Analysis of Synthetic Seismograms for Low-Angle Thrust Faults on Titan

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Abstract

Little is known of the structure and seismic nature of icy satellites, planetary bodies that have an outer shell of ice instead of a rocky crust. One such body, Saturn's moon Titan, is unique because of its thick atmosphere, hydrologic cycle similar to Earth's, and salty subsurface ocean. The Dragonfly mission, set to launch in 2026, will use a robotic rotorcraft to transport various instruments, including a seismometer, to the Shangri-La dune field on Titan. Until then, Titan's seismic regime can be estimated by simulating wave propagation through assumed layering using source models. Ridge belts with low slope angles suggest fold-and-thrust belts possibly caused by fluid overpressures in Titan's icy shell. These have been observed in synthetic aperture radar images from Cassini and may be a likely site for Titan-quakes. Synthetic seismograms are calculated for Titan-quakes using Instaseis, a Python-based software sourced by Green's function databases computed by the axisymmetric spectral element method. Back-azimuth angles are calculated for different source-receiver configurations. Very high amplitude waves are interpreted as surface waves. The PP wave is the first arrival at distances greater than 35 degrees. At 45 degrees, S waves are not distinguishable.

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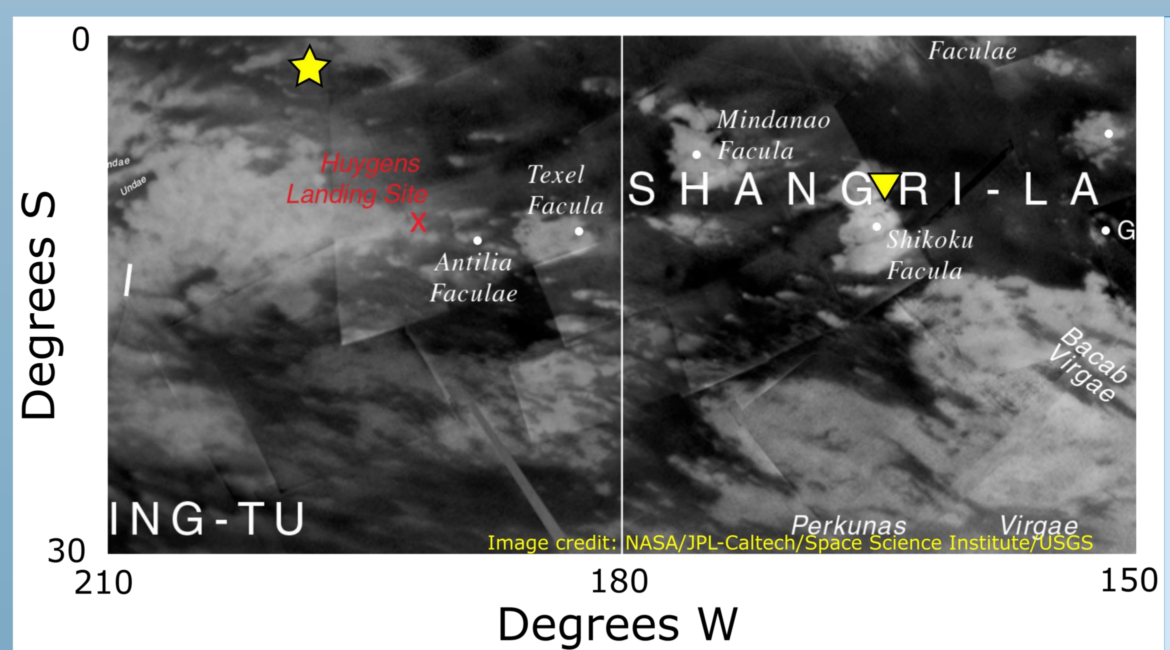
Location



Cassini ISS image of Shangri-La. Quake epicenter (E) is designated by the star. The triangle is Dragonfly's landing zone-our first receiver (R) location (Lorenz et al., 2018).

