PLANETARY SEISMOLOGY: THE SOLAR SYSTEM'S OCEAN WORLDS

A White Paper for the NRC Planetary Science and Astrobiology Decadal Survey

Authors:

S. D. Vance¹, D. N. DellaGiustina², K. Hughson³, T. Hurford⁴, S. Kedar¹, A. G. Marusiak¹, M. Melwani Daswani¹, M. P. Panning¹, N. C. Schmerr⁵, B. E. Schmidt³, S. Stähler⁶, S. Tharimena⁷, G. Tobies⁸, and R. C. Weber⁹

¹Jet Propulsion Laboratory, California Institute of Technology (svance@jpl.caltech.edu); ²University of Arizona, Lunar and Planetary Laboratory; ³Georgia Institute of Technology; ⁴NASA Goddard Space Flight Center; ⁵University of Maryland; ⁶ETH Zürich; ⁶University of Vienna; ⁸Université de Nantes; ⁹Marshall Space Flight Center

Introduction

Seismic investigations offer the most comprehensive view into the deep interiors of planetary bodies [1]. The *InSight* mission and concepts for a Europa Lander and a Lunar Geophysical Network herald a new era of planetary exploration, with a critical role for seismology constraining interior structure and thermal state. In oceanic icy worlds, measuring the radial depths of compositional interfaces using seismology in a broad frequency range can sharpen inferences of interior structures deduced from gravity and magnetometry studies, such as those planned for NASA's *Europa Clipper* and ESA's *JUICE* missions. On future landed ocean worlds missions, seismology may also offer information about fluid motions within or beneath ice—which complements magnetic studies—and can record the dynamics of ice layers. Seismology would thus reveal mechanisms and spatiotemporal occurrence of crack formation and propagation, and add ground truth to tectonic inferences from orbital imaging.

Unique Science from the Seismology

The strong velocity contrasts of the ocean-ice interfaces in icy moons have no global equivalent and therefore require dedicated techniques (as described in Panning et al. 2006, Stähler et al. 2018). **Table 1** summarizes possible techniques for several scientific objectives. Because of their unique characteristic of having an icy lithosphere floating atop a global liquid layer, icy ocean worlds will have distinct radial seismic sound speed profiles from those seen on Earth (**Figure 1**). The propagation of seismic waves through the different layers might be used to diagnose their thickness, composition, and associated rheological and thermal states. Modern computation enables the detailed propagation of the full seismic waveforms in three dimensions, creating a powerful tool for assessing possible experimental designs that couples well with analytical approaches [1]. **Figure 2** shows two such model results, for Europa and Titan.

Figure 1. Comparison of Earth's crust and mantle and associated compressional sound speeds with the different comparable layers in smaller and larger ocean worlds, here represented by Europa and Titan. From [1,2].

As an example, one diagnostic for the thickness of the floating ice shell is the Crary wave, a harmonic wave trapped within the ice with primarily radial displacement, and a frequency spectrum characterized by a peak at $f_{cr} = V_p / (2d \sqrt{V_p^2 - V_s^2})$ plus overtones. This spectral peak is a powerful tool for estimating ice thicknesses less than 40-50 km, as postulated for Europa. Thicker ice shells as predicted for Titan, can be constrained by seismic waves bouncing between the ice-ocean interface and the surface. On Enceladus, and to a lesser extent Titan, a combination of techniques will have to be used because the ice thickness varies globally [3,4]. All seismic techniques offer localized measurements of interior properties, but also place a spotlight on tectonic activity. For the Moon [5], as well as for Mars [6,7], seismic sources were identified at locations where faults were imaged from space and seismic source inversion constrained the tectonic setting of Cerberus Fossae on Mars [8]. Tectonic processes on icy worlds with a rheology completely different from terrestrial analogs can be much better understood by in-situ observations of fault motion.

Figure 2: Simulation of seismic wave propagation in Europa and Titan models for 20 km and 124 km thick ice shells from [1] reveal seismic signatures dramatically different from Earth's. Vertical component data (blue), horizontal (green) for the component in the source-receiver plane and for the transverse direction (red; see color guide). Unique labeled phases may be used to sound the thickness of the ice-I lithosphere and also the thickness of the underlying high-pressure ice(s) in Titan.

Strong Seismic Signals are Expected at Ocean Worlds

Detectable seismic activity should occur on tidally flexed ocean worlds exceeding the level of seismicity detected at the *Moon* the *Apollo* experiments. The ices of ocean worlds fracture more easily than rocks and dissipate more tidal energy than the <1 GW of the Moon and Mars. Icy ocean worlds also should create less thermal noise due to their greater distance from the Sun and consequently smaller diurnal temperature variations. They also lack substantial atmospheres (except in the case of Titan) that would create additional noise.

