Seismology on tidally-activated worlds

Mark Panning[1], Simon Stähler[2], Steven D. Vance[1], and Sharon Kedar[1]

1. Jet Propulsion Laboratory, California Institute of Technology
2. ETH Zürich

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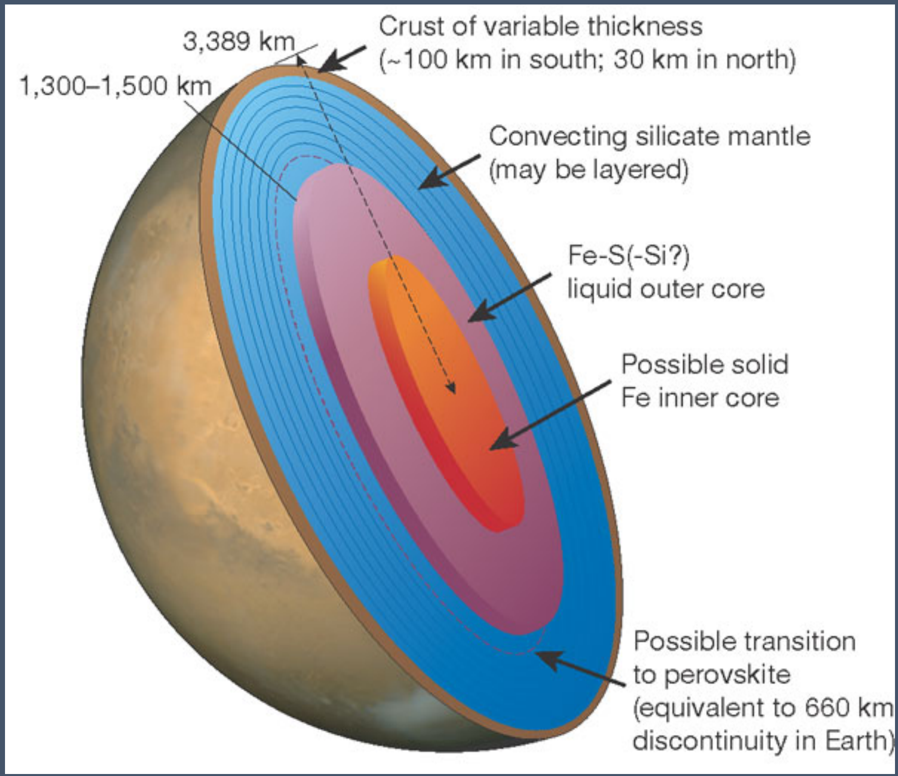
Jet Propulsion Laboratory
California Institute of Technology

ETH zürich

Why planetary seismology?

- Most of our detailed knowledge of the interior structure of the Earth comes from seismology
- Most of what we know about planetary interiors comes from gravity and topography measurements plus educated guesses about chemistry
- Trying to figure more about the evolution of Europa, Titan, Mars, or any other planetary body requires the extra detail that seismology gives us



Core radius on Mars currently has 100’s of kms of uncertainty and there is no constraint on an inner core. Figure from Stevenson, 2001

Europa, Titan and icy ocean world seismology

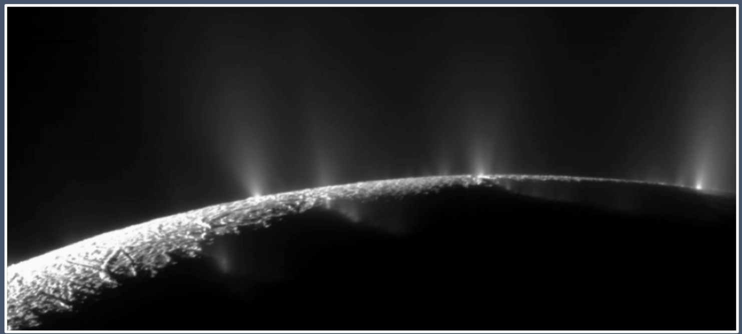
Seismology on Europa, Titan and ocean worlds

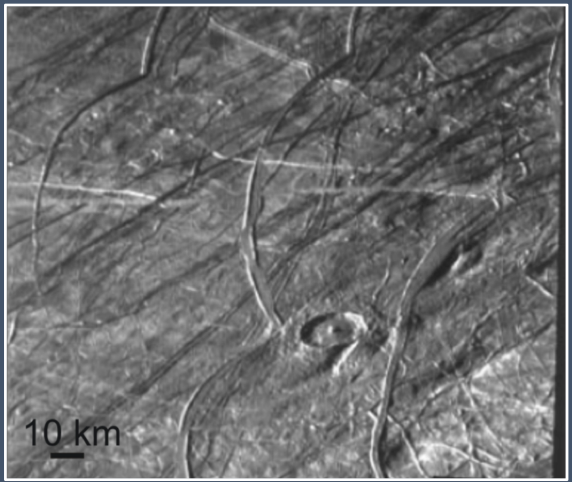
Sources

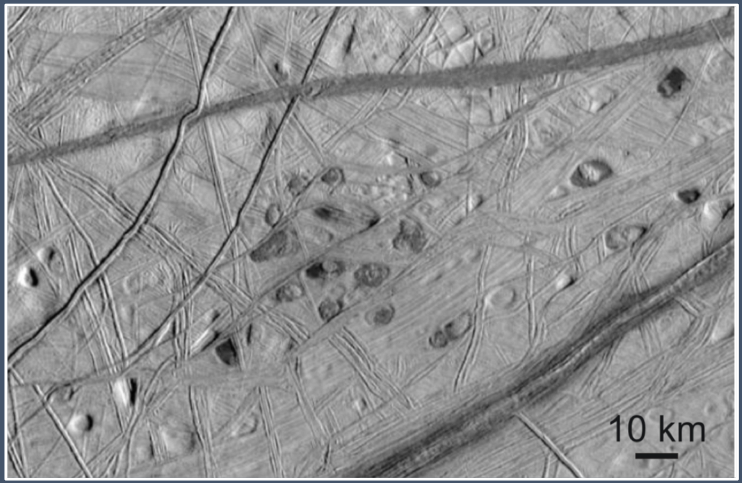
- Fracture
- Tides
- Fluid flow
- Cryovolcanoes
- (Impacts)

