LABORATORY ACOUSTIC PULSE TUBE STUDIES FOR SEAFLOOR AND SEA ICE GREENHOUSE GAS QUANTIFICATION

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1 INTRODUCTION

The acoustic pulse tube, or impedance tube, is a useful method for quantifying compressional wave properties of various materials. We use an instrument designed for studying wave propagation in porous media, especially seafloor sediments and latterly sea ice, and for broader applications to ocean acoustics research. Notable design improvements over extant systems include full ocean depth pressure rating (60 MPa), the ability to extract broadband signatures over 1 – 20 kHz using a novel sonar projector with a transmission line calibration/modelling approach, and jacket designs allowing porous medium effective pressure control. The temperature can be controlled between -5 °C to 55 °C. We obtain complementary shear wave velocity and attenuation measurements at 200 – 500 Hz (depending on material properties) using a separate geotechnical resonant column instrument rated to 20 MPa effective pressure with temperature control between -20 °C to 20 °C.

Novel scientific results on synthetic sea ice cores with different air contents, and sand samples as a function of water saturation and pressure, provide insights into wave propagation mechanisms for these complex porous media. The data are suitable for modelling using effective medium theoretical approaches (e.g. modified Biot theory[1] to estimate the volume and distribution of free gas, needed for constraining impacts of greenhouse gases in the seafloor and in sea ice, of interest to climate research in rapidly changing polar regions. We present below an overview of novel instrument developments and some example scientific results.

2 LABORATORY MEASUREMENTS

2.1 Acoustic pulse tube experiments on ice and sand samples

An acoustic source (located at the base of a 4.5 m long, 70 mm internal diameter, stainless steel, thick-walled tube filled with water; see Figure 1b) projects a Stoneley wave that approximates a plane wave propagating up the tube through the test sample suspended halfway[2]. Hydrophones in side-wall ports below and above the test sample record the acoustic signals from which sound wave velocity and attenuation (Q^{-1}) frequency spectra are calculated with respective accuracies of ± 2.4% and ± 5.8% for jacketed sediments, and ± 10% and ± 15% for synthetic ice samples (using a different arrangement shown in Figure 1a).