Given that several types of observed seismicity on our own Moon appears to be at least tidally modulated, initial estimates were made [9] of the expected tidally-driven seismicity in the ice shell of Europa by scaling the observed seismic moment release on the Moon to Europa using the expected tidal dissipation energy. This result was later generalized [10] to use for any tidally activated body as well as accounting for spatial and temporal variability through the tidal cycle. Using those estimates, Europa may be expected to have seismic events releasing $\sim 10^{17}$ NM of seismic moment per 3.5 Earth day tidal cycle, compared with the observed seismicity of the Moon of less than 10^{15} NM per 27.3 Earth day tidal cycle. Titan falls in between these bodies with greater than 10^{16} NM per 15.9 Earth day tidal cycle, while Enceladus would only release around 10^{14} NM per 1.4 Earth day tidal cycle. While these estimates may be upper bounds if lunar seismicity is not primarily driven by tidal energy, this does suggest the potential for high levels of activity on Europa and Titan in particular, while the small size and shorter tidal period of Enceladus suggest events will be much more observable on Enceladus than our own Moon, particularly when taking into account the observations of active geologic processes related to the plumes in the south polar region (discussed in more detail below).

Expected signal and noise levels

Many different signals are expected to be important on ocean worlds, at a wide range of possible amplitudes [1]. **Figure 3** shows examples of the range of expected signals at Europa, which has been studied the most extensively. Amplitudes on other ocean worlds for such signals may be broadly comparable, although the exact amplitudes are sensitive to details such as the thickness of the solid ice shell [e.g. 9] and the occurrence rate will vary greatly [e.g. 10]. To observe such signals on ocean worlds, the signal amplitudes will need to be above the noise floor of the observations, which will depend on (1) the background seismic noise of the planetary body, (2) the self-noise of the seismic instruments, and (3) the style of deployment of those instruments.

Figure 3: Europa is expected to be seismically active requiring a sensitive, broad-band, high-dynamic-range seismometer such as the SP (red). The expected sources are located in their relevant frequency and amplitude ranges, based on Earth analog (black text) and models (white text) [1-5], with italicized text indicating the science investigations enabled by recording these sources. The sensitivity of a 10 Hz geophone is shown in blue for comparison. Note that most of the expected signal will not be observable by a high-frequency geophone.

For airless bodies, which excludes Titan, the background seismic noise will likely be driven by tidal cracking [9,10], although ocean noise may be an important factor as well that needs further study. For Europa, such tidal cracking noise signal power was estimated at frequencies less than 1 Hz was estimated to be ~ -200 dB or less (**Figure 4**), which would correspond to a signal amplitude of $\sim 10^{-10}$ m/s², likely below the self-noise of candidate seismic instruments, although signals of expected larger ice-cracking event should be 1-3 orders of magnitude above this background noise. Background noise on other ocean worlds due to this source requires further forward modeling, but recent work [10] provides an appropriate initial assumption for background seismicity levels scaled to tidal dissipation energy on other likely targets which can be translated to expected noise levels by propagation through appropriate structure models for each body. In particular the noise level for each body will depend on the ice shell thickness and the radius of the planet, which affects the average distance from cracking events and the geometric spreading of the signals. Thinner ice shells and smaller worlds both would act to increase signal amplitude.

Figure 4. Modeled seismic power spectral density (PSD) of seismic noise from fracturing on Europa (left) and Titan (right). Titan may also have background noise from sea microseisms (blue box) and from the atmosphere, here scaled from Martian estimates (red) and Venus (yellow). Background color is probabilistic PSD calculated from 1–hour segments of a multi-week simulated noise record, with the mean in yellow. Orange lines are for segments with the largest events in the time period. Dashed lines show some representative seismic instruments’ self-noise. Modified from [3].

On Titan, (**Figure 4, right**) we need to consider atmospheric noise as well. While observed noise on Earth is dominated by ocean noise, Mars and Venus are dominated by atmospheric-generated noise. On Mars, observations from InSight suggest atmospheric noise near -150 dB based on recordings from the seismometer before being covered by the Wind and Thermal Shield [11]. While on Venus, very limited data from the Venera landers suggests a noise level comparable to the Earth (gray lines in **Figure 4**) [12]. We can scale these estimates by the acoustic impedance of the atmosphere, which controls transmission of seismic energy from the atmosphere while also accounting for reduced solar flux at Titan to drive atmospheric processes, or similarly by expected dynamic pressure which scales by atmospheric density and squared wind velocities, to obtain estimates for atmospheric noise on Titan ranging from -140 to -200 dB (10^{-7} to 10^{-10} m/s²), which will likely be the dominant noise source.