Structure

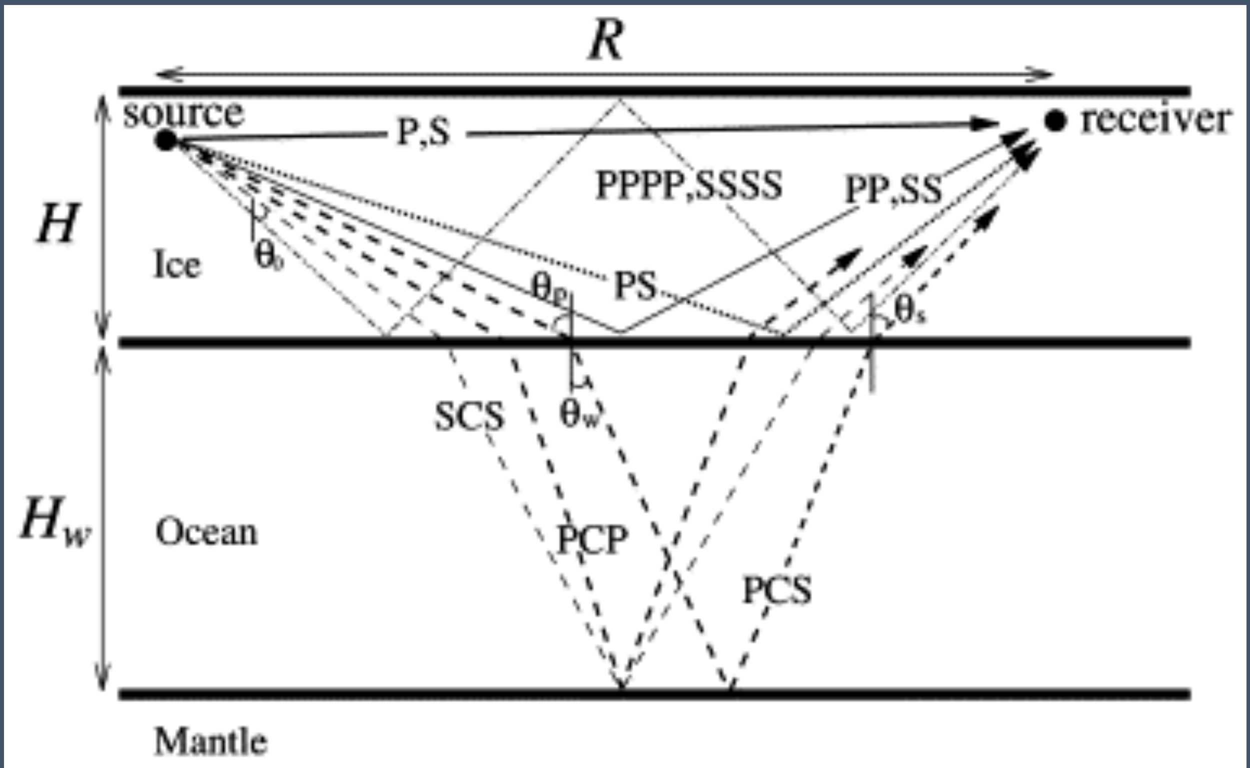
- Ice shell thickness
- Ocean depth
- High pressure ices
- Rocky interior
- Near-surface material







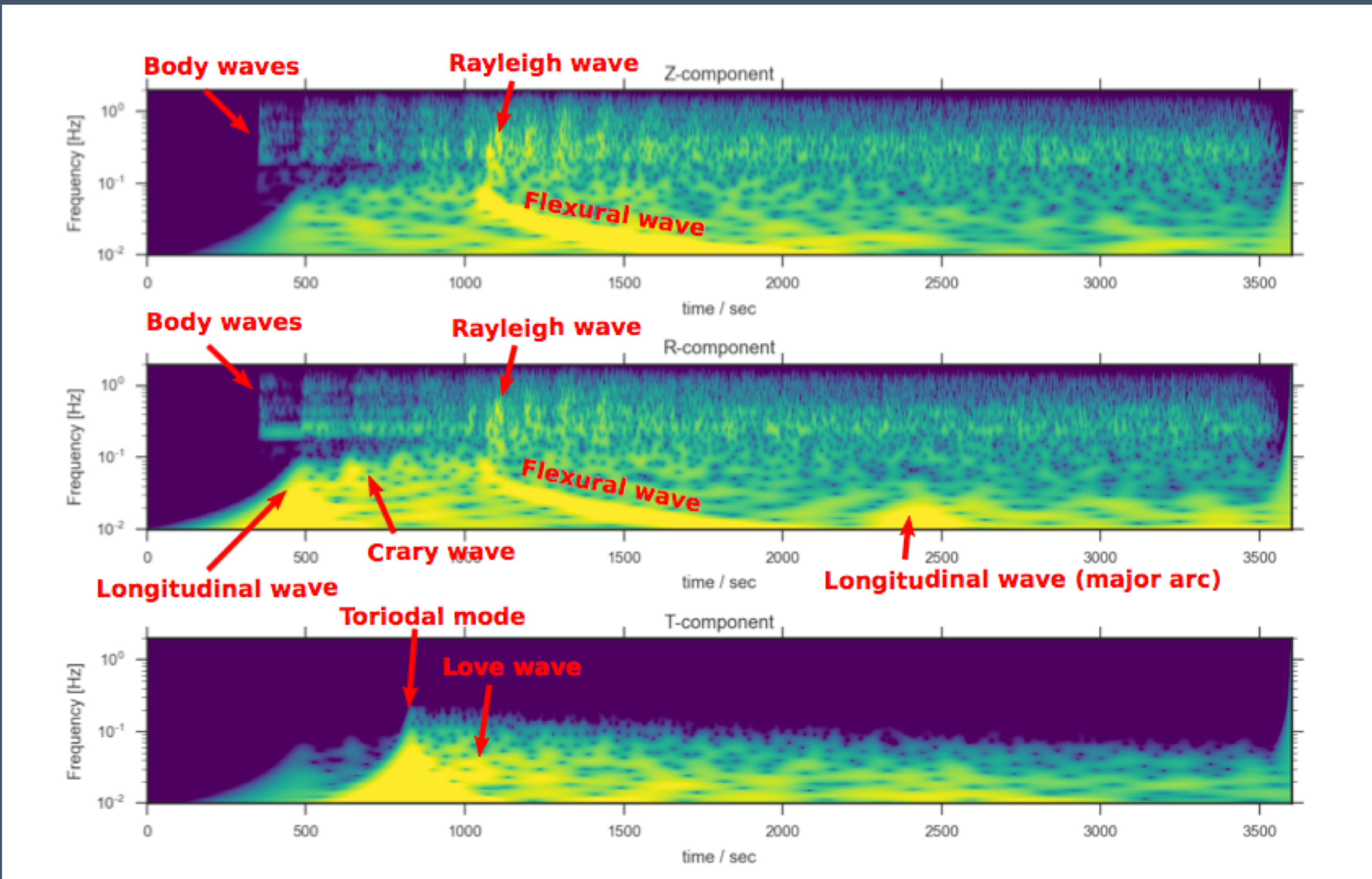
Icy ocean world structure from body waves



