Detection and characterization of water oceans on icy moons from geodetic measurements

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Why do we care?

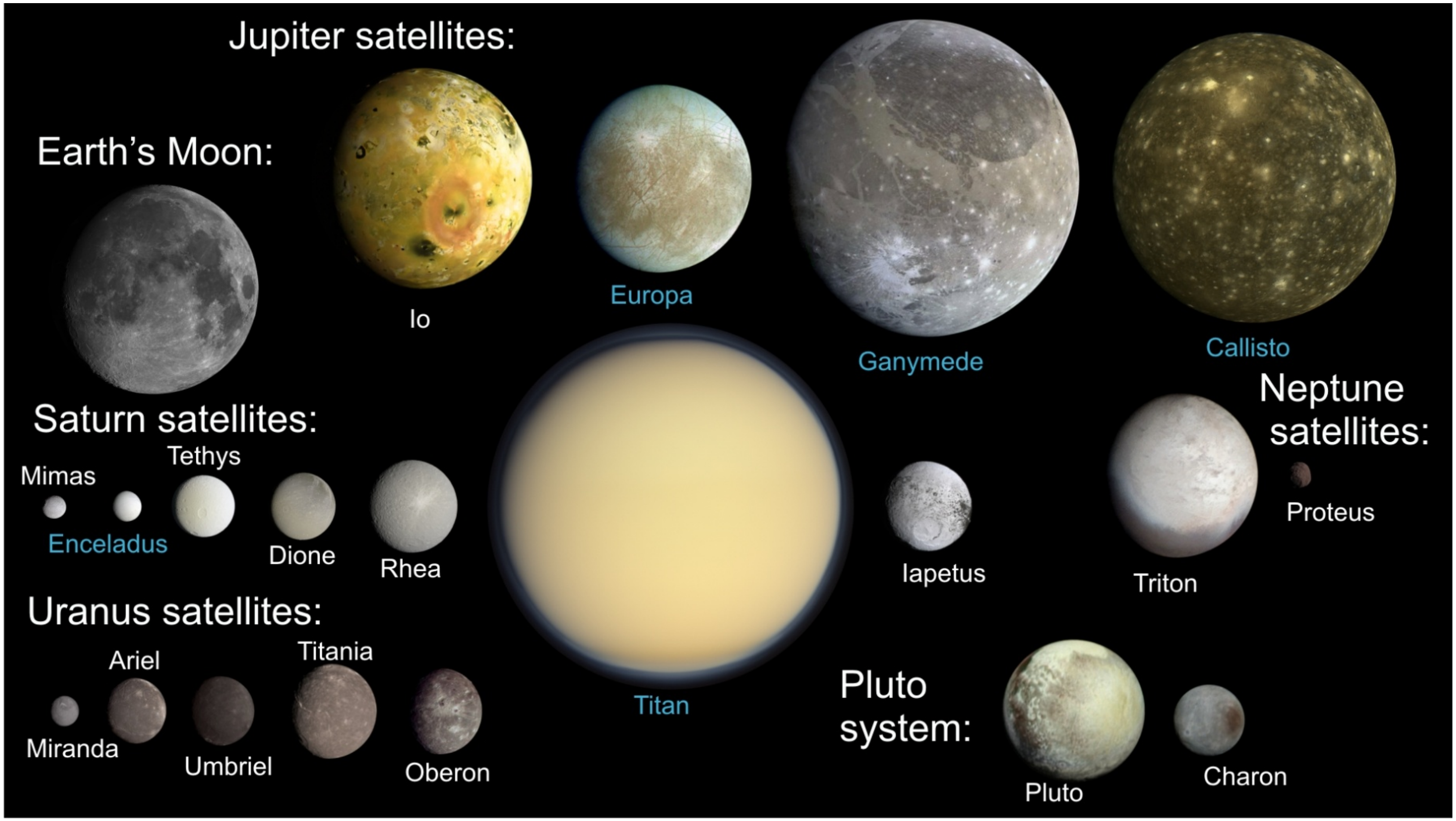
- Ocean worlds are (surprisingly?) common
- Potentially habitable environments
- Moons are intrinsically more complicated than planets
- A rich set of geodetic problems

Outline

1. Where are ocean worlds?
2. How have they been detected in the past?
3. Measuring active deformation and tidal dissipation.
4. Characterizing ocean properties
5. Habitability

1. Ocean Worlds are Common!

Nimmo & Pappalardo 2016

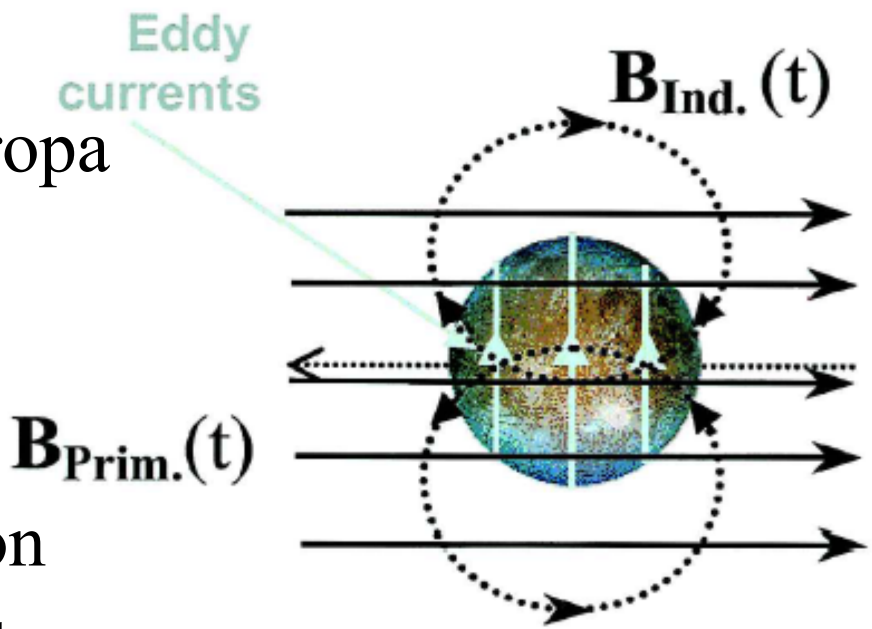


2. How do we detect them?

- 1. Magnetic induction (Europa, Ganymede, Callisto) [stretching the definition of geodesy!]
- 2. Librations (Enceladus)
- 3. Obliquity (Titan)
- 4. Tidal response
- 5. Static gravity
- 6. Seismology
- 7. Rotation variations
- 8. "Others" (Astrometry? Inclination?)

2.1 Induction

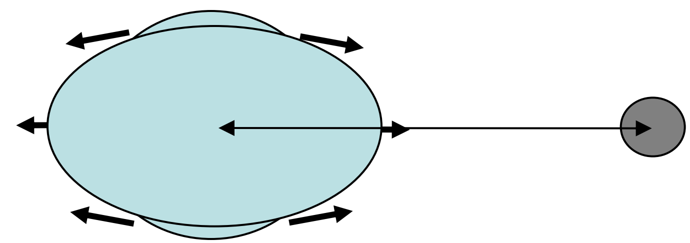
- Jupiter's varying field induces a current and a secondary magnetic field inside Europa
- *Galileo* detected this secondary field
- The *amplitude* of the secondary field depends on how conductive Europa’s interior is



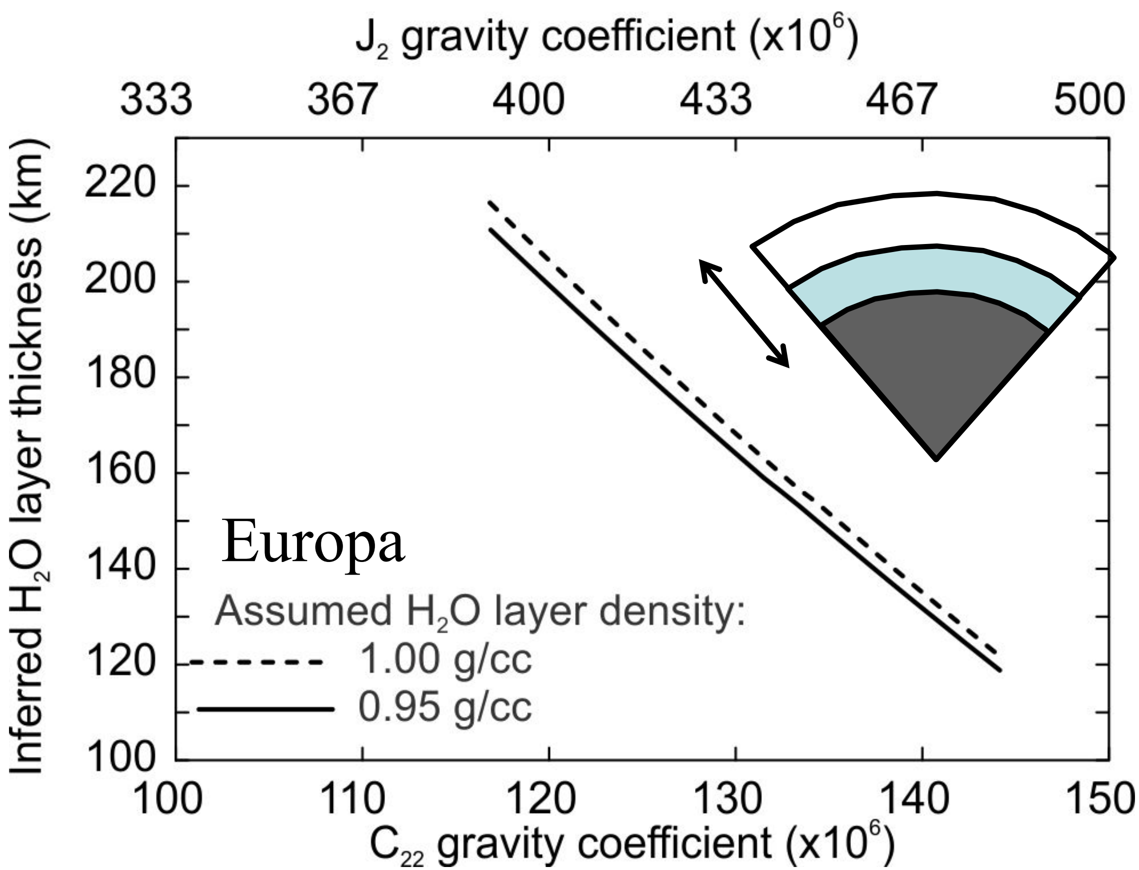
Khurana et al. 2002

- The results are consistent with a shallow salty ocean
- This approach doesn't work at Saturn, but would work great at Uranus or Neptune (Weiss et al. 2021)