Regardless of background noise, instruments will need to be sensitive enough to record the desired signals. For the largest events likely detectable given the seismicity estimates from Hurford et al. [10], this likely requires instrument and deployment noise near 10^{-8} m/s²/rtHz between 0.1 and 10 Hz, which is beyond the range of most high frequency geophones, but within reach for a variety of capable terrestrial and planetary seismometers. This will require an ongoing effort by NASA to ensure there are instruments available capable of meeting the environmental requirements of potential ocean world targets. Additionally, care will need to be taken in designing deployment of instruments. While

seismometers deployed on a landed asset will see significantly increased noise due to wind on bodies with atmospheres, this problem may be reduced on airless bodies, but will depend on the details of lander activities and processes [11].

Additional Seismic Sources

Tides at Enceladus, around Tiger Stripes: On Earth, seismometers deployed in the cryosphere have been able to link increases in seismic activity to temperature [13,14] and tidal cycle [15]. Seismometers have been used to monitor volcanoes and eruptions [16,17] analogous to the plume eruptions. At Enceladus, eruptive jets in the south polar terrain (SPT) likely result from shear heating [18] and tidally controlled opening [19]. A single-station seismometer or array of seismometers deployed around the stripes could test for correlations between the timing and location of seismic activity and Enceladus's tidal cycle and plume eruptions. Additional analysis on the recorded seismic source mechanisms would provide parameters for modelling the dynamics of SPT (see companion white paper by Vance *et al.*). The depths and locations of the seismic events can help inform where the plume materials originate and how the materials are transported.

Lakes on Titan: Titan's lakes [20] may be capable of producing microseismic background noise, similar to Earth's ocean microseism background [21]. Storms with wind speeds above 2 m/s may produce observable signals on a global-scale for a broadband seismometer or up to distances of ~ 1000 km for a space-ready seismometer [22]. A storm producing sustained 4 m/s winds would likely produce globally-observable signals for most short-period and broadband instrumentation, but even waves of 2 m/s winds could be picked up by a broadband seismometer at mid latitudes (but not by a geophone). Thus, a high-sensitivity seismometer would allow remote observation of strong storms in the polar regions. On top of the wind noise, the seismic energy of lake microseisms could be autocorrelated to constrain local ice structure and possibly to help constrain the ice shell thickness.

Fluid-Flow Induced Seismicity: Fluid flow generates a unique and distinguishable class of seismic sources. Unlike brittle failures in rock or ice, that are associated with distinct P, S, and surface waves, flow-driven seismicity results from a continuous interaction between the moving fluid and the surrounding rock or ice. Such seismicity can be caused by a range of fluid states, and flow regimes, yet they commonly appear as a continuous, quasi-monochromatic, low amplitude background vibration (**Fig. 5**). Fluids are likely present in tidal flexed ice shells like Europa that are undergoing solid state convection. Ocean worlds may share common attributes with terrestrial analogs (geysers, sub-glacial flow, volcanos, cryovolcanos, and ocean resonance) whose frequencies and amplitudes represent underlying physical processes and fluid properties.

Figure 5. Fluid flow induced ground motion is recognizable by its appearance as continuous background oscillation. From [1].

Analogs

In preparing for the seismic studies of ocean worlds, NASA should support polar environmental analog field studies on Earth and other terrestrial bodies. Seismic deployments in environmental analogs to ocean worlds, such as glaciers, ice sheets, and ice shelves on Earth are crucial for understanding the challenges to future space mission deployments. For example, a recent set of environmental analog studies to simulate single-station deployments on Europa [23] showed placement of seismic instruments in locally seismically quiet regions (e.g. on a stable ice sheet) detected a higher percentage of larger teleseismic events [14]. However, the study also demonstrated that instruments deployed in a seismically noisier environment (e.g. on an active glacier) were still able to detect teleseismic events, and recorded a wealth of smaller magnitude, more local events. Cryosphere studies have also shown that non-seismic equipment can generate non-intentional sources. For example, flags and poles left at analog field sites have been known to generate seismic signals that can obscure the detection of naturally occurring events [14, 24]. While known sources (e.g. signals generated by InSight's HP3) can be used to determine near-surface properties, unknown sources from lander or EDL (entry, descent, landing) equipment can hinder seismic investigations.

