to bring a unit mass from infinity to the point in question:

$$V = \int_{\infty}^{r} \frac{F(r)}{m} dr = \int_{\infty}^{r} g(r) dr$$

- For a spherically symmetric body we have

$$F(r) = -\frac{GMm}{r^2}$$

which gives us

$$V = -\frac{GM}{r}$$
The Figure of the Earth

- Spherically-symmetric, non-rotating Earth
- Potential outside Earth’s surface:
  \[ V = -\frac{GM}{r} \]
- Gravity at surface \( r=a \):
  \[ g = \frac{GM}{a^2} \]
- Geoid is the outer surface
Spherically Symmetric, Rotating Earth

• Centrifugal potential
  \[ V = -\frac{1}{2} \left[ r^2 \Omega^2 \sin^2 \theta \right] \]

• Total Potential
  \[ V_T = -\frac{GM}{r} - \frac{1}{2} \left[ r^2 \Omega^2 \sin^2 \theta \right] \]

The geoid is an **equipotential** i.e. we have to find a surface for which \( V_T \) is independent of \( \theta \)
What is the geoid?

• Find a surface of constant $V_T$: $r = a + \delta r(\theta)$

$$\delta r(\theta) = \text{const.} + \frac{\Omega^2 a^4}{2GM} \sin^2 \theta$$

• This is true for a rigid planet – for fluid planets it is only approximate

1. Centrifugal force offsets gravity at equator
2. Going from pole to equator is walking “downhill”
An Application

Asteroid Ryugu, ~1km across

- Many asteroids and small moons have equatorial ridges
- The equator is a potential low
- Material will tend to drift “downhill” towards the equator
Equatorial Bulge & Flattening

- Define the flattening $f$:
  \[ f = \frac{a - c}{a} \]

- From the previous page we have
  \[ a - c = \frac{\Omega^2 a^4}{2GM} \]
  So
  \[ f = \frac{1}{2} \frac{\Omega^2 a^3}{GM} = \frac{1}{2} \frac{\Omega^2 a}{g} \]

- What is the physical explanation for this expression?

- For the Earth, $f \approx 1/300$ i.e. small ($\approx 22$ km)

- What happens if $\Omega^2 a/g \approx 1$?

Remember these equations are approximate – assume a rigid body!
Fast-spinning asteroids

What is this diagram telling us about the mechanical properties of asteroids?

Critical spin rate:

\[ \Omega_{\text{crit}} = \left( \frac{4\pi G \rho}{3} \right)^{1/2} \]

Min. period \( \sim 2 \) hrs

(\( \rho \sim 3 \) g/cc)

Pravec et al. 2001

Minimum spin period \( \sim 2 \) hrs

987 asteroids total
Why do asteroids spin so fast?

- Photons carry momentum!
- Absorption and reradiation of photons can change the spins and orbits of small bodies
- Depends on surface area:volume ratio and distance from Sun
Satellite shapes

- Deformed by tides and rotation
- Triaxial ellipsoid (not oblate spheroid)
- For synchronous satellites (i.e. most of them)

The equipotential surface shape is given by:

\[
\begin{align*}
a &= \bar{R} \left(1 + \frac{35}{12} \frac{\Omega^2 \bar{R}}{g}\right) \\
b &= \bar{R} \left(1 - \frac{10}{12} \frac{\Omega^2 \bar{R}}{g}\right) \\
c &= \bar{R} \left(1 - \frac{25}{12} \frac{\Omega^2 \bar{R}}{g}\right)
\end{align*}
\]

This is the shape a fluid satellite would adopt.

