SUPPLEMENTARY MATERIALS FOR

Deep Ocean Passive Acoustic Technologies for Exploration of Ocean and Surface Sea Worlds in the Outer Solar System

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This supplement includes Figures S1–S6 and information on:

> Detailed Payload and Power Considerations for a Europa Mission

> PAM as a Tool for Public Engagement

> Shock and Vibration Requirements for Space Flight (Supplement)

> Acoustic Signal Detection and Evaluation

> Data Transmission Considerations

> Planetary Protection

FIGURE S1. Example of an autonomous surface vehicle with a sail deployed off the coast of California, USA (Meinig et al., 2019). Saildrones and other autonomous ocean vehicles deployed in Earth's ocean typically carry payloads with a variety of environmental sensors. The example saildrone pictured here has in the past been equipped with a hull-mounted hydrophone, while other passive acoustic monitoring projects are planned that will deploy a hydrophone via a winch mechanism and soft tether.

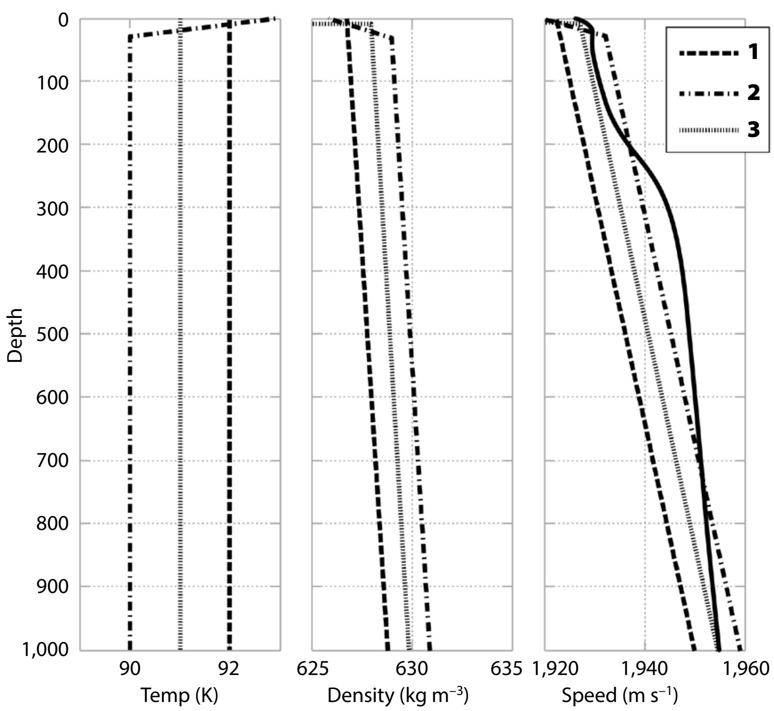

FIGURE S2. Depth profiles of temperature, density, and sound speed for the (1) isothermal, (2) thermally stratified), and (3) freshwater pool cases. A typical Arctic sea sound speed profile shifted by 490 m s^{-1} is included as the solid curve for comparison. *After Arvelo and Lorenz (2013)*

Detailed Payload and Power Considerations for a Europa Mission

Proposed parameters for a Europa mission include the ability to host a payload of 35 kg, ~24,900 cm^3, 2,500 W-hrs, and 2,700 Mbits for a roughly 30-day mission (COLDTech, 2016). If we assume that there will be five instruments on such a mission, then the design could be altered to use roughly one-fifth of these resources. This translates to per-instrument specifications of 7 kg and 5,000 cm^3, and the use of 500 W-hrs and 550 Mbits over a 30-day mission. These size restrictions are well within current, commercially available hydrophone design specifications. Moreover, the energy and data volume budgets translate to an average power of 0.7 W and a data rate of 222 bits sec^{-1}. The current power consumption of our NOAA/Pacific Marine Environmental Laboratory deep-ocean passive acoustic monitoring (e.g., PAM ocean glider) data logging and microprocessor is about 0.5 W, where available data rates average ~50 bits sec^{-1}. Thus, currently available passive acoustic monitoring systems are already within the sharp resource constraints for spaceflight, and it should be possible to successfully develop an ocean worlds hydrophone system that will be a good match for a future outer solar system exploration vehicle.