From Lee et al., 2003

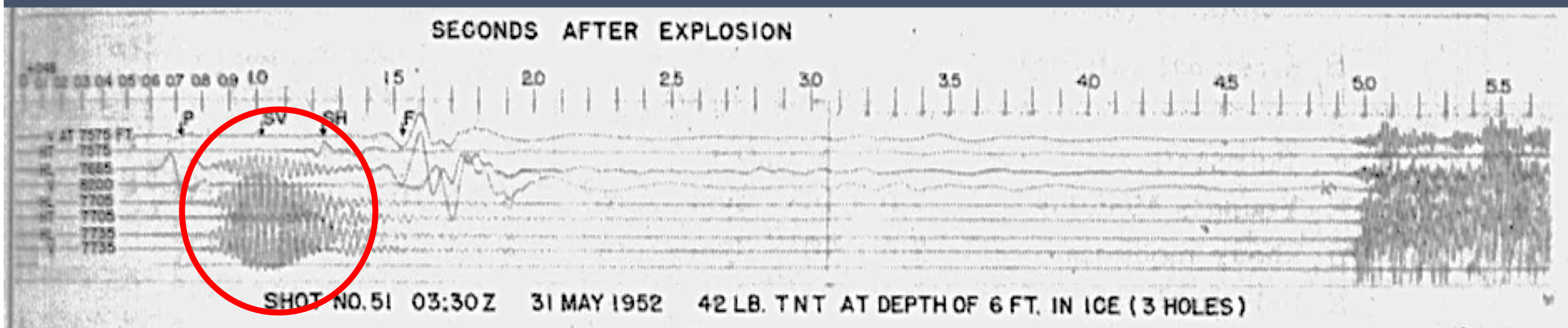
The most obvious target for seismology is to determine ice shell thickness and ocean depth via timing of reflected waves

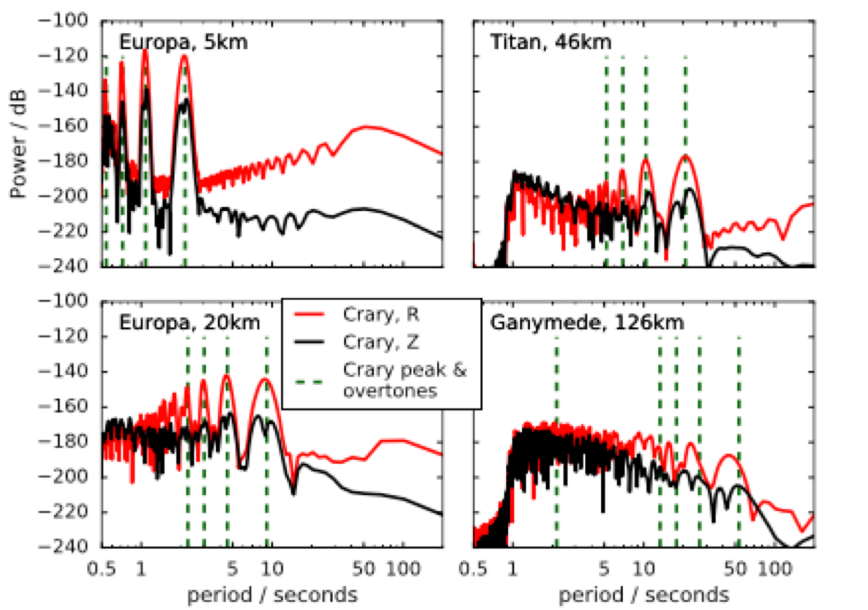
Broadband signals are powerful



Spectrograms from synthetic icy ocean world signals show several diagnostic signals to determine ice shell thickness and ocean depth. Figure from Stähler et al., 2018

Crary waves





A.P. Crary, Seismic studies on Fletcher's ice island, T-3 (1954), *Eos*

Resonant trapped SV wave with dominant frequency a function of ice shell thickness, discussed in Kovach and Chyba, 2001. Trapped SH waves create a distinctive Love wave dispersion, which may also be diagnostic

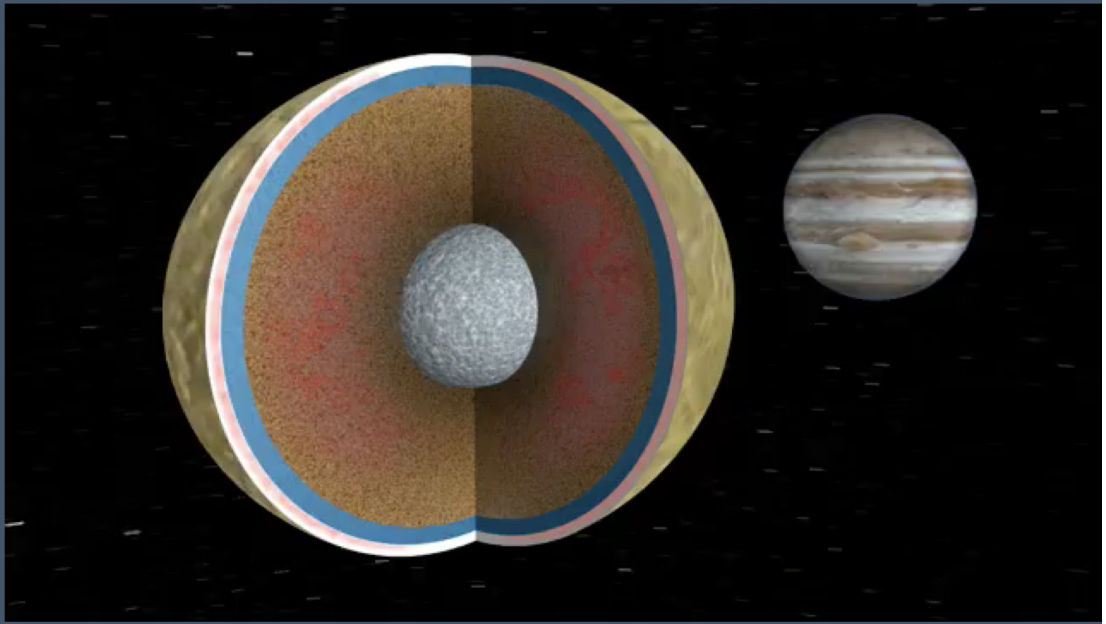
Figure from Stähler et al., 2018

Diagnostic signals to look for

- Transition frequency between flexural wave and Rayleigh wave behavior (between 10 and 100 second period)
- Disappearance of strong longitudinal mode (same frequency as flexural transition)
- Crary wave frequency and overtones (between 1 Hz and 15 second period)
- Reflected waves and reverberations (1 Hz and above)