Tides



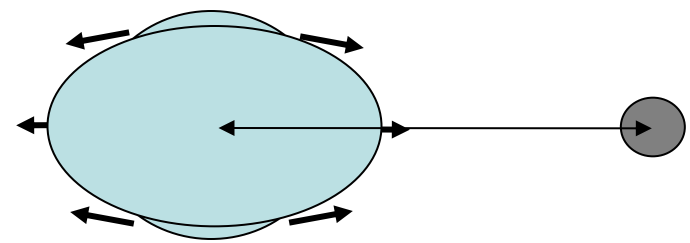
- Bodies develop a tidal bulge
- If we ignore elastic effects, the *size* of this bulge depends on the *moment of inertia* of the body ("Darwin-Radau")

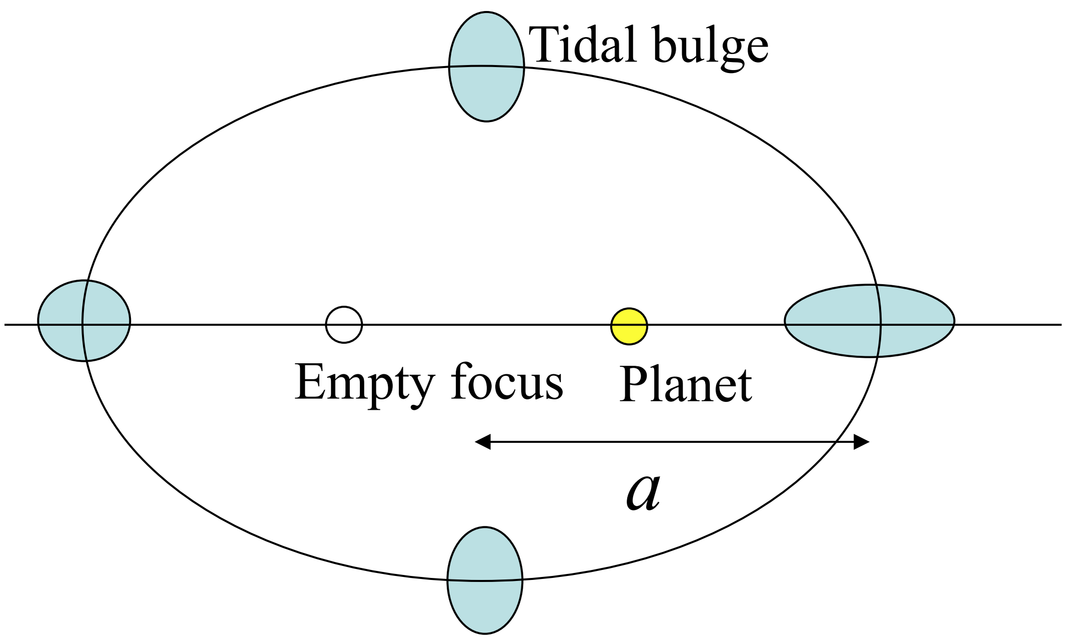


- We can use either degree-2 shape or degree-2 gravity to determine the moment of inertia
- This constrains the thickness of the hydrosphere (ice+water)
- But the body has to be *hydrostatic* ($J_2=10/3\ C_{22}$)

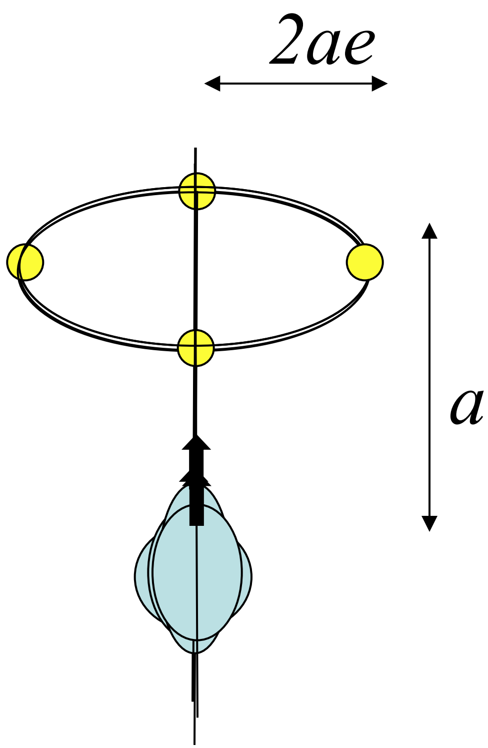
"Diurnal" Tides

- Bodies develop a tidal bulge
- If the orbit is eccentric, the size of this bulge changes over an orbit
- From the point of view of the satellite, the **planet moves back-and-forth overhead**

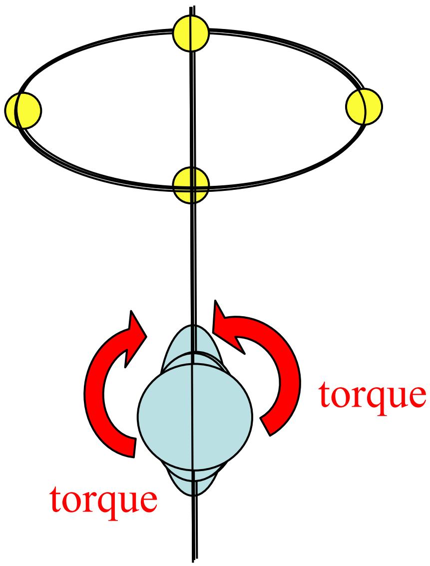




view from above



Tidal Torques

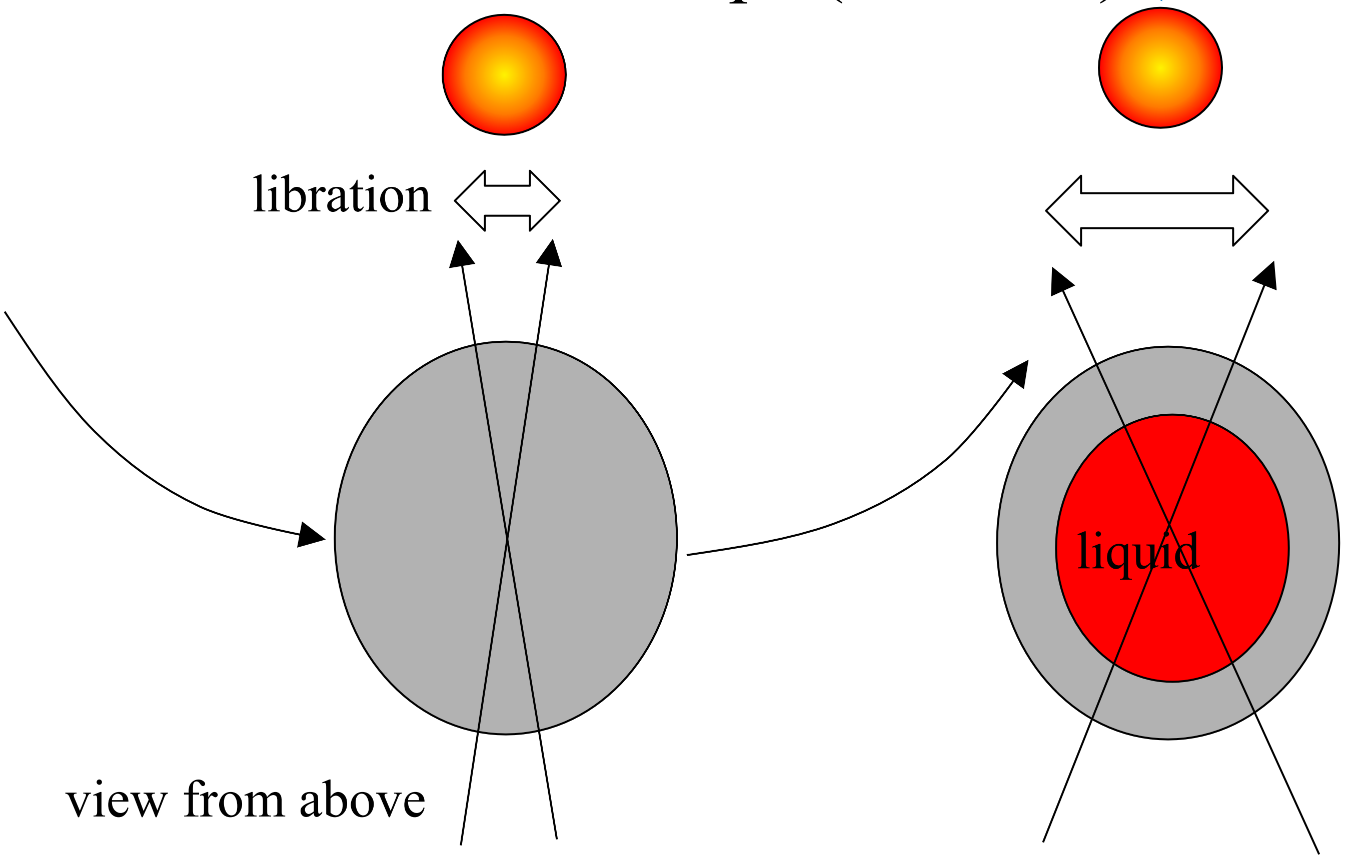


- Eccentric orbits cause **periodic torques** on the body
- These will cause the rotation period to vary periodically: the satellite will wobble back-and-forth (”physical librations")
- Librations are *sensitive to internal structure*