PAM as a Tool for Public Engagement

A significant motivation for planetary exploration is enabling virtual telepresence for exploration of the exotic worlds in our solar system. An example is the near ubiquity of cameras on most planetary exploration missions. In the low- or no-light conditions of these outer worlds' oceans, just as for Earth's ocean, vision is secondary to hearing. A hydrophone may be the critical virtual telepresence instrument needed for exploration of these ocean worlds. Indeed, as is the case in oceanographic research on Earth, underwater sound is under-appreciated (1) as a means for quantifying marine animal populations and their interactions within their habitats, and (2) as an outreach tool for enabling the public to simulate the sensation of being immersed in a deep-ocean environment. As high-resolution video footage of deep-ocean hydrothermal vents from Earth's ocean floor can visually captivate the public, high-fidelity records of the deep-ocean soundscape can also provide a truly engaging audio experience. Then, given that the audio record is from an outer solar system world, public interest could be profound.

Shock and Vibration Requirements for Space Flight (Supplement)

For Europa/Enceladus, a combination of a shunt resistor and protection diodes may need to be considered to avoid damaging preamplifiers during vibration, as that will induce a high voltage response on the piezoelectric sensor. Similarly for Titan, there is a need to guard against vibration-induced voltage spikes; the use of a shunt resistor on the piezoelectric sensor may be needed. Also, there is a need to protect against thermal gradient-induced voltage spikes as the hydrophone cools from a likely cruise temperature of –40°C to 0°C, then down quickly to –180°C upon landing on Titan.

Acoustic Signal Detection and Evaluation

Within the scope of the overview study presented here, development of a self-optimizing three-stage method as used for marine mammal applications on Earth (e.g., Klinck and Mellinger, 2011; Baumgartner et al., 2019) would also be very useful for detecting signals of interest on Europa, Enceladus, or Titan. As a first step, acoustic data will be recorded on board the mobile ocean or surface sea platform for at least 24 hours. This will enable acquisition of noise statistics, which will provide information on frequency-specific noise level fluctuations over the entire bandwidth of the recordings (Merchant et al., 2013). Figure S3 shows an example for a spectral probability density (SPD) plot summarizing noise statistics for one year of data collected in the North Atlantic-European Arctic using an autonomous moored hydrophone (Klinck et al., 2012). The noise statistics are important for two tasks: (1) to assess (and automatically adjust) proper gain settings of the acoustic system, and (2) to automatically identify frequency bands of interests for further processing. In the example shown in Figure S3, a peak in the 20–25 Hz range indicates the presence of a signal (in this case fin whale calls). Various spectral and temporal resolutions would need to be tested to determine which parameters are best suited for achieving these two tasks efficiently with the available computational resources. An additional advantage of the SPD statistics is the small data size (kilobyte range), which enables transmission back to Earth for further evaluation.

In the second step of signal evaluation, the acoustic recording microprocessor would use the noise statistics as a basis for automatically adjusting the system gain and applying a band-limited energy detector (Klinck and Mellinger, 2011; Hood et al., 2016) to frequency bands of interest (e.g., 20–25 Hz in the example in Figure S3). The detector would flag discrete signals with amplitudes exceeding an adjustable detection threshold based on an average of ambient noise levels (measured over several minutes of duration) derived from the noise statistics in the respective frequency bands.

Following signal identification and classification algorithms, a reasonable next step would be to rank detected events using an information entropy metric approach (Erbe and King, 2008). Figure S4 shows entropy curves associated with certain signal types, in this case the vocalizations of a beluga whale, where an information theory context of entropy is used to measure the amount of information contained in a signal. The entropy of acoustic power spectrum densities measures the peaked-ness, or concentration, of the energy distribution across frequency and is therefore a good metric for ranking detections because it enables removal of general broadband noise bursts.