Conclusion

The return to planetary seismology marked by the *InSight* mission is enabled by the development of lightweight and sensitive instrumentation, and modern computational sophistication. Instrumentation is currently ready for investigating Europa [25,26] and Titan [27,28]. In the coming decade, NASA should support continued innovation in planetary seismology through further research and analysis, development of autonomous seismic networks [e.g. 29], and innovation in new sensors and electronics.

References: [1] Vance, S. *et al.* (2018) *Astrobiology*, **18**, 37–53. [2] Stähler, S. *et al.* *JGR-Planets* **123**, 1–27. [3] Hemingway, D.J. and Mittal, T. (2019) *Icarus*, **332**, 111–131. [4] Souček, O. *et al.* (2019) *Icarus*, **328**, 218–231. [5] Watters, T. R. *et al.* (2019) *Nat. Geosci.*, **12**, 411–417. [6] Lognonné, P. *et al.* (2020) *Nat. Geosci.*, **13**, 213–220. [7] Giardini, D. *et al.* (2020) *Nat. Geosci.*, **13**, 205–212. [8] Brinkman, N., *et al.* (2020), [essoar](#). [9] Panning, P. *et al.* (2018) *JGR-Planets*, **123**, 163–179. [10] Hurford, T. A. *et al.* (2020). *Icarus*, **338**, [113466](#). [11] Panning *et al.* (2020a), *J. Geophys. Res.*, **125**. [12] Lorenz, R. and Panning, P. (2018) *Icarus*, **303**, [273–279](#). [13] Lombardi, D., *et al.* (2019) *Annals of Glaciology*, **60**, [45–56](#). [14] Marusiak, A. G. *et al.* (2019) [AGU Fall Meeting](#). [15] Olinger, S. D. *et al.* (2019) *GRL*, **46**, [6644–6652](#). [16] McNutt, S. R. (1996). In *Monitoring and mitigation of volcano hazards*, 99–146, Springer. [17] Rowe, C. *et al.* (1998) *GRL*, **25**, [2297–2300](#). [18] Nimmo, F. *et al.* (2007) *Nature*, **447**, [289–291](#). [19] Hurford, T. A. *et al.* (2007) *Nature*, **447**, [292–294](#). [20] Stofan, E. R. *et al.* (2007) The lakes of Titan. *Nature*, **445**, 61–64. [21] Gutenberg, B. (1947) *J. Meteorology*, **4**, [21–28](#). [22] Stähler, S. C. *et al.* (2019) *EPSL*, **520**, 250–259. [23] Marusiak, A. G. *et al.* (2020) *SRL*, **91**, [1901–1914](#). [24] Carmichael (2019) *Annals of Glaciology*, **60**, 231–237. [25] Tharimena, S. *et al.* (2019) [AGU Fall Meeting](#). [26] Pike, W.T. *et al.* (2016) *Proc. 3rd Internat. Workshop on Inst. Plan. Missions* [27] Hand, K.P. *et al.* (2017) *Report of the Europa Lander Sci. Def. Team*. [28] Lorenz, R.D. *et al.* (2019) *LPSC* [2173](#). [29] Panning, M.P. *et al.* (2019). [AGU Fall Meeting](#). [29] Song, W. *et al.* (2019) *Sensors*, **19**, [301](#).

Acknowledgements: A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004). © 2020.

Table 1. Summary of Objectives and Target Seismic Science

Scientific objective	Seismic observable	Signal strength	Source type	Reference
Tectonic activity	Location of seismic events	strong	Quakes, near source, regional, global	2
Ice thickness	Crary wave frequency	strong	Quakes, regional, global	2, 24
	Transition frequency Rayleigh to flexural wave	intermediate	Quakes, global	2, 24
	Reverberations in coda	strong	Quakes, near source, regional, distant	2, 24
	Autocorrelation of ambient noise	strong	Atmosphere or microcracking	9
Ocean depth	Reverberations in coda	intermediate	Quakes, regional, distant	2, 24
	Autocorrelation of ambient noise	intermediate	Atmosphere or microcracking	9
Ocean chemistry (via sound velocity in water)	Reverberations in coda	intermediate	Quakes, distant	2
High-pressure ice phases	Reverberations in coda	intermediate	Quakes, regional, distant	2
	Scholte waves	intermediate	Quakes, distant	2
	Coda of Sn waves	intermediate	Quakes, distant	2
Core diameter	Observation of specific phases	intermediate	Quakes, global	2
	Reverberations in coda	Intermediate	Quakes, global	2
	Autocorrelation of ambient noise	weak	Atmosphere or microcracking	9