Any such satellite will have \((a-c)/(b-c)=4\) and \(f=5 \Omega^2 a/g\)
# Table of Shapes

<table>
<thead>
<tr>
<th>Body</th>
<th>$\Omega^2 a/g$</th>
<th>$a$ (km)</th>
<th>$b$ (km)</th>
<th>$c$ (km)</th>
<th>$(a-c)/a$</th>
<th>$(a-c)/(b-c)$</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>0.0034</td>
<td>6378</td>
<td>6378</td>
<td>6357</td>
<td>0.0033</td>
<td>1</td>
<td>fluid</td>
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<td>Jupiter</td>
<td>0.089</td>
<td>71492</td>
<td>71492</td>
<td>66854</td>
<td>0.065</td>
<td>1</td>
<td>fluid</td>
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<tr>
<td>Io</td>
<td>0.0017</td>
<td>1830.0</td>
<td>1819.2</td>
<td>1815.6</td>
<td>0.0079</td>
<td>4.0</td>
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<tr>
<td>Titan</td>
<td>0.000040</td>
<td>2575.15</td>
<td>2574.78</td>
<td>2574.47</td>
<td>0.00026</td>
<td>2.2</td>
<td>Not fluid</td>
</tr>
<tr>
<td>Mars</td>
<td>0.0046</td>
<td>3397</td>
<td>3397</td>
<td>3375</td>
<td>0.0065</td>
<td>1</td>
<td>Not fluid</td>
</tr>
</tbody>
</table>

Fluid planet predictions:

\[
\frac{a-c}{a} \approx \frac{\Omega^2 a}{2g} \quad \frac{(a-c)}{(b-c)} = 1
\]

Fluid satellite predictions:

\[
\frac{a-c}{a} \approx \frac{5\Omega^2 a}{g} \quad \frac{(a-c)}{(b-c)} = 4
\]

Remember these equations are approximate
A more rigorous expression is given in EART162
Hypsometry

Lorenz et al. 2011
Topographic Roughness

Local slopes at 0.6, 2.4 and 19.2 km baselines (Kreslavsky and Head 2000)

Global topography
Variance spectrum

Nimmo et al. 2011
Effect of elastic thickness?

- Short-wavelength features are supported elastically
- Long-wavelength features are not
- Crossover wavelength depends on $T_e$
Summary – Shapes, geoid, topography

- How do we measure shape/topography?
  - GPS, altimetry, stereo, photoclinometry, limb profiles, shadows

- What is topography referenced to?
  - Usually the geoid (an equipotential)
  - Sometimes a simple ellipsoid (Venus, Mercury)

- What controls the global shape of a planet/satellite?
  - Rotation rate, density, (rigidity)
  - Fluid planet $f \sim \Omega^2 a/2g$  Satellite $f \sim 5 \Omega^2 a/g$

- What does shorter-wavelength topography tell us?
  - Hypsometry, roughness, elastic thickness?
Earth

- Referenced to ellipsoid
- Bimodal distribution of topography
- No strong correlation with gravity at large scales
- Long-wavelength gravity dominated by internal density anomalies
  - Mantle convection!

All maps from Wieczorek, Treatise on Geophysics, 2nd ed, 2015
Venus

- Referenced to ellipsoid
- Unimodal hypsometry
- Geoid dominated by high topo, volcanic swells
Mars

- Referenced to ellipsoid
- Bimodal hypsometry (hemispheric dichotomy)
- Huge gravity/geoid anomaly, dominated by Tharsis
- High correlation between topo and grav.
Moon

- Topo dominated by South Pole-Aitken
- Nearside and farside very obviously different
- High gravity anomalies in large craters
  - MASs (Mass Concentrations)
  - What’s up with these?
  - Negative correlation
- GRAIL has provided us with truly amazing data
Mercury

- Gravity only well-determined in northern hemisphere (why?)
- Not much correlation between gravity and topography
- Muted gravity suggests most topography is compensated
End of lecture
Height and geoid height

\[ H = h - N \]

- **H**: Orthometric Height
- **h**: Ellipsoidal Height from GPS
- **N**: Geoid Height

**Diagram:**
- GPS
- Topography
- Ellipsoid
- Geoid
- Oceans
Pluto! (and Charon)