Once a section of data is classified, or ranked, as having a signal, the data segment will then undergo lossless data compression (e.g., Free Lossless Audio Codec, FLAC) or, if it's necessary to further reduce data size, undergo lossy compression

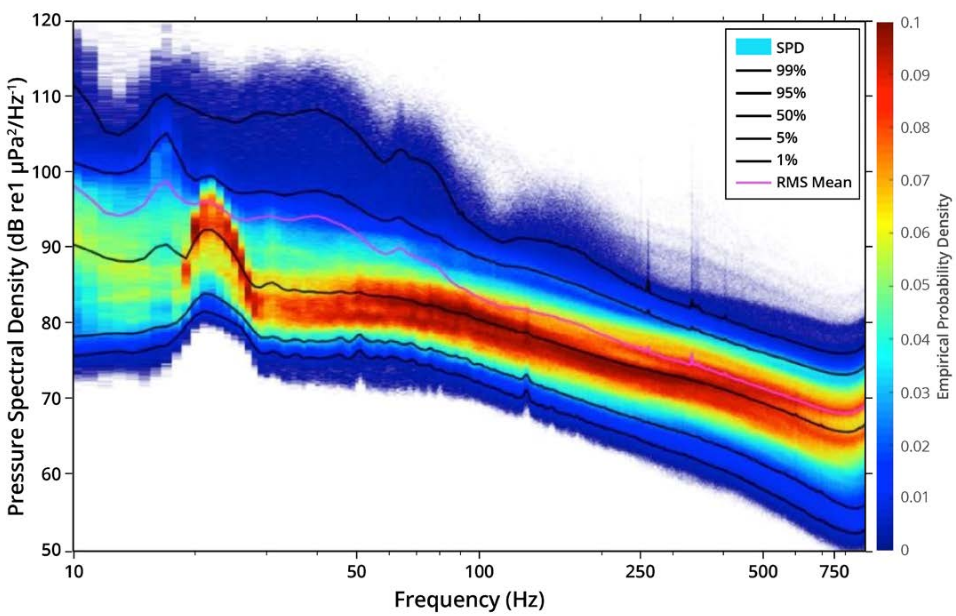

FIGURE S3. Spectral probability density (SPD) plot for one year of data collected in the European Arctic. The sound levels representing the 1st, 5th, 50th, 95th, and 99th percentiles of the soundscape are shown. The spectral peaks at 20–30 Hz (up to 50% of background sound levels) are the vocalizations of fin whales within the recording range of the hydrophone.

(using OGG format algorithms) before being sent back to Earth for human inspection. It should be feasible to train an acoustic detection system to choose an appropriate data bandwidth, duration, and compression to preserve the information content of the detected signal. The signal processing system will need to be designed in a way that already collected data can be analyzed retrospectively throughout the mission. The ability to remotely override detection and ranking criteria (if necessary) should provide a robust approach to recording, detecting, and transmitting sounds of interest in a completely unknown soundscape.

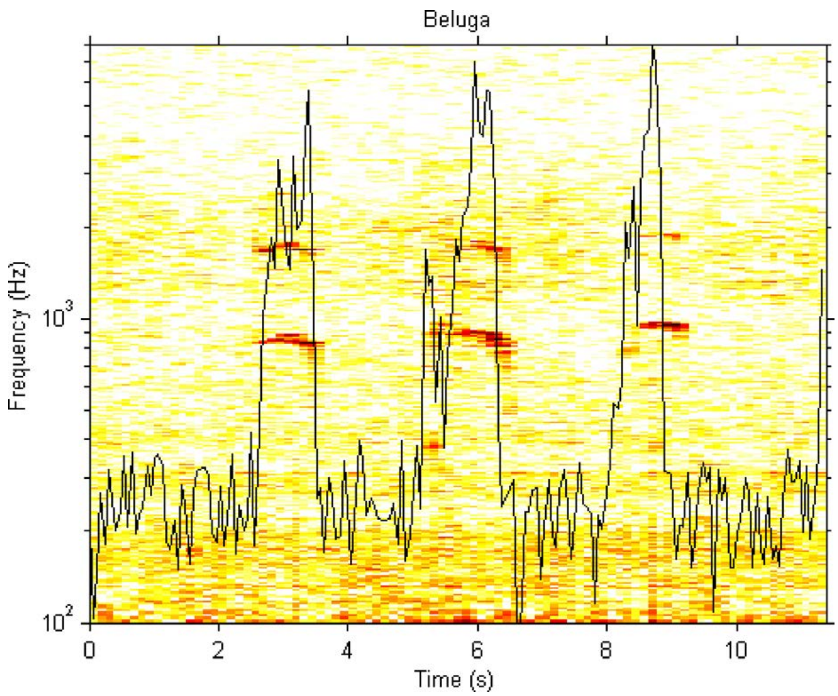

FIGURE S4. Spectrogram of a beluga whale call with the entropy curve overlain. Beluga whales are odontocetes (toothed) whales that typically vocalize in higher frequency bands (>1 kHz) than baleen whales, such as blue whales (e.g., Figure 3e). The entropy is high at times of the call and low in between (when no signal is present; Erbe and King, 2008).