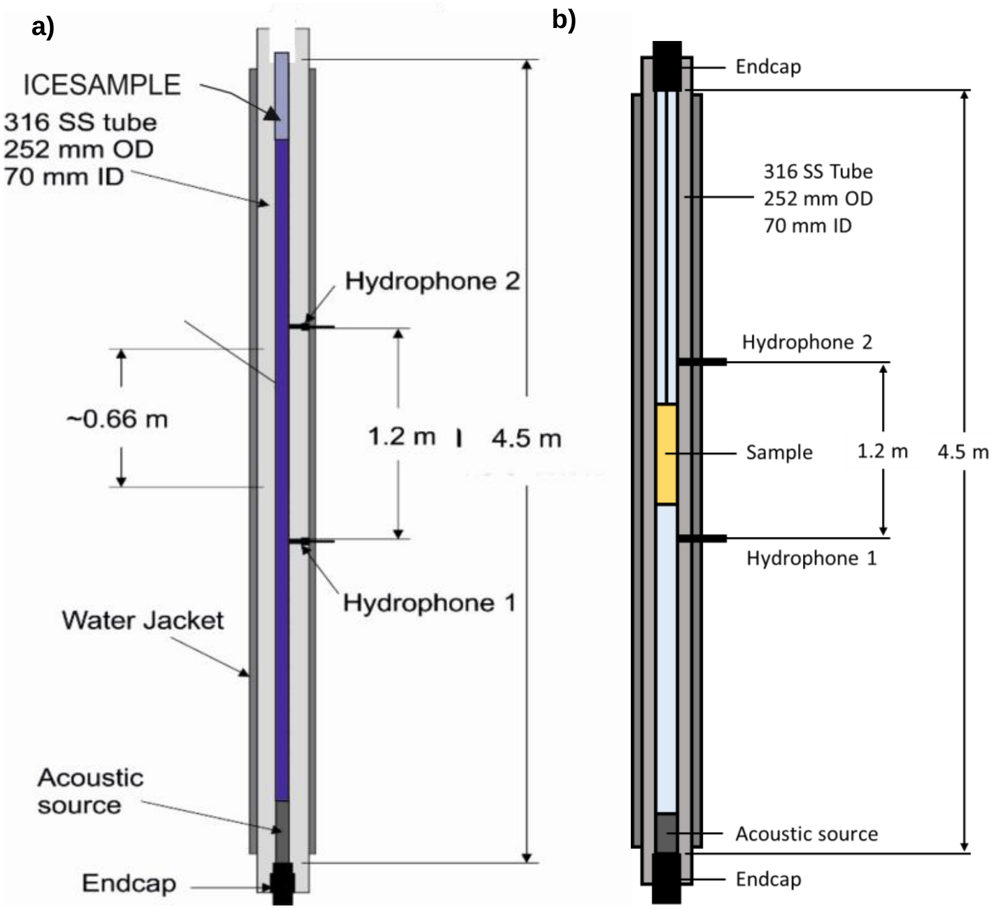

Figure 1. Cross-section through the acoustic pulse tube showing different arrangements for measurements on a) ice cores, and b) sediment samples.

The main innovation from the method presented in McCann et al.[2] is the ability to extract spectral signatures over the 1 – 20 kHz bandwidth, as opposed to single average values of velocity and attenuation over the frequency bandwidth. An acoustic chirp pulse is projected into the pulse tube and the recorded signals are deconvolved to obtain the time series of transmitted and reflected broadband pulses at the hydrophones. Example chirp and deconvolved time series are given for a Nylon calibration sample in Figure 2.

For samples suspended inside the tube (Figure 1b), we use the scattering matrix method to remove the effects of extraneous reflections from the pulse tube end caps and multiple reflections from the sample ends. See Equation 1 and Figure 3. We assume that the tube system is a 1-D transmission line with one input and one output without any harmonic distortion. The wave is assumed to propagate only in one dimension, i.e., a plane wave without any propagation at the sidewalls, multiple paths, or shear-wave coupling.

$$\begin{pmatrix} B \\ C \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} A \\ D \end{pmatrix}, \qquad (1)$$

where A represents the incoming wave from the sound source and reflections from the bottom endcaps of the pulse tube, B is the reflection from the sample, C is the outgoing wave from the sample, and D is the second incoming wave from the reflection from the top pulse tube endcap. To simplify