A useful reference is Tiscareno et al. 2009

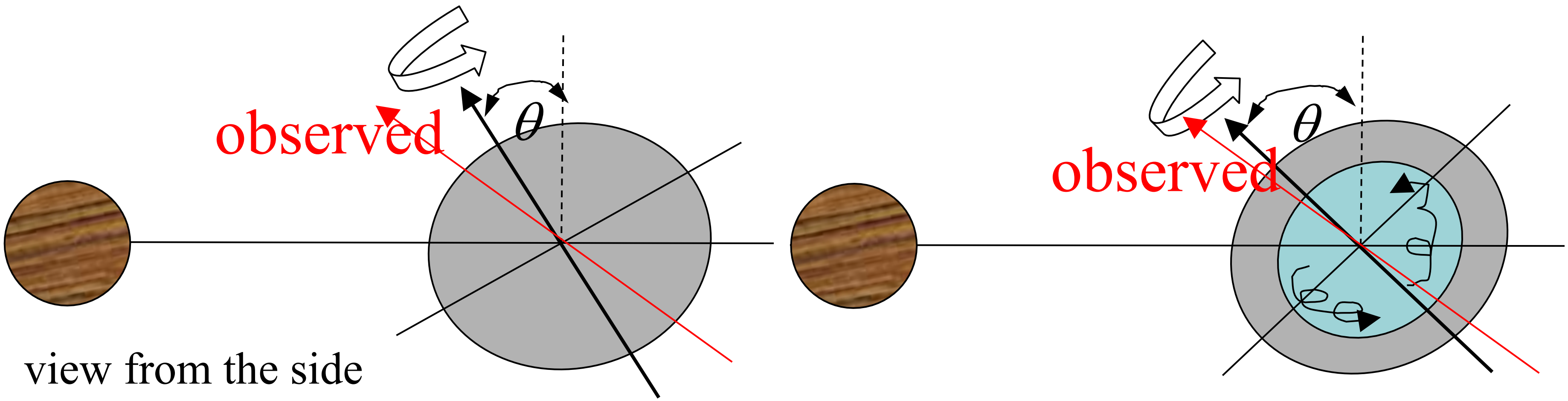
2.2 Librations

- Periodic variations in rotation rate, forced by tides
- *Amplitude* of librations tell us whether there is a decoupling (liquid) layer inside
- Doesn't work at Europa (bad luck) (Van Hoolst et al. 2013)



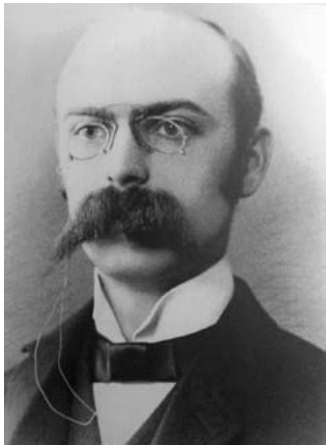
Margot et al. 2007 (Mercury); Thomas et al. 2016 (Enceladus); etc.

2.3 Obliquity (θ)



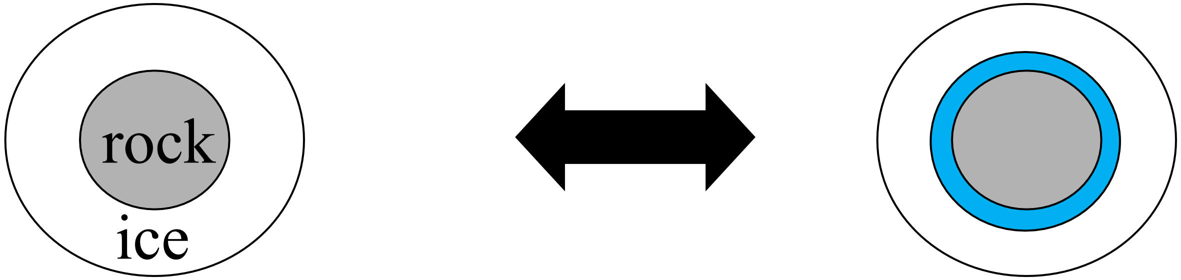
- For *tidally-torqued bodies*, obliquity θ can be predicted if moments of inertia are known ("Cassini state")
- Obliquity can be measured by radar from Earth (e.g. Mercury, Galilean satellites?) or by spacecraft
- For Titan, obliquity is so large that the surface must be decoupled from the interior, implying an ocean (Bills & Nimmo 2011)

2.4 Amplitude of Tidal Response



A.E.H. Love

- Amplitude of tidal response described by dimensionless Love numbers (k_2, h_2)
- Liquid layer *increases* tidal response



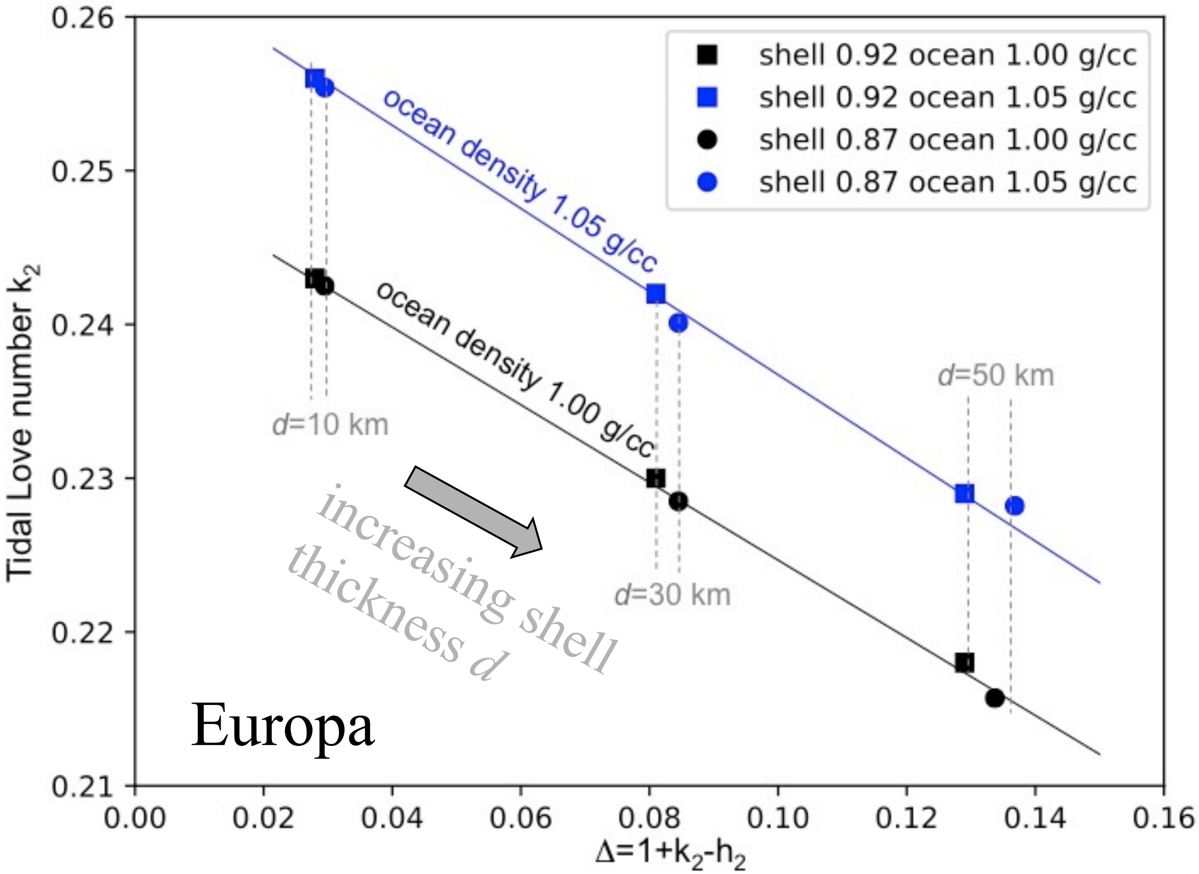
Smaller tidal response (smaller k_2, h_2)

Larger tidal response (larger k_2, h_2)

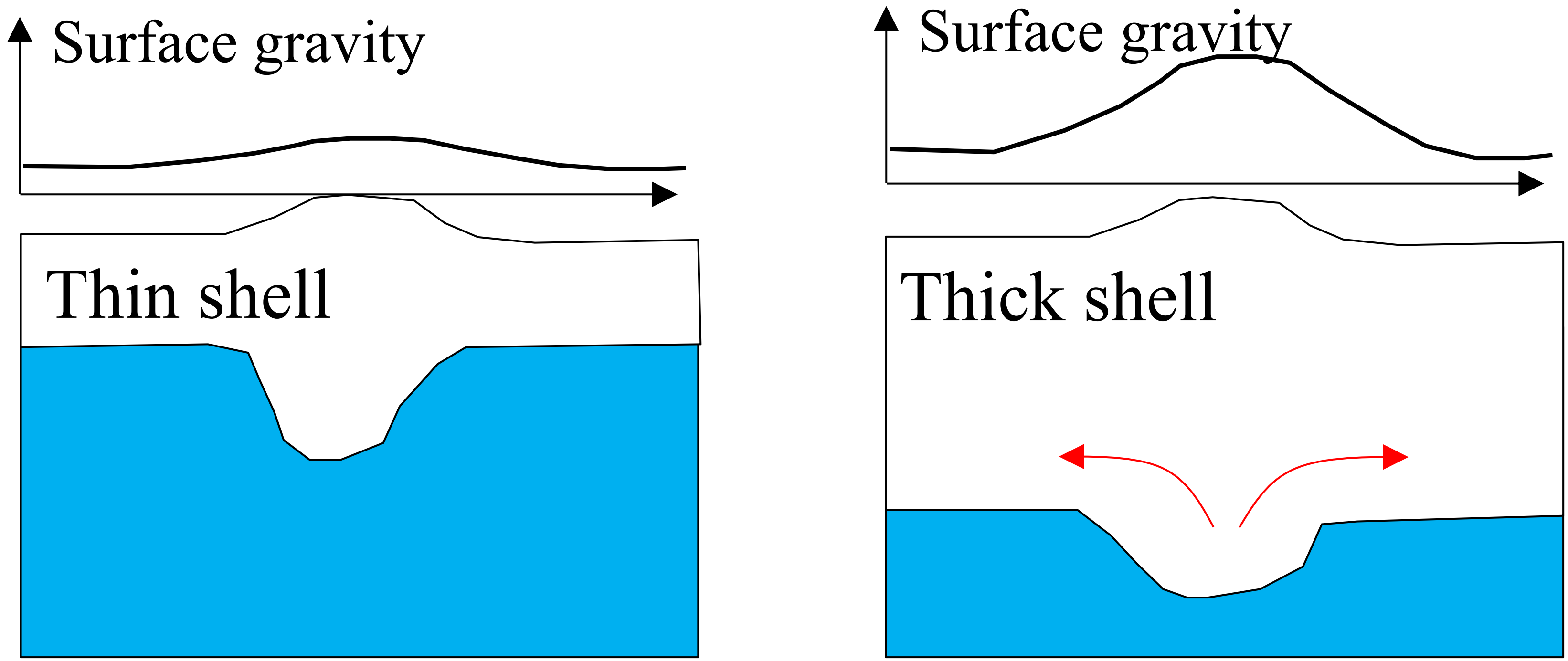
- k_2 involves changes in gravity – easy to detect
- h_2 involves surface deformation – need altimeter
- Beware: Love numbers are *frequency-dependent*