Data Transmission Considerations

As for the actual transmission of data back to Earth, we need to weigh the most efficient quantity of data to transmit (after compression) versus what format provides the most desirable information. Three data styles seem to be of highest interest: (1) a file of metrics derived from a detected signal, (2) a jpg (or similar format) image of a small window of raw data converted to a spectrogram (frequency-time) calculated by the microprocessor onboard the probe, and (3) a small packet of actual binary, raw data. The original audio data may appear to offer the greatest benefit, allowing for more detailed analysis back on Earth. However, each data style would be transmitted at some point during the mission. The binary data packets can be broken down again into three subtypes: signal events that fit a described pattern, signals we cannot classify but are of interest due to crude measures like amplitude or duration, and time slices that don't have signal identified by the probe but that may yield either baseline or unexpected data when processed Earth side.

For example, a 100 Hz cryogenic tremor signal, at 30 seconds long (Figure 3c), would be a 15 KB sized binary data file. The jpg image of the same signal would be ~100 kB, whereas a small file of a few cryogenic signal metrics (e.g., signal duration, frequency, maximum amplitude) could be a few tens of bytes. Using jpg images for signal detection would be suitable for current machine learning (ML) algorithms and hardware that could be installed on the probe if the power level were sufficient. The higher computational and power resources on the orbiter can apply ML techniques to process audio in near-real time, creating templates that are downloaded to low power ML hardware on the rover probe. This method allows the rover to produce metrics for audio events that have only just been discovered, while only transmitting the associated event's raw audio a few select times. The probe is colloquially saying: "There is that sound again—we hear it several hundred times every morning." On the other hand, signals from seafloor bubble streams can be much higher frequency (1–45 kHz; Figure S5), and therefore have much larger file size requirements. In our view, the best approach for capturing both the low (<100 Hz) and high (<45 kHz) frequency signals would be to run multiple detection algorithms on more narrow frequency bands (0.1–1 kHz, 1–10 kHz, 10–50 kHz) in order to find all possible signals of interest. However, signals in the 10–50 kHz band will, of course, have much higher data file sizes (1.4 MB) and may require jpg or metric files (even after compression).

The Mars Opportunity rover had direct-to-Earth maximum data transmission rates of just 32 kbits sec^{-1}, whereas the data rate from the Mars Reconnaissance Orbiter rover was 2 Mbits sec^{-1}. By transmitting to the orbiter, the rover could use less power, while the orbiting spacecraft, with a much longer field of view of Earth, could transmit significantly more data. An orbiter is able to hold more electrical and computational power that does not have to endure the stress of planet fall. Presumably, a similar architecture would be used for a Titan mission, with a tandem saildrone and orbiter to improve data transmission rates back to Earth.

As for data transmission from a Europa mission, previous studies have argued that use of an acoustic modem on an autonomous underwater vehicle (AUV) may not be a realistic method. There are too many unknowns regarding long-term noise levels in the under-ice environment to allow assessment of the reliability and/or performance of a modem (McCarthy et al., 2019). As of now, an AUV tethered by a fiber-optic cable to the planetary surface for data and power transmission seems the most feasible method for data transmission back from Europa. However, this would require a long cable (tens of kilometers), which presents numerous challenges as well. An alternative would be to build a fixed docking station on the underside of the ice (presumably where the AUV first melts through) that would have a cable up to the surface. The sub-ice AUV could then explore autonomously and return to the docking station to get new instructions and transfer data to Earth via the trans-ice cable and planetary surface transmitter (McCarthy et al., 2019).