R: 165W, 10S
E: 200W, 3S

Methods

Instaseis was used to generate seismograms from defined source functions and receiver locations. Receiver locations were chosen starting at the center of the Shangri-La region and incrementally shifted by 5 degrees away from the source. Seismic sources were defined by estimated strike, dip, rake, and moment magnitude parameters based on similar low-angle thrust faults on Earth. Back-azimuth angles (α) were calculating using the following equation:

$$\alpha = 180° - \arctan\left(\frac{P_E}{P_N}\right),$$

where P_E is the PP-wave magnitude on the east component and P_N is the PP-wave magnitude on the north component (Stein & Wysession, 2003). Phase arrivals were estimated using a Python implementation of TauP (Crotwell et al., 1999) and manually picked in SAC (Seismic Analysis Code). S-wave velocity was estimated using the standard calculation of quake distance using the S-P arrival difference and an assumed V_P and Poisson's ratio (Vance et al., 2018).

Objectives

- To characterize the expected seismic response from slip of low-angle thrust faults on Titan by a Dragonfly-like seismometer
- To evaluate the application of body wave analysis techniques on an icy ocean world
- To determine if quakes from low-angle thrust faults will produce signals above expected seismic noise

Results

Estimating S-wave arrival
D = 1604 km

$V_{P,\ ice\ Ih} \approx 3.9$ km/s $t_P = 410$ s

$$D = 1.37(t_S - t_P)V_P$$

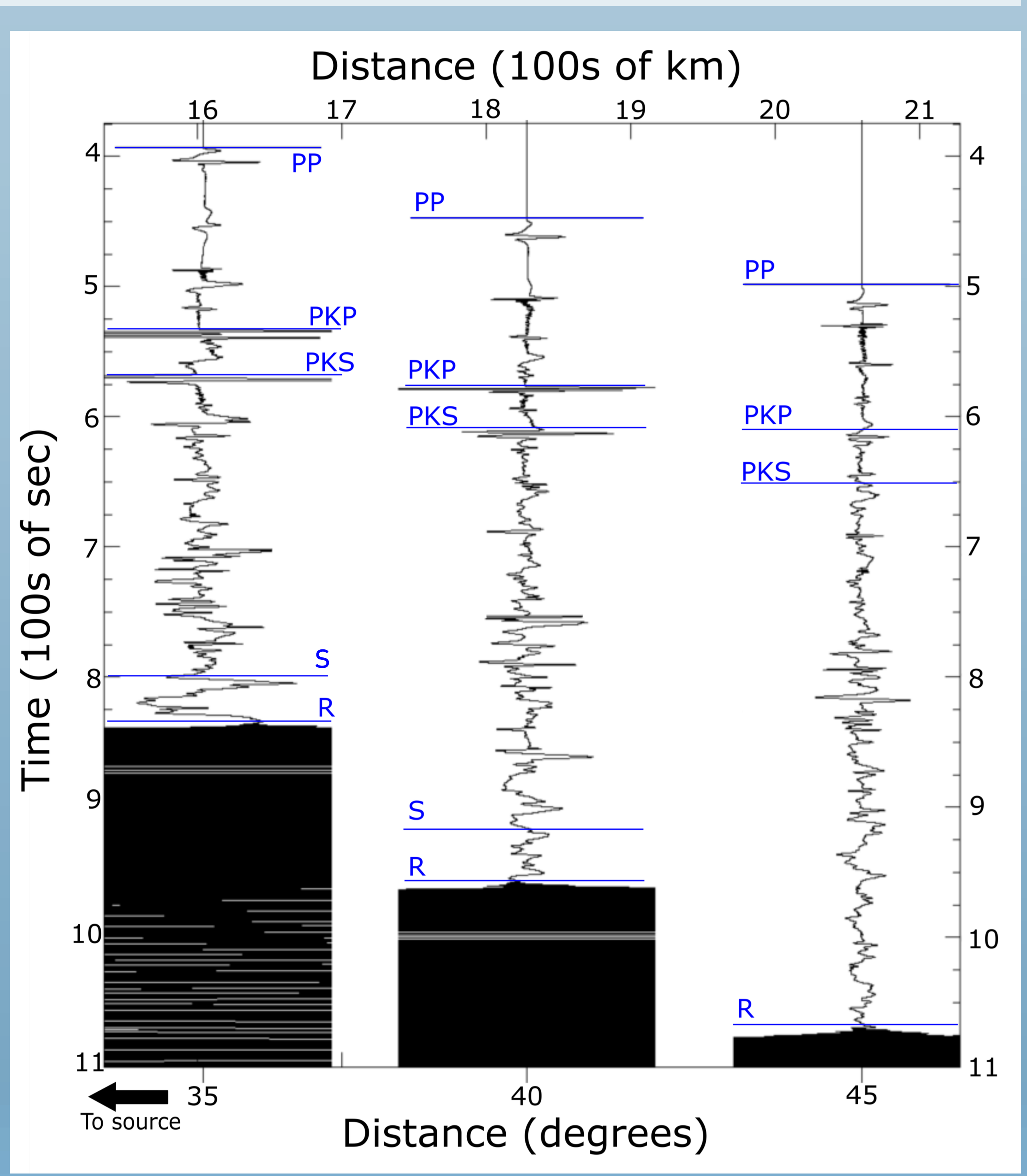
$$t_S = \frac{D}{1.37V_P} + t_P$$

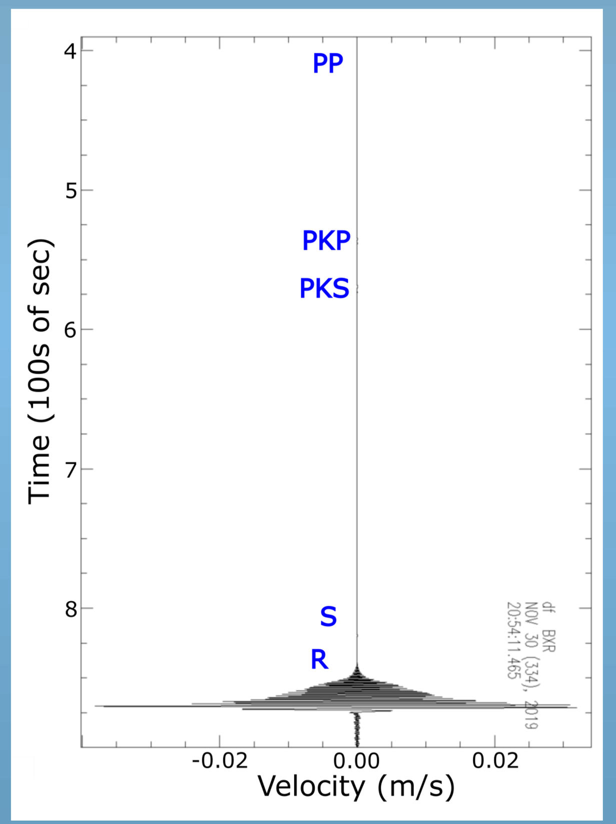
$V_{S,\ ice\ Ih} = 2.3$ km/s $t_S = 710$ s

Method	t_P	t_S
Visual	410 s	710 s
TauP	407 s	816 s

Right: Record section of 3 synthetic seismograms with the same azimuth.

Below: Trace of the receiver at 35 degrees from the source. Velocity scale shows the full range of amplitudes through the record.