Effect of oceans

- Love numbers are sensitive to thickness of *rigid ice shell*
- If we can measure both k_2 and h_2, the number of tradeoffs is significantly reduced (Wahr et al. 2006)



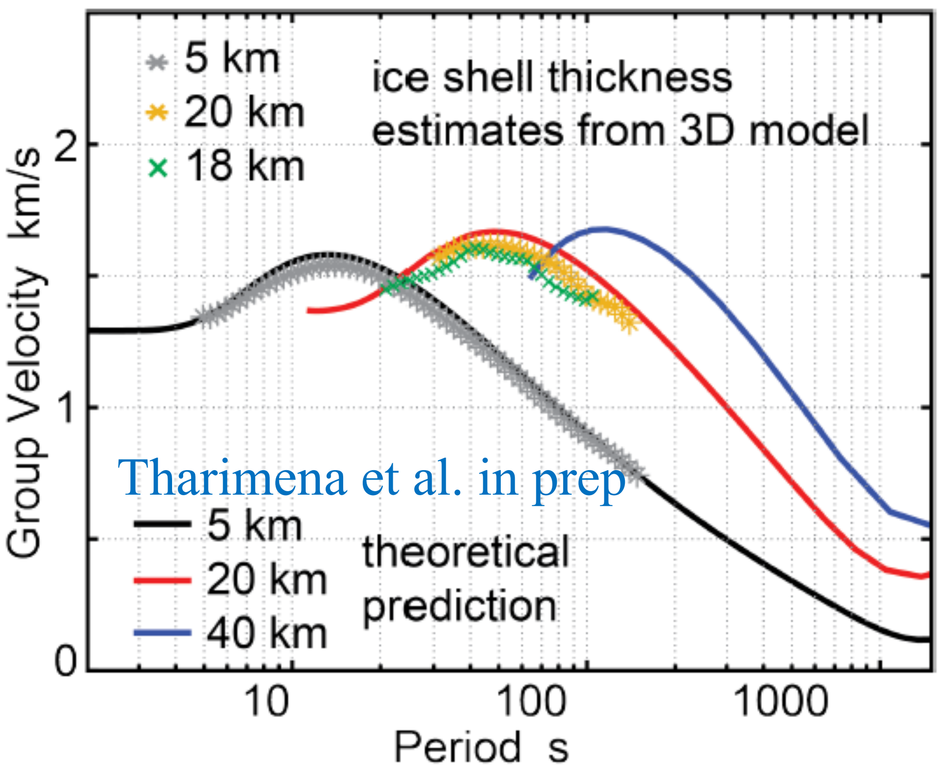
2.5 Static gravity & topography

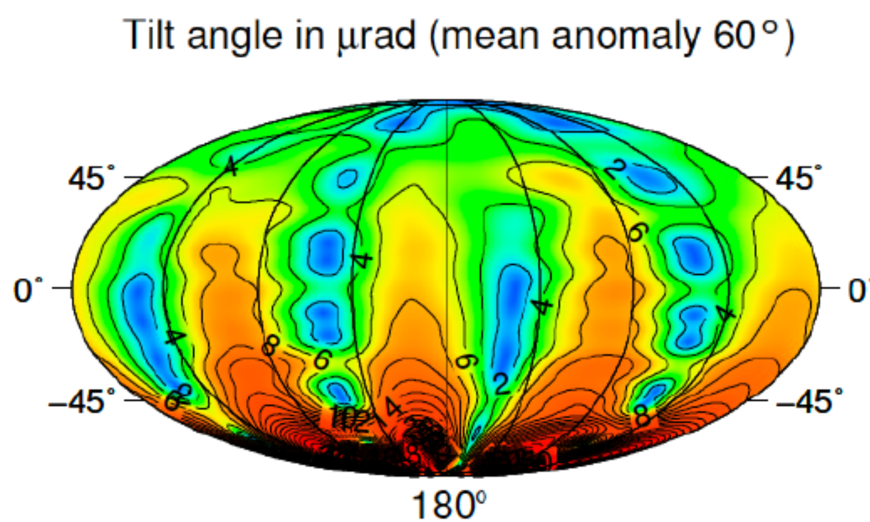


- Combination of gravity & topography (admittance) can be used to infer shell thickness
- Tradeoffs arise if *flexure* or *lateral flow* occur
- E.g. Titan, Hemingway et al. 2013

2.6 Seismology

- Surface waves probe shell thickness
- A seismometer can also act as a gravimeter [measures $1+h_2-(3/2)k_2$] or tiltmeter



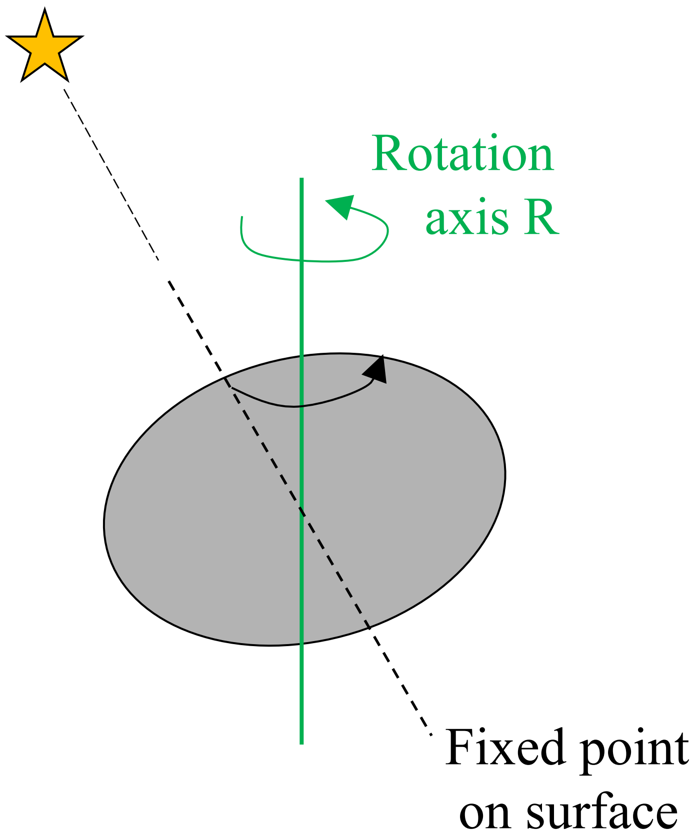


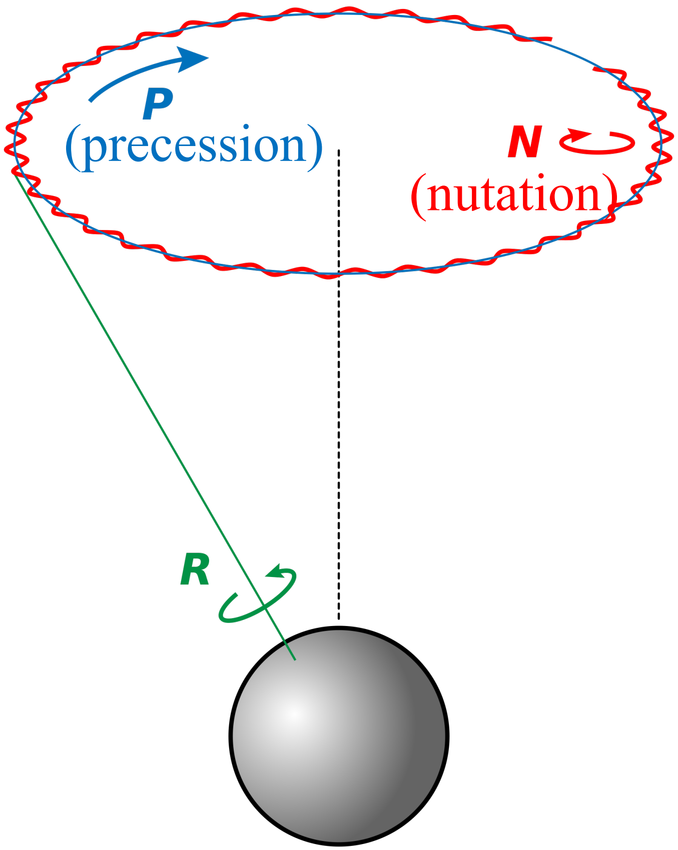
Enceladus

(Vance et al. EDGE report)

2.7 Rotation variations

- *Chandler Wobble* can be sensitive to liquid layers (e.g. Smith & Dahlen 1981)
- *Nutations* can also be sensitive to liquid layers (e.g. Defraigne et al. 2003)



