SEISMIC MODELS OF TITAN FOR THE DRAGONFLY MISSION. A. S. Bryant[1,2,3], M. P. Panning[3], A. G. Marusiak[3], [1]Department of Physics, The University of Chicago (asbryant@uchicago.edu), [2]Johns Hopkins Applied Physics Laboratory, [3]Jet Propulsion Laboratory, California Institute of Technology.

Introduction: Seismic wave propagation through icy moons can potentially reveal the interior structures of icy ocean worlds will be revealed. Observation of seismic sources may also be the best tool to determine the "vital signs" (fluid flow induced ground motion) of these worlds [1].

Saturn's moon Titan is of particular interest as it is the second largest moon in the Solar System and contains both an atmosphere and a subsurface ocean. On its surface there are sand dunes and methane lakes. Beneath the surface there is thought to be a 45-120 km thick [2,3,4] ice shell, and beneath the thick ice there is a >80km deep ocean [5]. Beneath the ocean there could perhaps be a layer of high-pressure ice depending on the thermal profile, however the presence or absence of high-pressure ice would significantly affect the rock-ocean interactions.

The Dragonfly rotorcraft is currently planned to launch in 2027 and land on Saturn's moon Titan in the mid-2030s [6]. The rotorcraft itself is a dual-quadcopter that would hold many instruments, including a seismometer and two geophones, within the DraGMet (Dragonfly Geophysics and Meteorology) instrument package, to measure ground motion [7].

For this study we simulated a range of models both shallow and deep (3, 25, 411, and 525km) within Titan while varying the methane clathrate lid thickness, in order to study the expected seismic signal from a single station seismometer on Titan.

Methods: We generated three, spherically-symmetric interior structure models using Planet-Profile—a MATLAB software used for constructing 1D interior structure models [8]. These interior structure models all contain a 100 km thick ice I layer with varying clathrate thickness, a pure water ice shell containing no clathrates, and clathrate-lids thicknesses of 10km and 20km respectively.

Using the interior structure models as inputs, we then simulate four source depths, or titanquake hypocenters for each interior structure model.

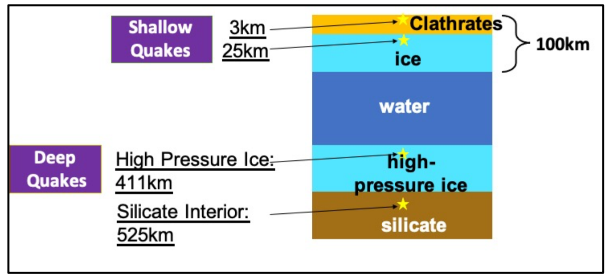

Figure 1. Schematic of the Source Depths Simulated with AxiSEM and Instaseis. Shown is the schematic for a 20km clathrate lid. Note the two quake regimes: Shallow (3km and 25km) and Deep (411km and 525km).

Waveform propagation is simulated using AxiSEM [9], the spectral element solver, to model the global wavefield of Titan for each of the source depths. The source depths fell into two regimes, namely shallow quakes and deep quakes. The shallow quakes took place within the top ice layer, at 3km (within the clathrate layer) and 25km respectively, while the deep quakes took place within the high-pressure ice and the silicate interior, or 411km and 525km respectively (Figure 1).

Noting the afore mentioned, PlanetProfile and AxiSEM, to complete wavefield models the Python package Instaseis [10] was used to reconstruct seismograms for hypothetical source and receiver location from the AxiSEM models. The TauP software package was used to calculate theoretical arrival times [11].

Results: Of all the twelve model runs (from 3 different structural models and 4 different source depths), the shallow events produced the largest amplitudes. The most notable feature in the shallow events was a large Rayleigh pulse, although this varied as a function of the different attenuation structure of the models due to different thermal profiles due to the lower thermal conductivity of clathrates. Models run with a high level of seismic attenuation (low Q values) lacked the large Rayleigh pulse.

Impact of Source Depth. We found that the seismic amplitudes differed within several orders of magnitude depending on the source depth (Figure 2). In Figure 2 the Shallow quakes dominates the seismogram so much so that the Deep Event seems to no longer be present.

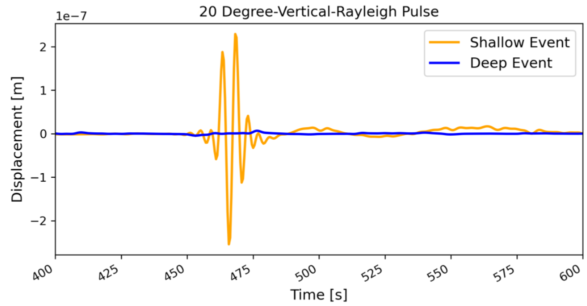

Figure 2. Displacement [m] versus Time [s] for a 20 Degree titanquake, Vertical Component. Both seismograms correspond to events that lack a clathrate lid. The Shallow Event is a 3km quake and the Deep Event is a 525km quake within the rocky interior of Titan. The time interval is from 400 to 600 seconds in order to zoom in on the Rayleigh pulse present within the Vertical component.

Clathrate Lids: In agreement with Marusiak et al 2022 [12] we found that P and S wave sound speeds slightly decrease in the presence of methane clathrates versus pure ice. Surface waves therefore travel slightly slower in the presence of clathrates versus pure ice. This is clearly seen in the Figure 3 where a Rayleigh pulse is seen first within the pure-ice seismogram (blue) and a Rayleigh pulse is seen within the 20km clathrate-lid (magenta), at a later time and also at a lower displacement amplitude.

The Rayleigh pulse becomes small in the 10km clathrate-lid due to a very thin thermal lid (Figure 3: orange). The thinner thermal lid leads to a higher temperature and lower Q, and therefore results in reduced seismic amplitudes.

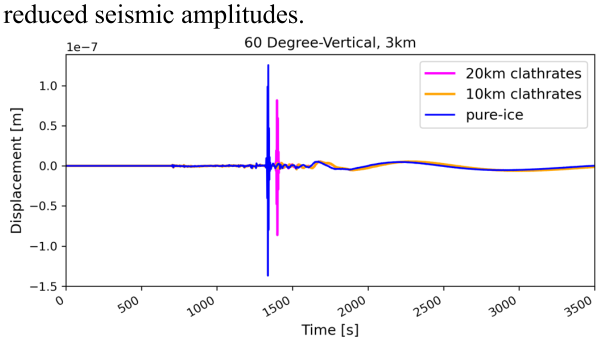

Figure 3. Displacement Amplitude [m] versus Time[s] for a 60 Degree, Vertical Component, 3km source depth titanquakes for 20km and 10km clathrate-lid (magenta and orange, respectively), and pure-ice (blue). Total seismogram duration is 3500 seconds.

Summary & Conclusions: Here, we investigate the expected seismicity of Titan in the presence of deep and shallow source depths in the presence of a 10 km and 20 km thick methane clathrate lid would have on seismic signals. We generate 1D synthetic waveforms for a 100 km ice shell (total thickness) with varying source depths, ranging from within the top ice shell to the deep within Titan's interior, totaling twelve, 2D spherically symmetric Titan models. Preliminary results suggest that the clathrates create notable differences in seismic phase arrival times and changes to the waveforms.

The outcome of the seismic models is highly dependent upon inputs into the PlanetProfile model of Titan. Future models will explore other species of clathrate hydrates (ie. ethane), as well as adding surficial organic material layers. In addition to expanding the seismic catalog to regional-scale 3D seismic meshes of Titan's interior to include topography and a variety of heterogeneities within the ice shell (eg. fractures, melt lensing, etc).

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