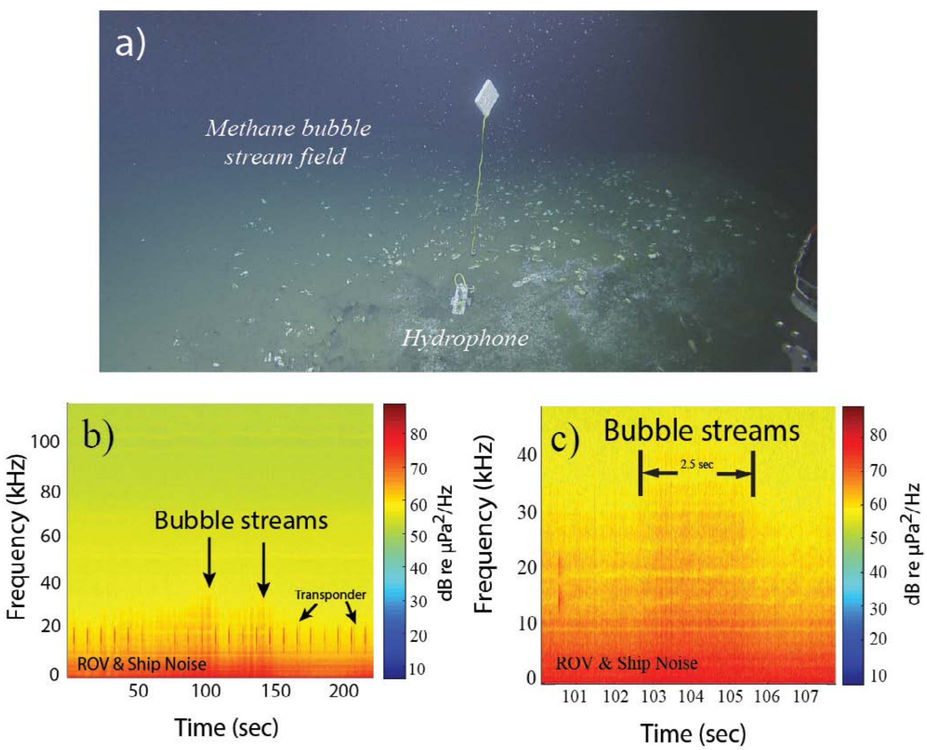

FIGURE S5. (a) Remotely operated vehicle (ROV) image of hydrophone and float in a field of bubble streams at 1,280 m water depth off the coast of Oregon, USA. (b) and (c) Spectrograms showing broadband signals of methane bubble streams recorded by a hydrophone (Dziak et al., 2018). Sounds are created by oscillation of bubbles as they break free from seafloor conduit. (b) Spectrogram showing 225 seconds of hydrophone data over the 116 kHz band. The acoustic signatures of bubble streams are labeled. Transponder pings used for ROV navigation and ship propeller noise dominate the record at 1–5 kHz. Bubble stream sounds can be seen as broadband signals between transponder pings. (c) Smaller scale sound spectrum covering a six-second time period and 40 kHz. The spectral trace of bubbles appears as the 2.5-second-long band of energy in the 10–40 kHz range.

Design for Planetary Conditions

For a hydrophone system to be included on a Europa/Enceladus lander or Titan saildrone, the system would need to be tested under space flight shock and vibration conditions. For deep-ocean deployment on Earth, the hydrophone element and data logging electronics would typically be contained in a large pressure case made of titanium or composite to withstand the 80–100 bars of hydrostatic pressure exerted at sound channel depths of 800–1,000 m. Obviously, the weight of these Earth protections are prohibitive for space flight, and it would be necessary to develop a much more modest housing. However, it is essentially impossible to test the system under a final flight configuration until the whole spacecraft is more fully designed. Nevertheless, because of the electromechanical nature of the hydrophones, it is important to shock and vibration test the hydrophone sensors early in their development to reduce any potential risk from this system to the spacecraft in the early stages of a potential flight program. The Titan hydrophone can be tested in liquid nitrogen (LN_2) conditions, which is a laboratory proxy for Titan's sea conditions. Both hydrophone designs can readily be tested in Earth deep-sea conditions in a sea trial, with the Europa/Enceladus design lowered to ~1,300 m below the surface of the ocean. A depth of 1,300 m in Earth's ocean is roughly equivalent to 10 km depth on Europa, or ~120 km depth on Enceladus. These are the expected depths beneath the ice shells and within fluid oceans on either of these worlds. The Europa/Enceladus hydrophone will be exposed to ~130 bars of pressure, which is well within the hydrostatic pressure design tolerances that hydrophone elements and pressure cases have previously been built to withstand (e.g., Dziak et al., 2017).