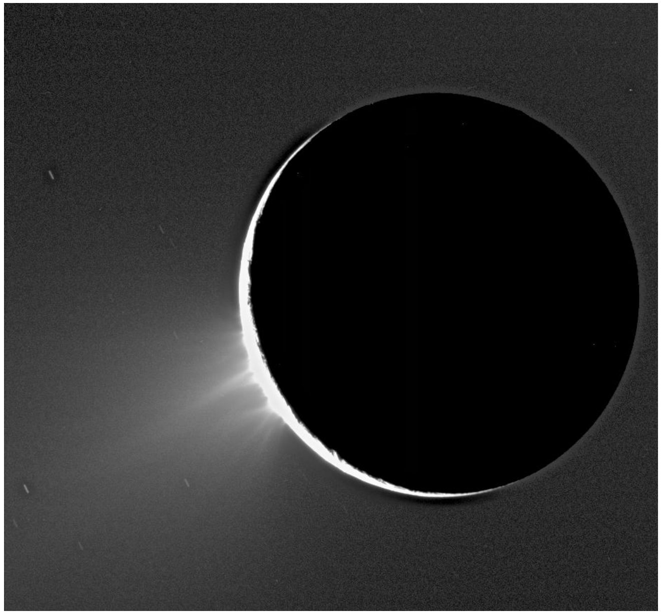


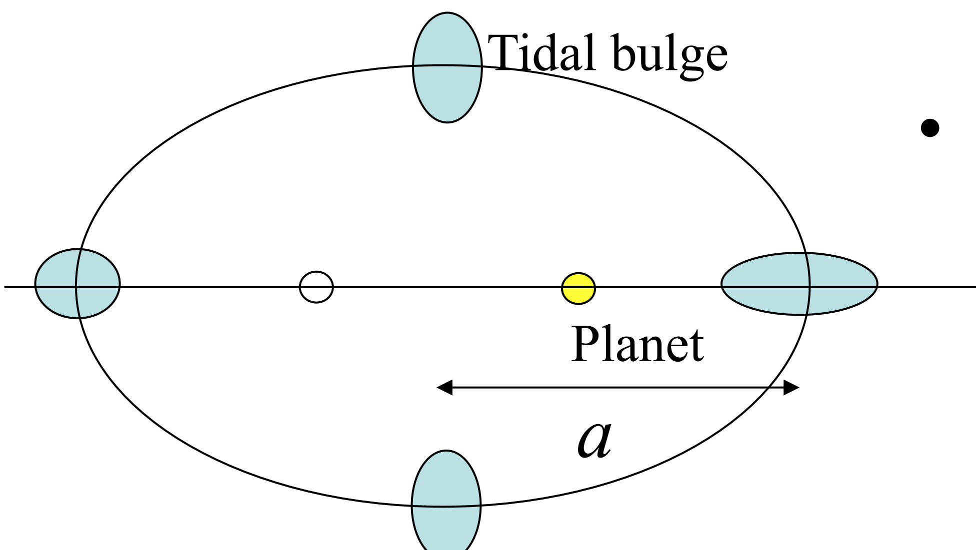
2.8 Others

- Orbital evolution rate (astrometry) depends on satellite k_2/Q, where Q is a dissipation factor. k_2/Q is expected to be larger for ocean-bearing worlds
- If an ocean is present, inclination damping is much more rapid than eccentricity damping (e.g. Downey et al. 2020). We can use inclination to test for the presence/absence of a subsurface ocean.
- These are both semi-quantitative (at best)

[pause]

3. Detecting active deformation





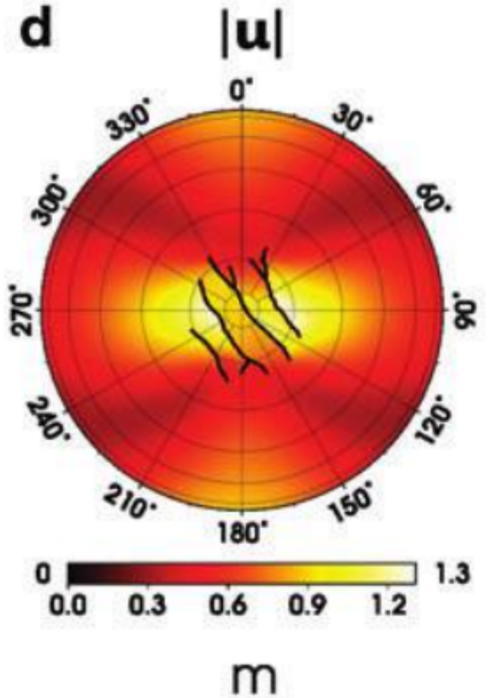
- Surface deformation is *time-dependent*
- E.g. cracks opening and closing modulate Enceladus's plume activity

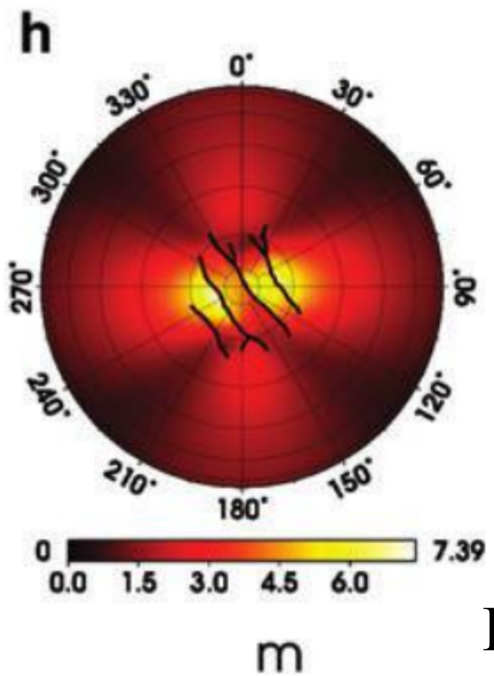
  (Hurford et al. 2007)

- Lateral variations in material properties make calculations much more complicated

Surface deformation

- Surface deformation measurable by:
  - Altimetry
  - Gravity
  - Imaging(?)
  - **Interferometry**
  - **Surface assets**
- Lateral variations in material properties produce shorter-wavelength features

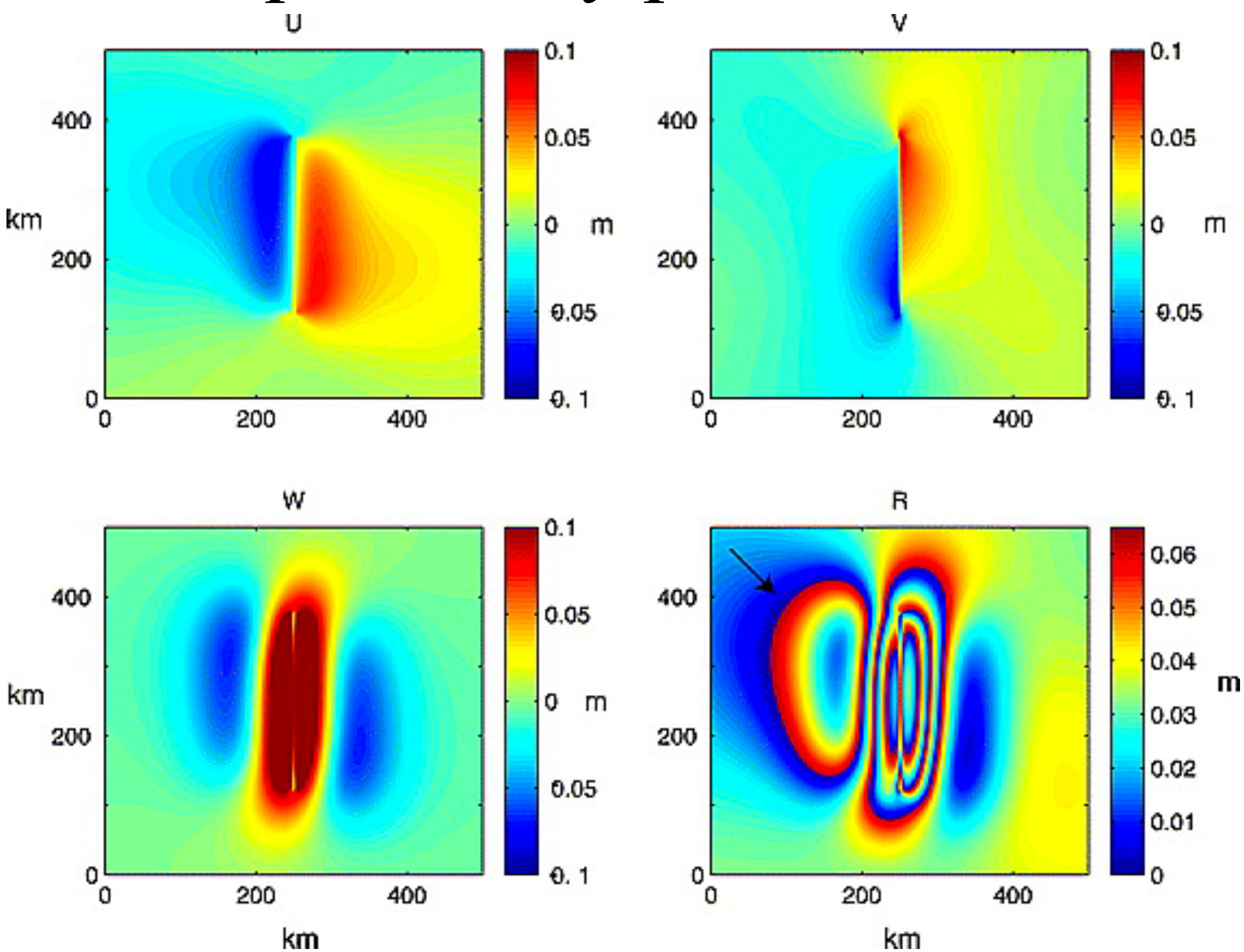




Enceladus, Behounkova et al. 2017

Repeat-Pass Radar Interferometry

- A good way of detecting active deformation
- Requires very precise orbit knowledge