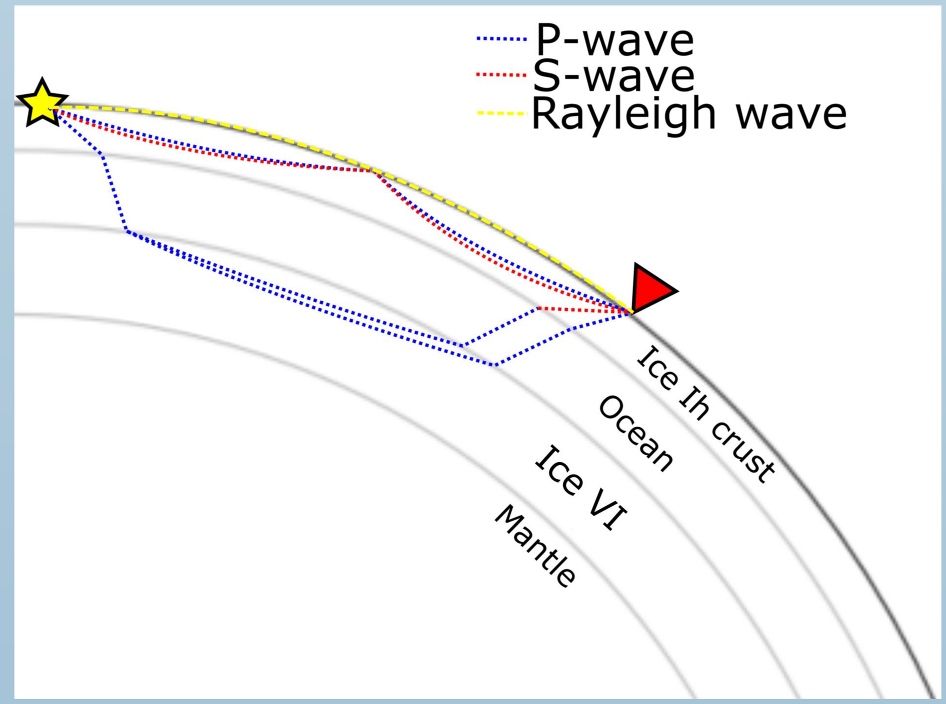


Phase	Description
PP	PP-wave in upper ice shell
S	S-wave in upper ice shell
PKP	P-wave bottoming in HP-ice
PKS	P-wave bottoming in HP-ice, converting to S-wave during return through upper ice shell
R	Rayleigh wave at the surface

Back-Azimuth

Receiver distance	P_N (m/s)	P_E (m/s)	$\alpha = 180° - \arctan\left(\frac{P_E}{P_N}\right)$
35.7°	4.5E-7	-2.7E-6	80.5°
40.7°	1.4E-7	-1.6E-6	85.0°
45.7°	0.5E-7	-0.3E-6	80.5°
Actual: 35.7°	7°	35°	78.7°

Raypaths and Layers of Titan



Layer	Thickness	V_P	V_S
Ice I_h shell	118.54 km	3.88 km/s	1.96 km/s
Ocean	188.95 km	1.94 km/s	0.00 km/s
Ice VI	229.60 km	4.20 km/s	2.21 km/s
Mantle	2037.61 km	7.99 km/s	4.53 km/s

At distances 35 degrees or greater, the first phase to arrive is PP. No P-wave can travel from the source to receiver without reflecting off the free surface or the ocean. Phases shown are PP, S, PKP, PKS, and the Rayleigh wave.

Discussion and Conclusions

- T_S estimation using our method does not match TauP arrival times. If no P-wave is truly reaching the receiver at 35 degrees or greater, the PP-phase is probably the first arrival. T_{PP} should not be substituted for T_P in this estimation.
- Back-azimuth calculations consistently over-estimated the actual back-azimuth.
- Seismic phase identification using TauP estimated arrival times is recommended only as a first-order guide. TauP lists multiple arrivals as the same phase, possibly due to wavefront geometry.
- For receiver location 40 degrees and closer to the source, large-amplitude phases arrive at the same time as TauP PKP and PKS arrivals. These waves traverse the icy crust and ocean as P-waves, bottom in the high-pressure ice, travel through the ocean, and return through the icy crust (PKP as a P-wave, PKS as an S-wave). Stähler et al. (2018) do not provide a phase name for waves bottoming in the high-pressure ice. Because "H" and "P" have already been used for hydroacoustic phases and P-waves, we propose labeling these phases as PFDFP and PFDFS. "D" indicates traversal of high-pressure ice, using the German word *Druck*.

Future Work

- Generate seismograms for receiver locations along Dragonfly's path to Selk crater.
- Calculate receiver functions for all seismograms.
- Invert arrival times to estimate subsurface discontinuities.
- Repeat these analyses for a thin-ice shell (no HP-ice layer) model and an intermediate model.

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