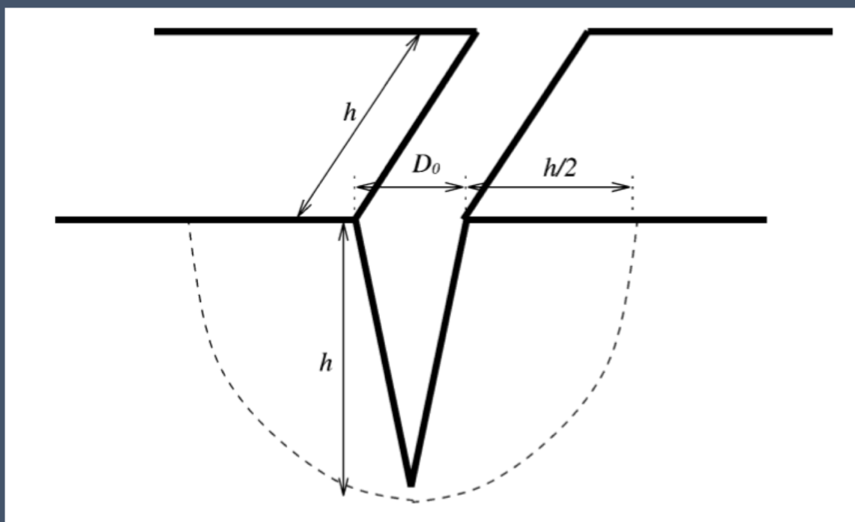
Seismicity and noise sources on icy ocean worlds

- Tidal cracking (icequakes) – Estimate using tidal dissipation
- Ocean noise – Requires better ocean turbulence modeling
- On Titan, two other noise sources are relevant
  - Waves on ethane/methane lakes – important at high latitudes (?)
  - Atmospheric noise – may be the dominant noise on Titan



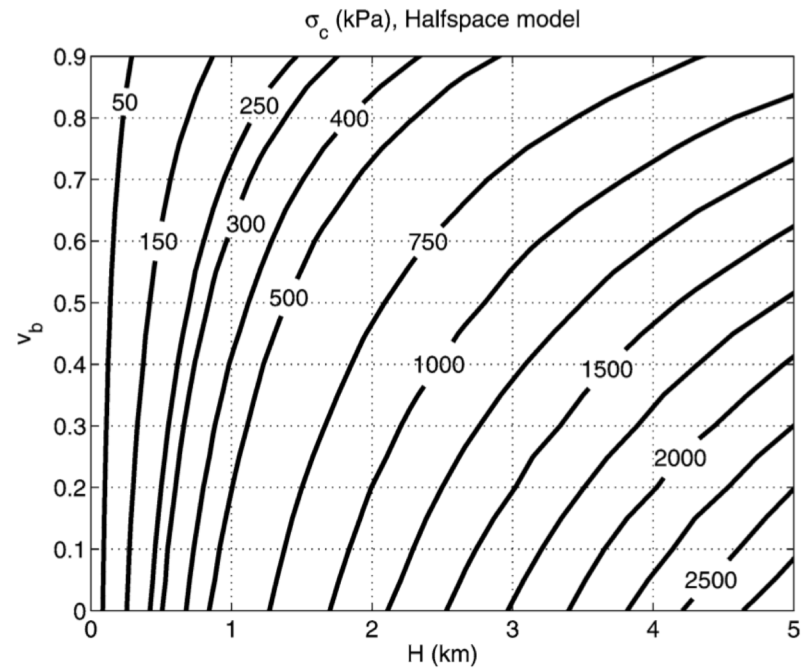
Movie credit: JPL/Caltech

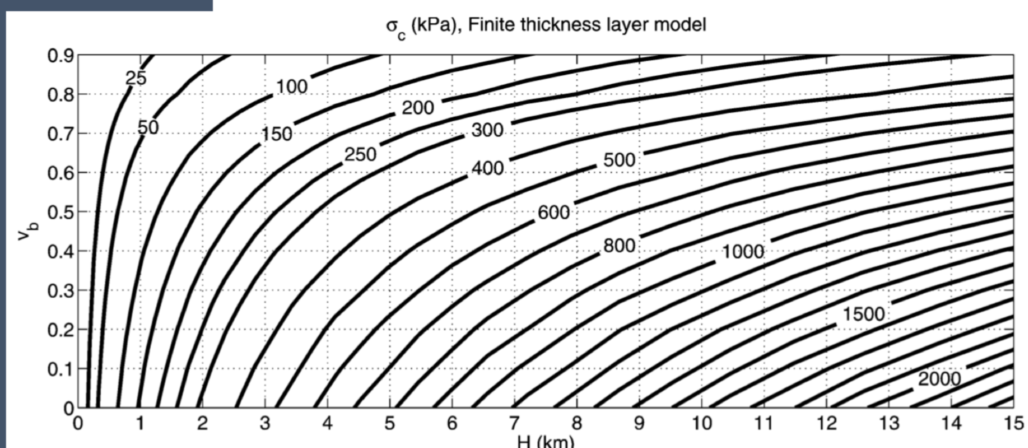
Stress modeling to generate ice cracking events



From Lee et al. (2003; 2005)

How big can an event be? We can simplistically calculate crack depths based on when tidal stress is balanced by overburden pressure… not necessarily simple…