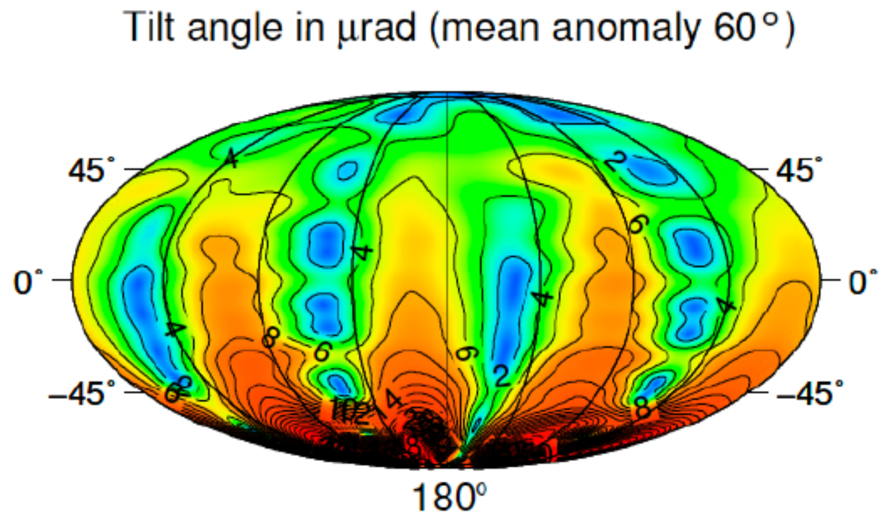


Simulated interferograms from active normal fault on Europa

Sandwell et al. 2004

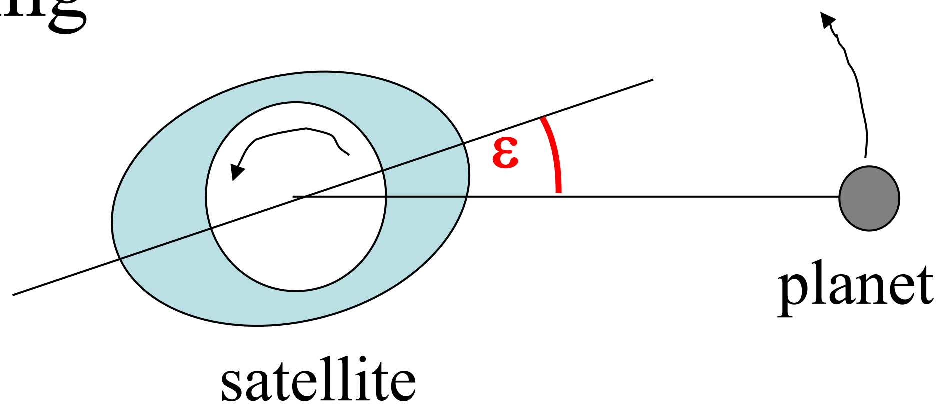
Surface assets

- E.g. seismometer, gravimeter, laser reflector
- Very successful on the Moon (long-baseline observations)
- Typically high-precision, but very spatially restricted compared to orbital measurements
- Good for measuring librations, obliquity, local tilt, rotation rate variations, induction



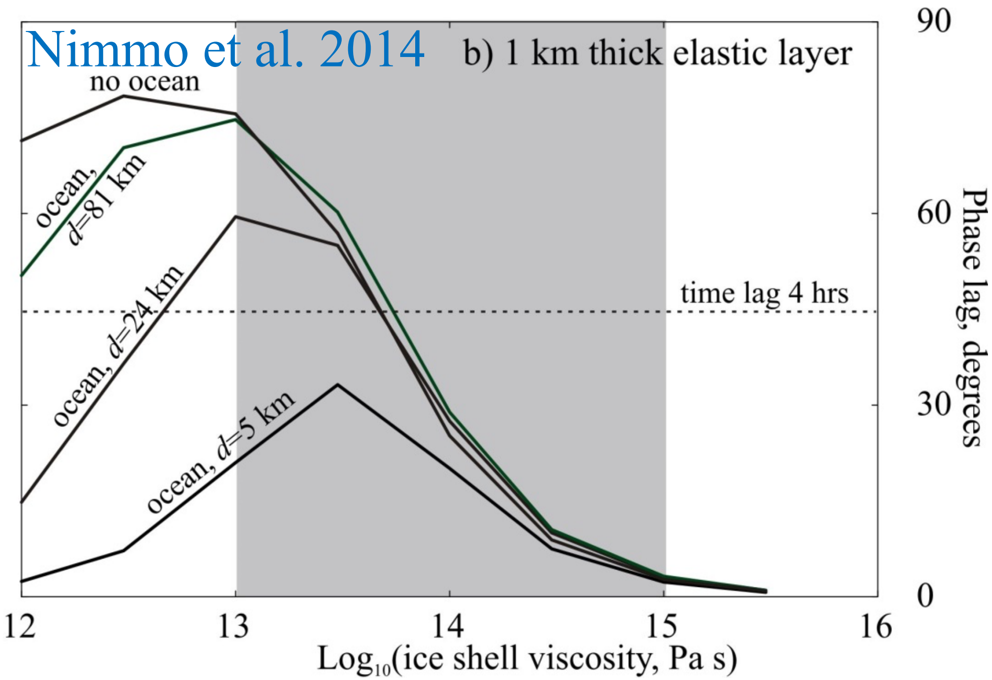
Phase of tidal response

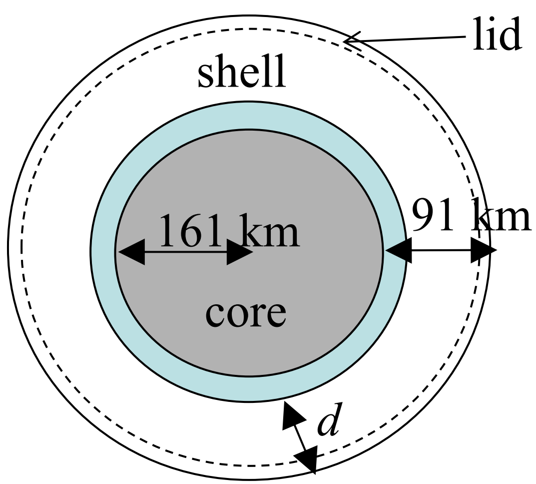
- Tidal response lags forcing
- This lag causes
  - spin-down
  - tidal heating
  - eccentricity & inclination damping



- The phase lag ε is described by the **dissipation factor** Q: $Q \sim 1/\varepsilon$
- Tidal heating rate scales with k_2/Q or $Im(k_2)$
- Low Q or large phase lag = high heating rate

What phase lag tells us



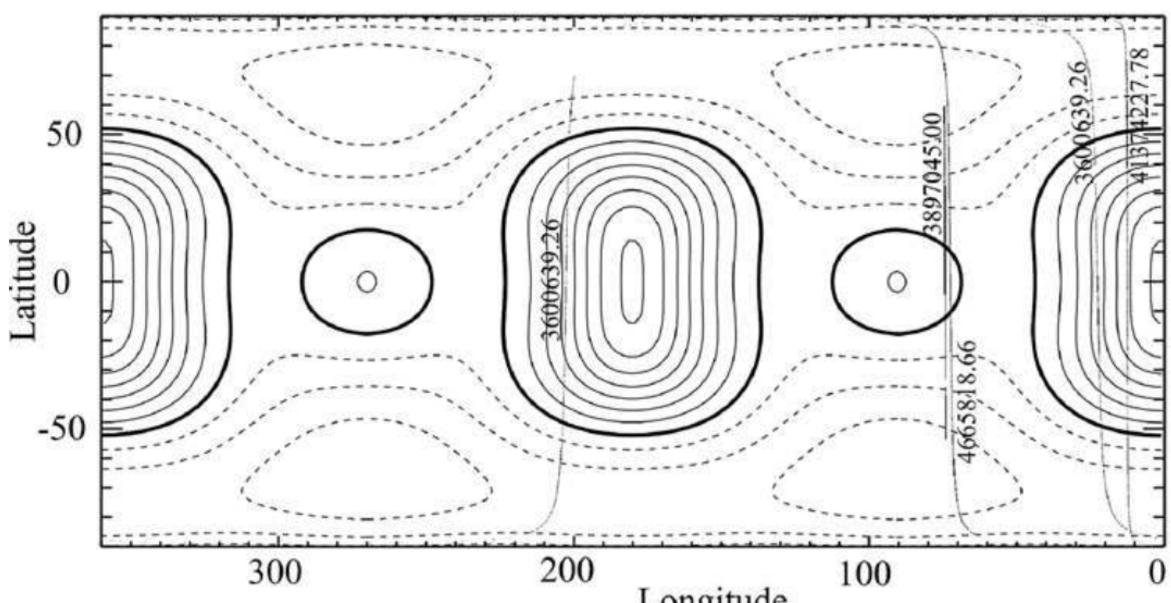


- Phase lag implies a *viscous response*
- Amount of phase lag depends on viscosity and thickness of layer
- Presence of an ocean usually reduces the phase lag
- Enceladus plumes have a phase lag

Tidal heating & surface heat flux

- Tidal heating is *spatially-variable*
- It can be measured directly (Enceladus, Io)
- Or indirectly, via shell thickness variations
- Patterns of heating in core, in ocean and in shell are different from each other
- Oceans can *redistribute* heat (e.g. Soderlund et al. 2014)

Predicted Europa surface topography (Nimmo et al. 2007)



