A SEISMIC SIGNAL AND NOISE BUDGET FOR TITAN: PREPARATION FOR DRAGONFLY.

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Introduction: The Dragonfly mission to Titan was recently selected to be the next New Frontiers mission, launching in 2026 and landing on Titan in 2034. Among other instruments, it would include a geophysical and meteorological package (DraGMet), that would likely give us our first seismic measurements of an icy ocean world [1,2]. A seismic instrument would allow constraint of the level of seismic activity of Titan and, depending on Titan's seismic environment, potentially constrain interior structure, particularly the thickness of the ice crust overlying an internal water ocean [e.g. 3,4]. Dragonfly is a rotorcraft, which is planned to have a seismometer lowered to the ground with a windshield by a belly-mounted winch. In addition, geophones would be mounted on its landing skids. While there are existing literature discussions of the kinds of seismic observations we may expect to see in tidally activated icy ocean worlds [3,5,6], quantitative estimates of the amplitudes and uncertainties of likely seismic signal and noise sources on Titan for the Dragonfly mission are critical.

In this study, we attempt to summarize estimates of expected signal and noise amplitudes for: (1) ice-cracking events in the ice shell [e.g. 3,6], (2) microseismic noise from waves on Titan's surface seas [5], and (3) atmospheric noise. We compare this with expected instrument noise, as well as discuss other possible seismic sources.

Ice cracking: Following the approach of Panning et al. [3] and Hurford et al. [6], we assume tidally driven ice-cracking events can be assumed to follow a Gutenberg-Richter statistical distribution, for which we can define a power-law relationship [7] for the number of seismic events greater than or equal to a given seismic moment as a function of that seismic moment:

$$N(M_0) = AM_0^{-B},$$

Where M_0 is the seismic moment, and A and B are empirical parameters governing a particular event catalog. The cumulative moment release can then be defined as

$$\Sigma M_0 = \frac{AB}{1-B}(M_0^\star)^{1-B},$$

where ΣM_0 is the cumulative moment release, and $M_0^\star$ is the maximum event size. This allows us to define seismicity based on three parameters: the cumulative moment release, the maximum event size, and the slope of the power law (B). We assume the cumulative moment release on tidally activated bodies like Titan is related to the available tidal dissipation energy [6], and scale the cumulative moment from observed cumulative activity on Earth's moon. We assume a slope consistent with most Earth catalogs (B=2/3), and choose the maximum event size such that nearly all accumulated moment is released over 10 tidal cycles rather than being released in larger, rarer events. From this, we predict seismicity (Figure 1).

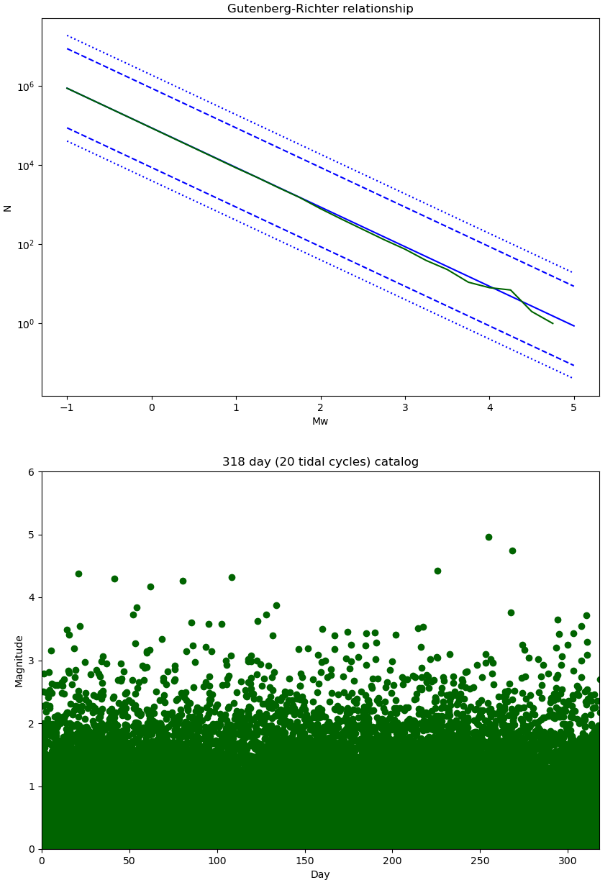

Figure 1: (Top) Predicted number of events as a function of moment magnitude (Mw) over 20 tidal cycles based on [6] is shown as solid blue line, while dashed and dotted lines show range for order-of-magnitude uncertainties in cumulative moment and maximum moment. The green line is for the catalog realization shown in the bottom panel.