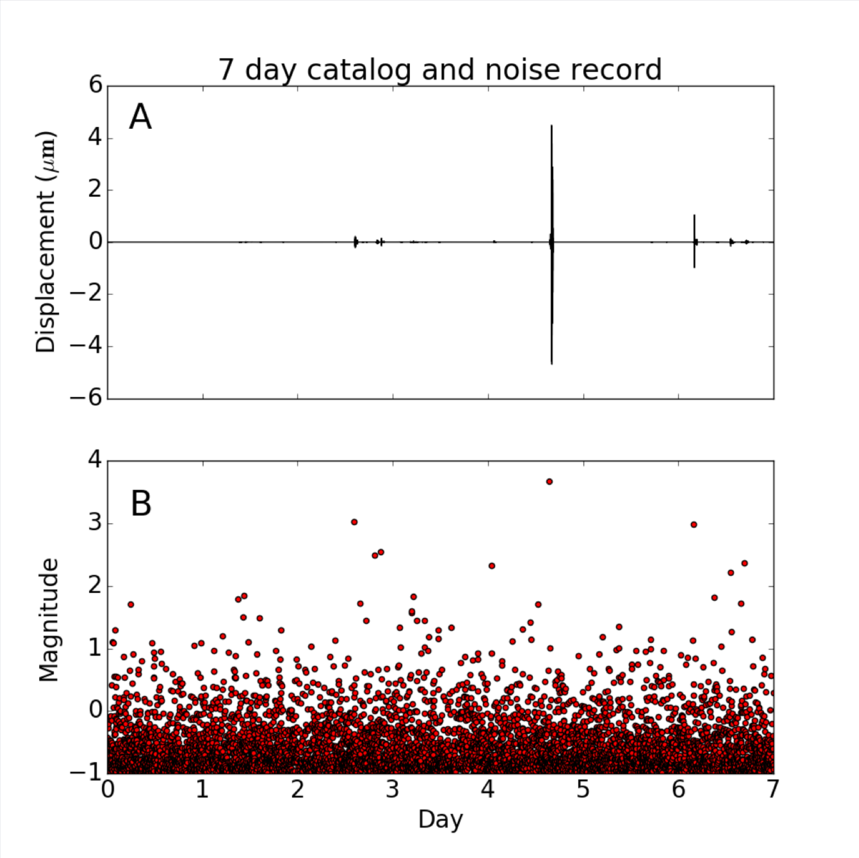


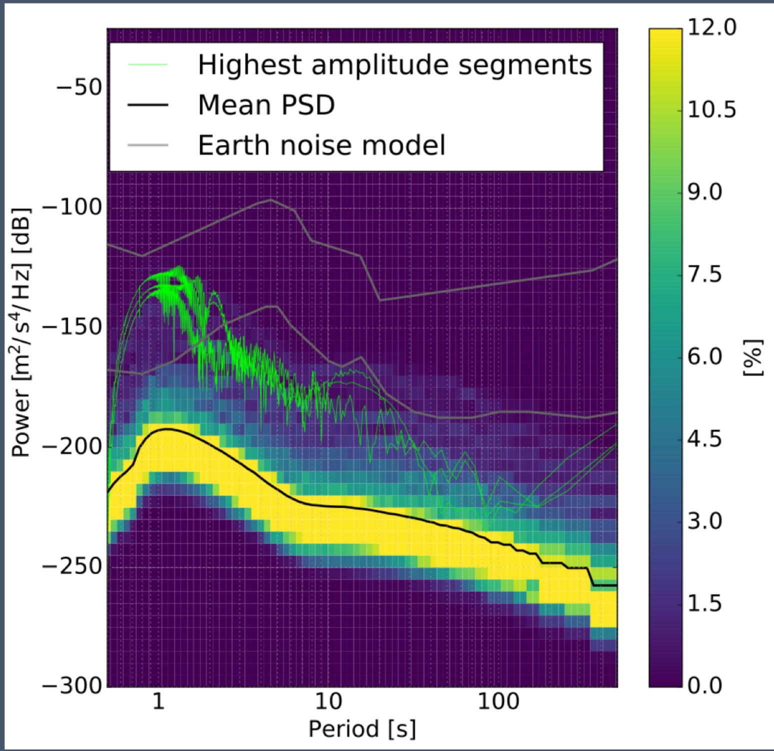


Building a statistical icequake seismicity model scaled to dissipation

- Assume icequakes follow a Gutenberg-Richter relationship, $\log_{10} N(M_W) = a - bM_W$, so we can define expected seismicity through a and b
- We can tie this to energy constraints, by rewriting in terms of seismic moment as $N(M_0) = AM_0^{-B}$
- With some manipulation, we can relate this to cumulative seismic moment and maximum event size as $\underbrace{\Sigma M_0}_{\text{Cumulative seismic moment}} = \frac{AB}{1-B} (\underbrace{M_0^{\star}}_{\text{Maximum event size}})^{1-B}$

Simulated Europa icequake catalogs and noise





Icequake catalog and synthetic seismic record (left) and estimated acceleration power spectral density for best guess model of Europa seismicity

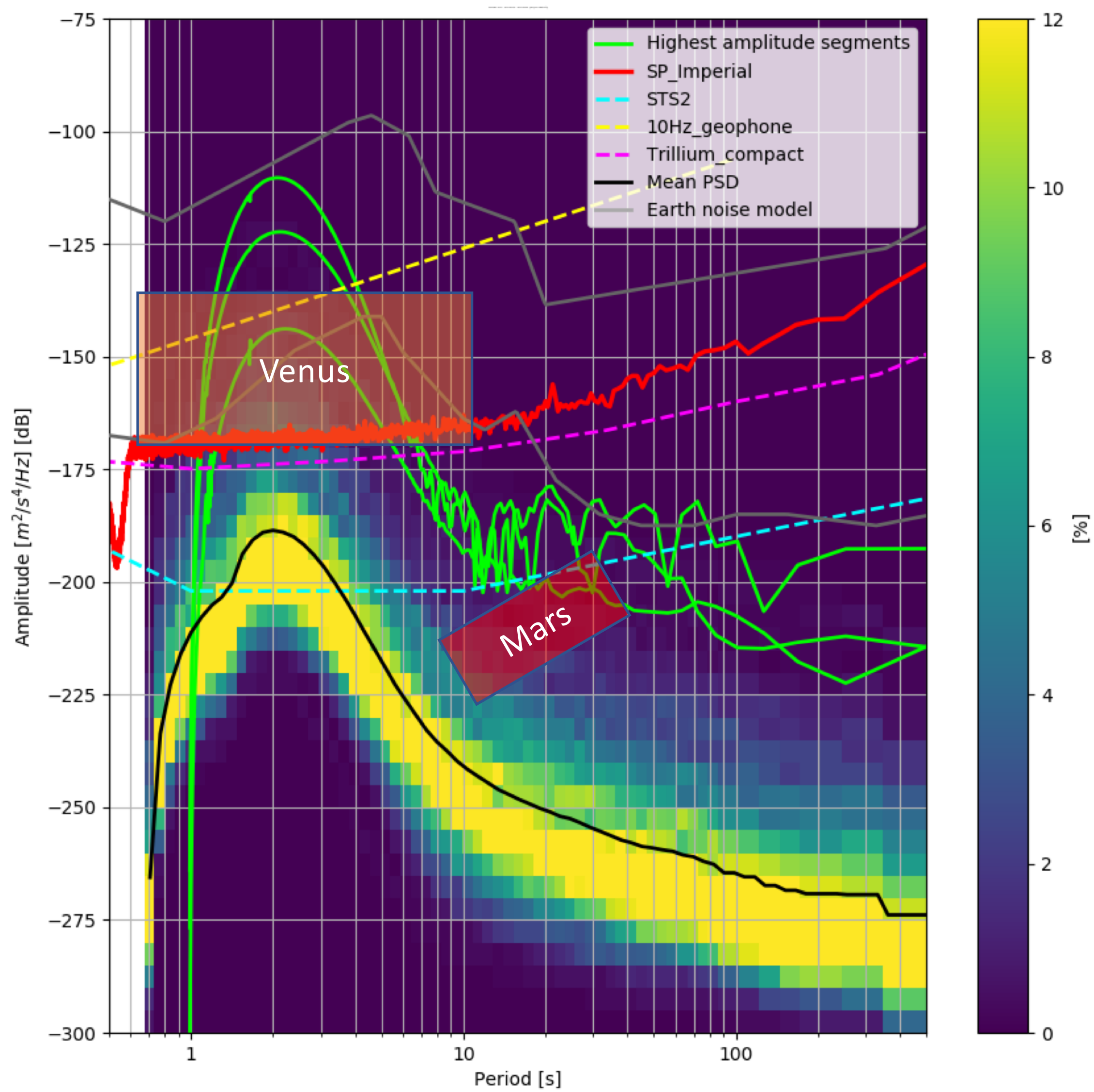
How does Titan complicate things?