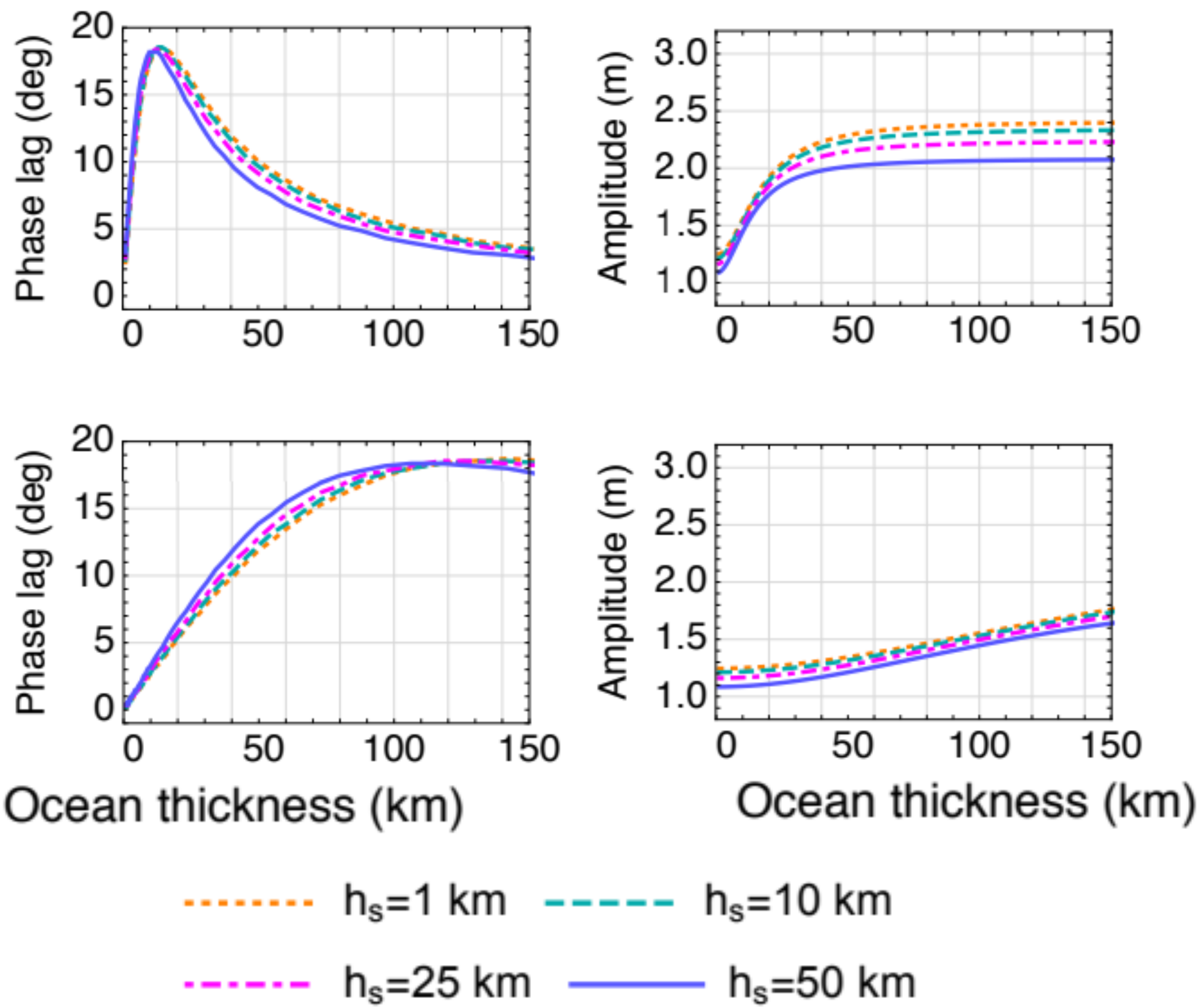
4. Ocean Properties

- Best way of probing ocean papers is by **induction sounding** (either active or passive)
  - Sensitive to total shell thickness and ocean thickness
  - Can be combined with other techniques
  - Cornerstone of *Europa Clipper* approach
  - Advantageous if you have a lander/orbiter pair
  - Not strictly a geodetic technique, mostly not discussed further

- Four fairly outlandish ideas . . .

Dynamic ocean tides?

Europa (Matsuyama et al. 2018)



"Dynamic" ocean tides (sloshing) can produce a phase lag which is sensitive to depth

But tradeoff with degree of turbulent dissipation assumed

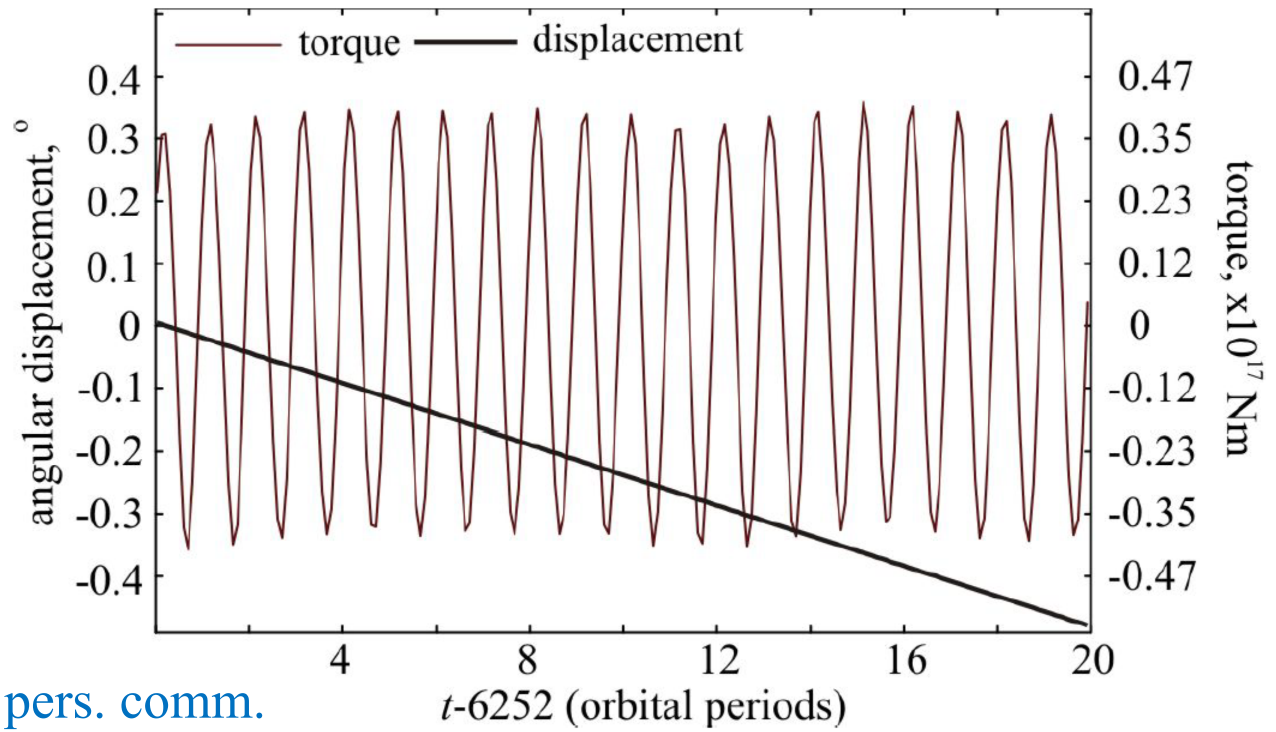
Induction?

- A moving conductor in a static field gives rise to an induced magnetic field
- In principle, these could be detectable and used to deduce ocean currents (Tyler 2011)
- But the effects are *small*
- For Europa:

Induction term	$\frac{\lvert F_r' \rvert}{\lvert F_r \rvert}$	$\frac{\text{time-variable field}}{\text{background}}$	250 nT
Advection term	$\frac{l \lvert u \rvert}{\Omega R}$	$\frac{\text{current speed}}{\text{rotation speed}}$	1.3 nT
Stretching term	$\frac{\eta}{h}$	$\frac{\text{tidal displacement}}{\text{ocean depth}}$	~0.1 nT

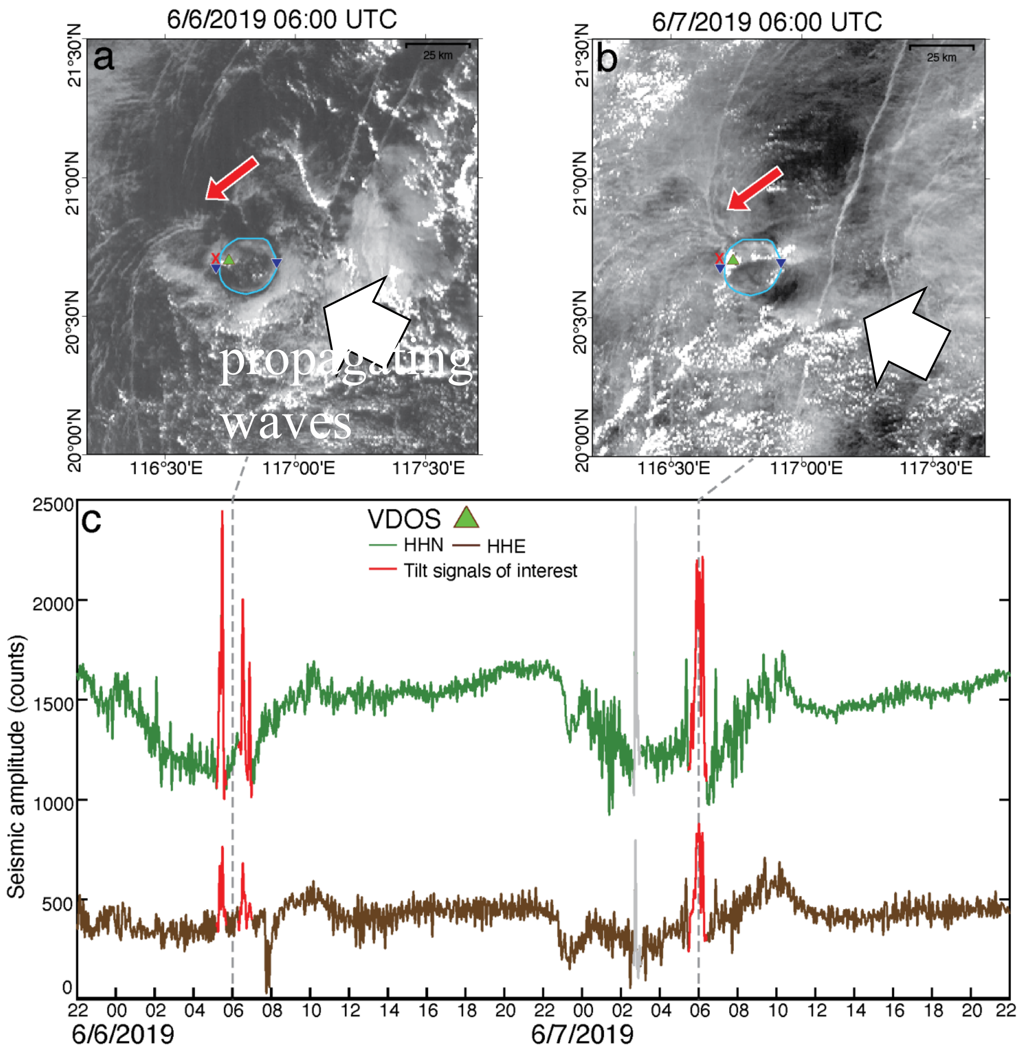
Length-of-day variations?