The signal processing electronics would need to undergo the same at-sea trials, using the system architecture with a path-to-flight. As an example, the electronics could be installed within a standard, watertight, NOAA/PMEL pressure housing (15 cm wide by 150 cm long, shown in Figure S6), and run by a small alkaline battery pack for deployment up to a week. The signal identification/classification algorithms could thus be tested with real terrestrial marine signals (geophysical and biological) during the sea trials. This ocean deployment should test the autonomous signal identification/classification algorithms well, and thus position this instrument system for any potential mission opportunity.

Another important consideration is that of planetary protection. Per the UN Outer Space Treaty, a legal obligation exists to avoid contaminating potential extraterrestrial habitats with terrestrial biota. This obligation means that equipment to be delivered to environments in which such biota might flourish, such as certain areas of Mars, and the water oceans of Europa and Enceladus, must be sterilized. It places further demands on the tolerance of the equipment, depending on the process adopted: a standard procedure is dry heat microbial reduction, which involves baking to >110°C for 60 hours (for example) or exposure to hydrogen peroxide vapor.

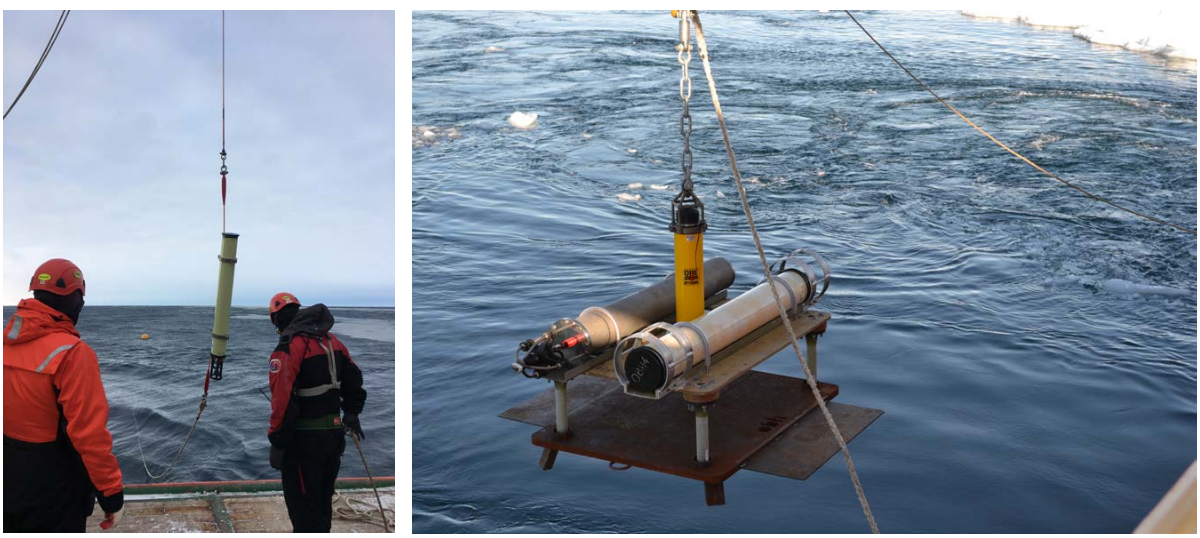

FIGURE S6. Photos show examples of NOAA-Pacific Marine Environmental Laboratory hydrophone mooring systems being deployed from the South Korean icebreaker R/V *Araon* in the Ross Sea, Antarctica. (left) A deep-ocean pressure case made of composite material (green cylinder) with the hydrophone transducer element (black ball at bottom) extending below it. The pre-amplifier, data storage drives, and battery packs are housed within the pressure case. (right) Two hydrophone pressure cases, mounted on a seafloor platform, being lowered near ice-edge waters in the Ross Sea. An acoustic release (vertical yellow cylinder) drops a metal anchor plate at the seafloor; floats bring the package to the surface for recovery.