Microseismic noise on Titan

- Microseismic noise due to ocean waves are the dominant noise source on Earth
- Surface high latitude methane/ethane lakes may produce analogous signals on Titan
- Initial calculations suggest this could be important in high latitudes, and even globally during storm events
- Presented at EGU by Stähler et al. in 2018, final work still unpublished

Atmospheric noise

- For Mars, noise has been simulated with atmospheric circulation models (Murdoch et al., 2017)
- For Venus, background noise may be similar to a quiet Earth station (Lorenz and Panning, 2018)
- Scale between those estimates by the estimated acoustic impedance of the atmosphere at the surface
  - Venus ~ 25 x Titan
  - Titan ~ 220 x Mars

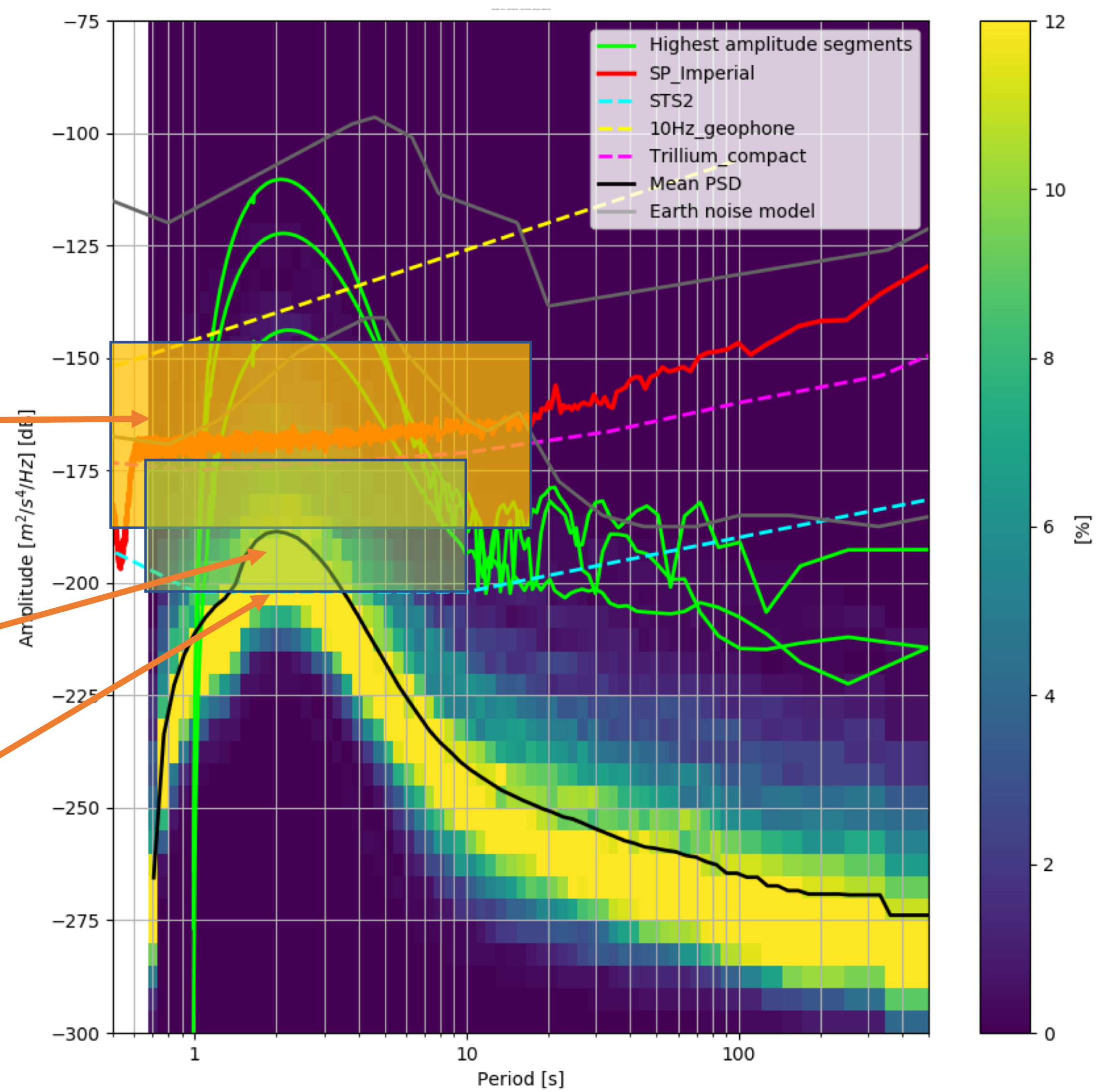


Signal and noise

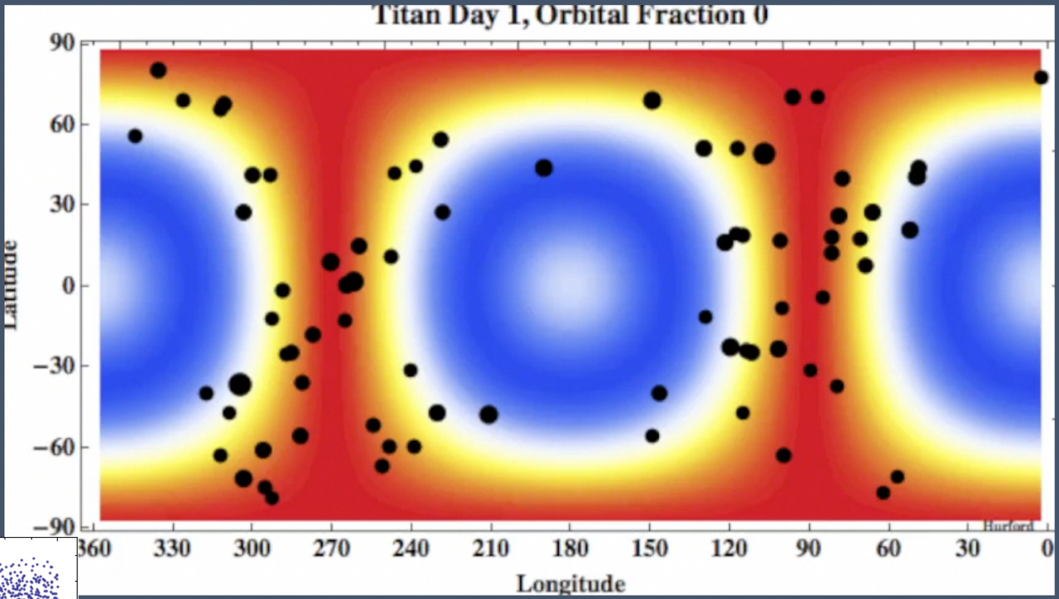
Estimated atmospheric noise

Estimated lake wave noise at equator

Estimated tidal cracking noise

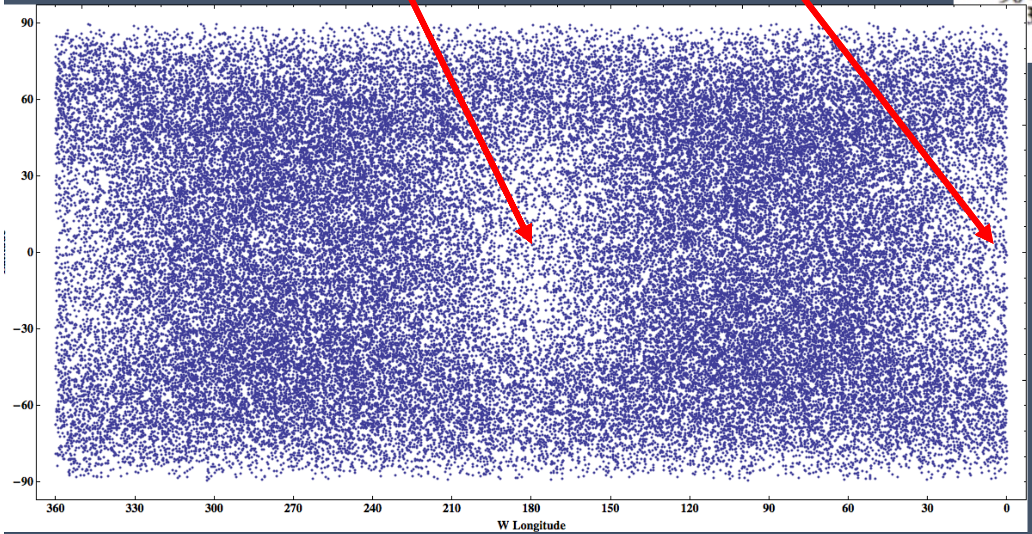


Spatial variability through tidal cycle



Anti-Saturn point

Sub-Saturn point

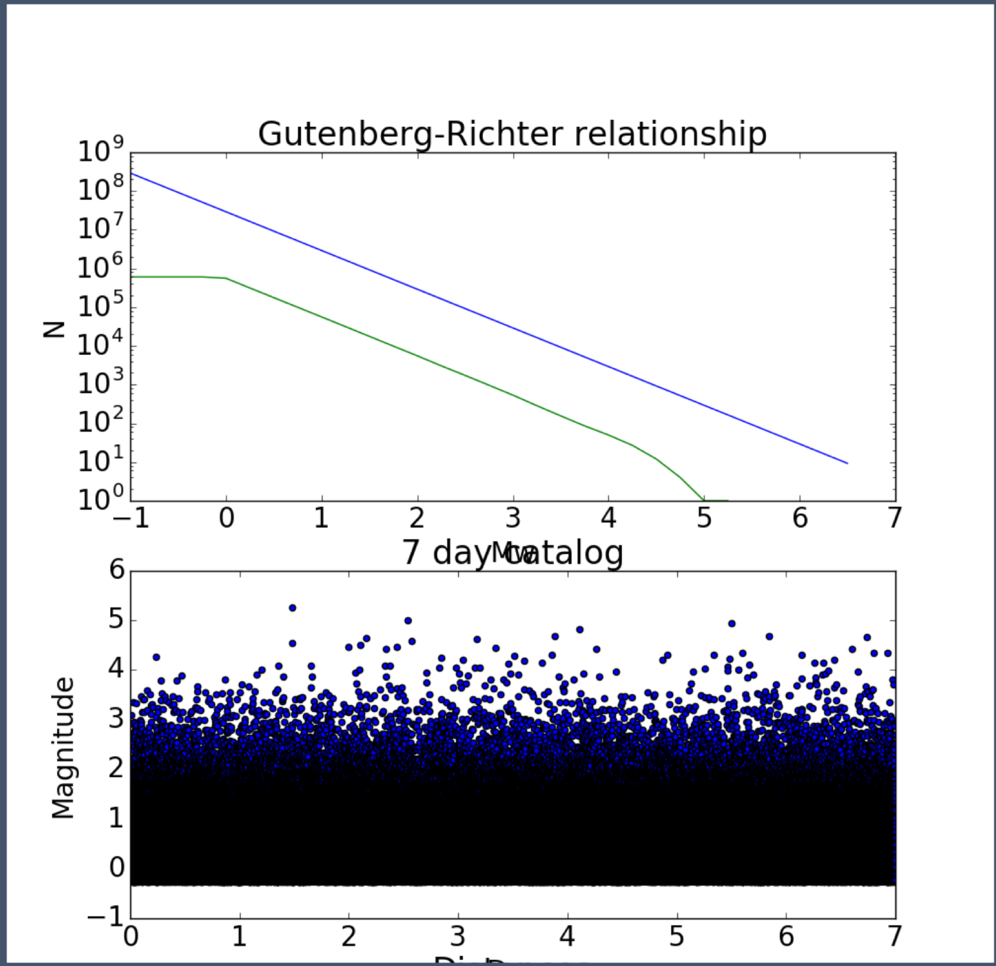


Modify event probability by spatial and temporal variability of tidal dissipation energy. Taken from modeling by T. Hurford presented at 2018 Lunar and Planetary Science Conference.