- Ocean currents will impose torques on shell
- Similar processes to core-mantle boundary interactions on Earth (many papers by Bruce Buffett; Karatekin et al. 2008)
- These produce "length-of-day" & obliquity variations

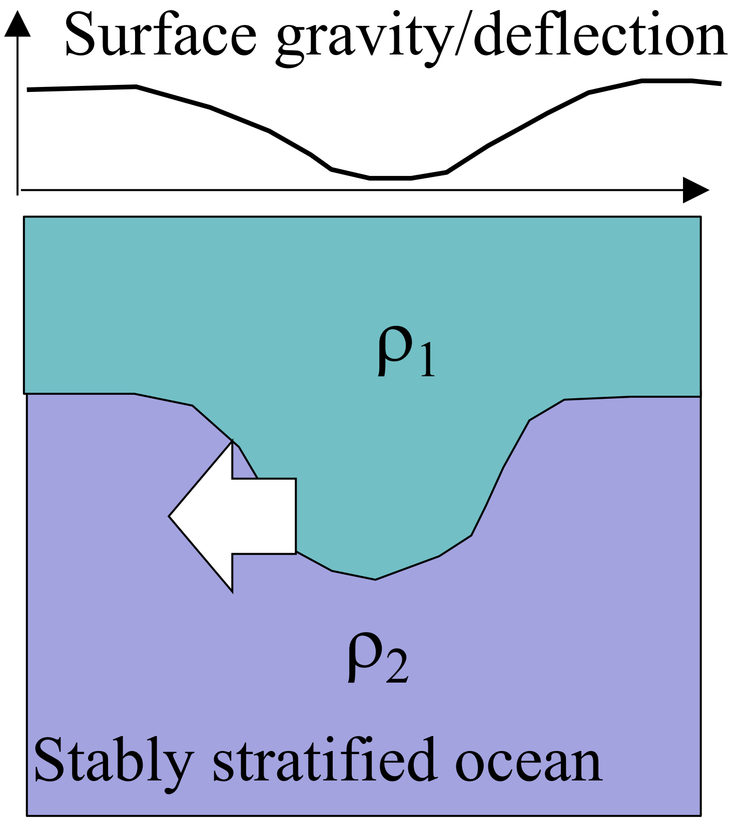


Glatzmaier, pers. comm.

Internal waves?



Shaddox et al., submitted

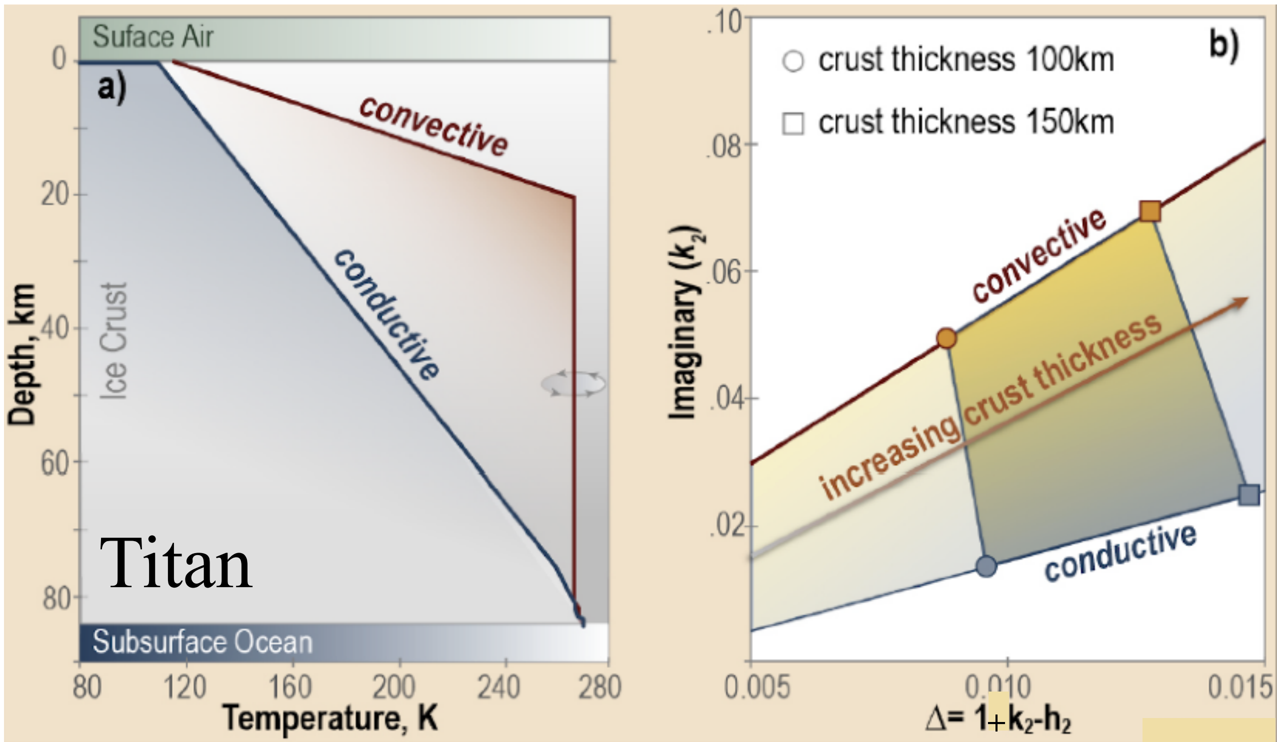


5. Habitability?

- Habitability is usually thought to require:
  - Water
  - Raw materials (C,H,N,O,P,S . . .)
  - Energy Source

- Geodesy is *not* ideal for probing habitability. But
  - Whether the ice shell is **conductive or convective** affects transport of raw materials to ocean from surface
  - Silicate **tidal heating** and **water-rock** reactions could both provide a source of energy

Conduction vs. Convection



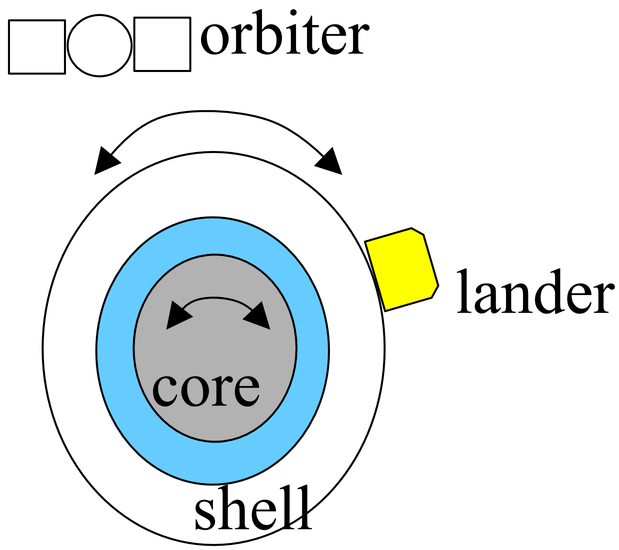
- Conductive and convective ice shells have different temperature structures, and different tidal responses
- Active tectonics could also be detectable by InSAR, seismology etc.

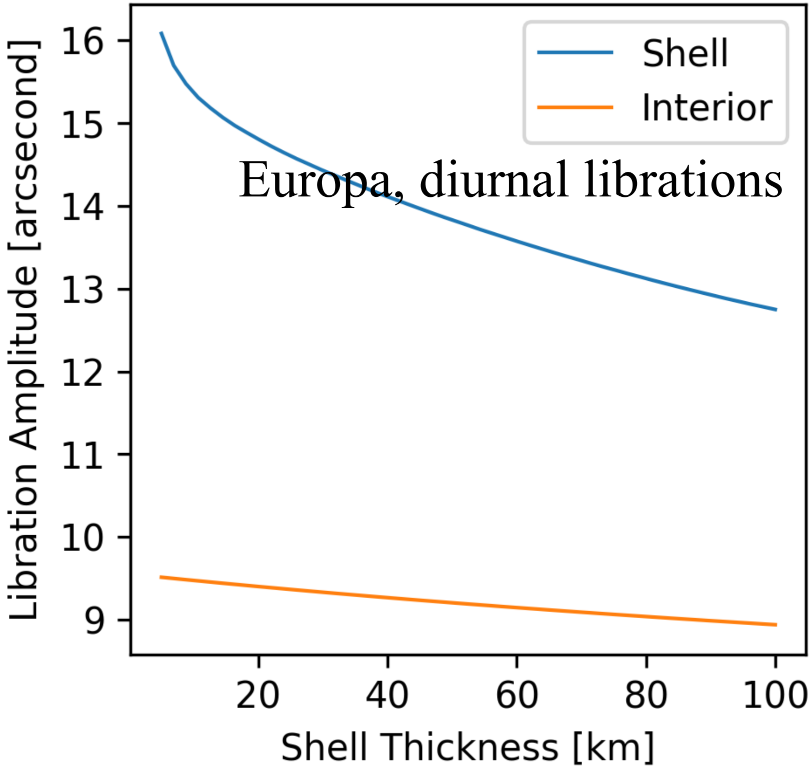
Tidal heating & Water-rock reactions

- A cold mantle will produce larger gravity anomalies than a warm mantle (e.g. Dombard & Sessa 2019)
- A tidally-heated mantle will produce a larger phase lag (e.g. Hussmann et al. 2016) and a different spatial heating pattern
- The silicate core of Enceladus is so low density that it is either porous or hydrothermally altered

Differential libration?

- If the shell and core librate by different amounts, an orbiter and lander *will see different gravity variations*
- This would help separate core and shell effects





Calculations courtesy Wencheng Shao

Summary

- Many geodetic techniques are available to *detect* oceans and measure tidal deformation
- *Characterizing* oceans with geodesy is hard
- Habitability by geodesy is very hard
- Rotating, fluid-filled shells and their coupling to the solid ice above is a fruitful area for research
- Combining surface and orbital assets is powerful