From such a catalog, we can calculate simulated long seismic records on Titan using numerical wave propagation models [4], from which we can calculate likely largest observed signals (green lines in Figure 2) and background noise from regular small events (probability density function in background color of Figure 2). Some instrument responses are included as well, including the short period penetrator seismometer from the JAXA Lunar-A mission [7] that is a precursor of the proposed instrument for Dragonfly.

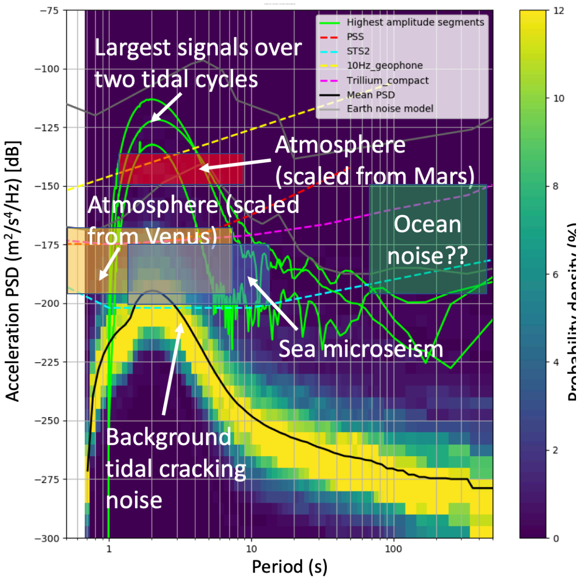

Figure 2: Summary of anticipated power spectral density of signal and noise sources considered in this study. Dashed lines are instrument self-noise for a variety of seismic instruments, including the precursor of the JAXA instrument proposed for Lunar-A mission (PSS [7]), as well as an extremely broadband Earth instrument (STS2 [8]), moderately sensitive broadband instrument (Trillium Compact [8]) and a typical less-sensitive geophone [9].

Microseismic noise: On Earth, seismic background noise is dominated by noise generated from waves in the ocean [e.g. 10]. Titan has surface hydrocarbon seas that can generate an analogous signal [5]. While such signals may be significant close to Titan's polar seas, such signals are likely below the sensitivity of the proposed JAXA instrument at a more equatorial site, as planned for Dragonfly, although possibly within reach of a more sensitive instrument (Figure 2).

Atmospheric noise: 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 2) [12]. We can scale these estimates by the acoustic impedance of the atmosphere, which controls transmission of seismic energy from the atmosphere 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 (red and orange boxes on Figure 2).

Other sources: It may be possible to sense seismic signals from the subsurface ocean (green box in Figure 2 shows an estimate for such a signal on Europa [3]). The extensive dunes on Titan may produce signals analogous to "booming dunes" observed on Earth [e.g. 13], which produce vibrations in the audible frequencies (80-120 Hz) due to avalanche processes. Nitrogen bubbles in Titan's seas can exsolve explosively [e.g. 14], which is suggested as an explanation for observations of Cassini "magic island" radar reflections, and such a process could produce significant seismic signals, although once again unlikely to be observed from a more equatorial landing site.

Conclusions: Estimated seismicity in Titan's ice shell produces simulated seismic signals from the largest events over a few tidal cycles that are well above the instrument sensitivity of the proposed JAXA instrument on Dragonfly, and possibly above that of a typical geophone, while the background noise produced by small events is likely quite low. Atmospheric noise is expected to be the largest noise source, possibly also above the JAXA instrument noise, while other sources are likely to be smaller.

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References: [1] Lorenz et al. (2017), Johns Hopkins APL Technical Digest. [2] Turtle et al. (2020), 51st LPSC, Abstract 2288. [3] Panning et al. (2018), *J. Geophys. Res.* [4] Stähler et al. (2018), *J. Geophys. Res.* [5] Stähler et al. (2019), *Earth Planet. Sci. Lett.* [6] Hurford et al. (2020), *Icarus*. [7] Yamada et al. (2015), *Adv. Space Res*. [8] Ringler and Hutt (2010) *Seis. Res. Lett.* [9] Rodgers (1994) *Bull. Seism. Soc. Am.* [10] Longuet-Higgins (1950), *Phil. Trans. R. Soc. Lond. A*. [11] Panning et al. (2020), submitted to *J. Geophys. Res.* [12] Lorenz and Panning (2018), *Icarus*. [13] Hunt and Vriend (2010), *Annu. Rev. Earth Planet. Sci.* [14] Farnsworth et al. (2019), *Geophys. Res. Lett.*