What about Io and Enceladus?

Seismicity on Io

- Scaling up from Europa approach, Io's tidal dissipation energy is ~2 orders of magnitude greater
- This implies lots of seismicity (~10^{20} Nm/yr – 10's of events > M4 every week)
- To put this in perspective, Io and Earth have similar total heat flow (100 TW vs. 46 TW), while Earth has ~10^{22} Nm/yr
- Meanwhile, Enceladus is ~2 orders of magnitude lower, but may be very focused on SPT



Where do we go from here?

What kind of seismometers?




Earth	Streckeisen STS-2	Trillium Compact	Geophone	MEMS Accelerometer*
Planetary	InSight VBB	InSight SP	Apollo Active Experiment	?*

* Technology has not yet reached sensitivity requirements of Earth & planetary science, although the InSight SP is partially MEMS-based

- Very Broad Band (VBB)
- High Dynamic Range
- Ultra sensitive
- $$$$

1.4kg

- Broad Band
- High Dynamic Range
- Sensitive
- $$

~0.1Kg
~3cm

- Narrow Band
- Limited dynamic range
- Strong motions
- $

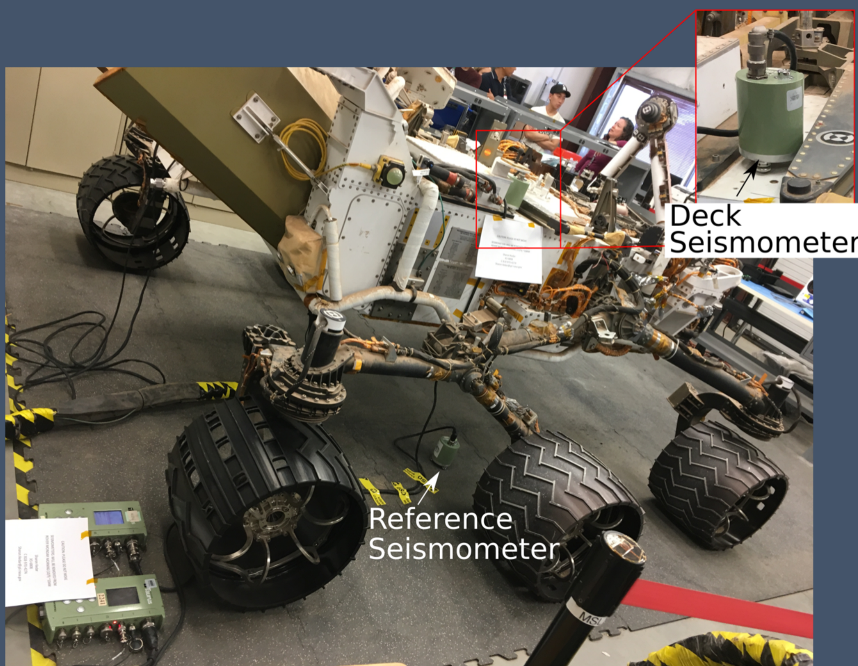
~0.01Kg
~1cm

- Broad Band
- High dynamic range
- Sensitive
- $

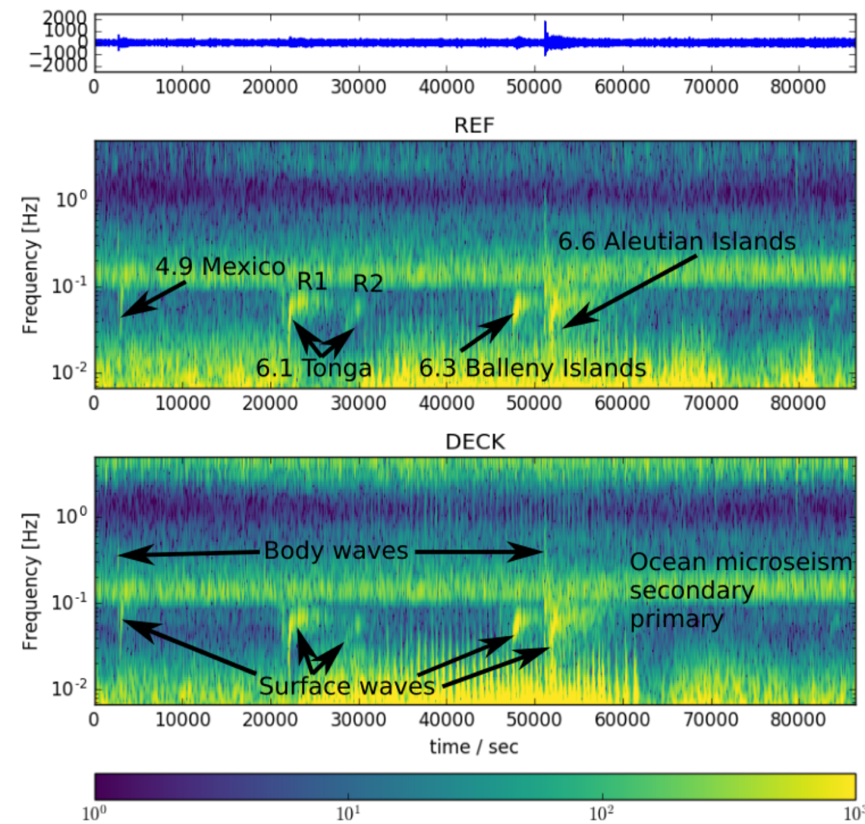
Seismometers on every lander

Investigations for deck deployment

Useful seismic data can be obtained from a simple deck deployment below spacecraft resonant frequencies. Enables seismology without complex deployment.



Panning and Kedar, 2019



Conclusions

- Planetary seismology is key to detailed interior modeling
- Seismology on icy ocean worlds looks very different from what we're used to on terrestrial bodies like the Earth (or Mars or the moon)
- There are several signals that can be exploited to learn critical things about icy ocean worlds
- Signals should be large enough on both Europa and Titan to be recorded by a moderately sensitive instrument (InSight SP or Trillium Compact), but not a high-frequency geophone
- Io should be very seismically active, indeed