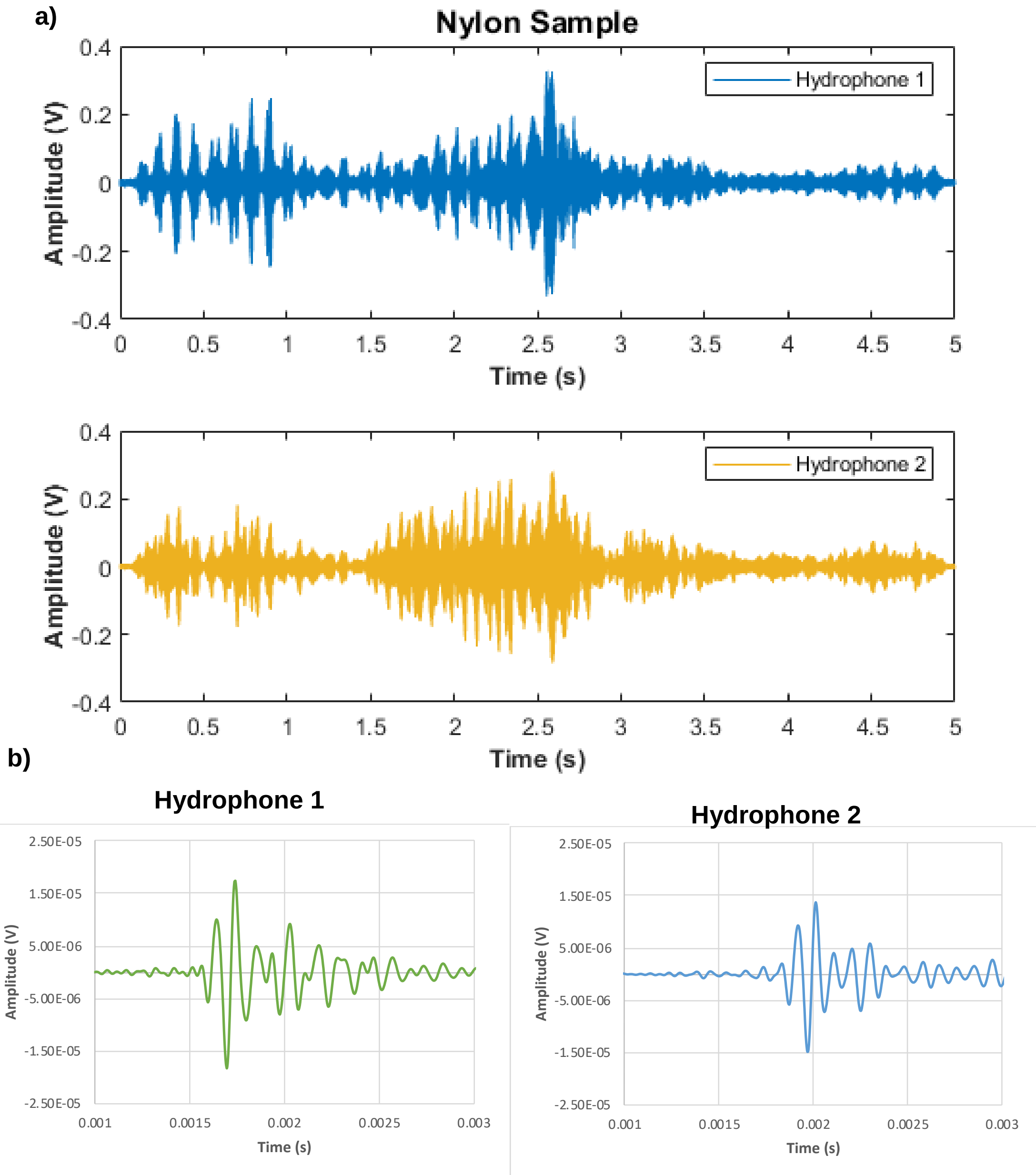

Figure 2. Example acoustic pulse tube time series for a Nylon calibration sample recorded at Hydrophones 1 and 2 in Figure 1. a) Raw chirp data, b) Time gated first arrivals of deconvolved signals (note relative time scale). After Sutiyoso et al.[3.]

the calculation, we assume the sample is cylindrically symmetrical. The attenuation Q^{-1} (inverse of the quality factor Q) is calculated from the complex velocity output from the scattering matrix method according to[4]

$$Q^{-1} = \frac{1-e^{-2\pi\frac{v_1}{v_2}}}{2\pi}, \qquad (2)$$

where v_1 and v_2 are the real and imaginary parts of the complex velocity, respectively. The time series of the water-filled pulse tube both with and without the sample are required in the above analysis. A frequency domain analysis is used to represent the geometry of ice samples floating on top of the water column without a metal end cap (Figure 1a).

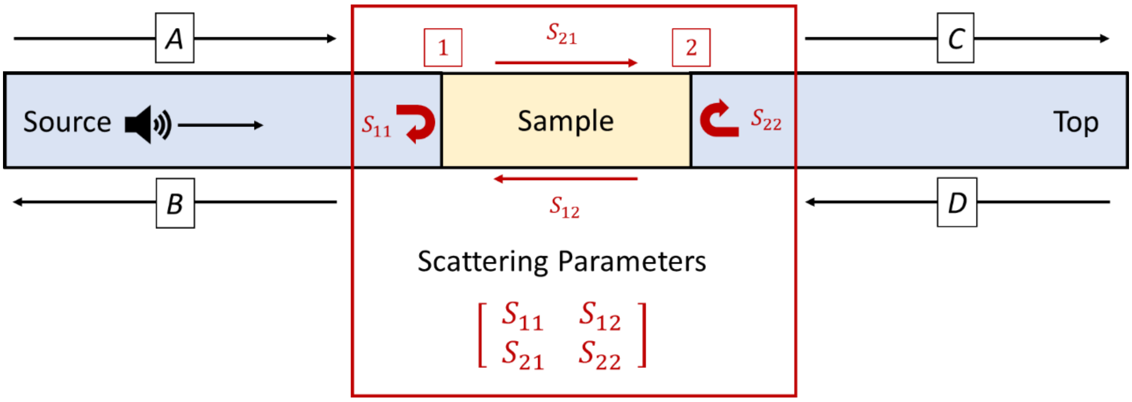

Figure 3. Transmission line model for extracting acoustic velocity and attenuation spectra from pulse tube time series. After Sutiyoso et al.[3].

2.2 Sediment and synthetic sea ice sample preparation

Sample preparation is an important step in the experimental work requiring a number of considerations. For loose seafloor sediments such as gravel, sand and mud, the method lends itself to either sub-sampling of actual seafloor sediment cores[2] or use of synthetic granular materials (e.g. quartz sand packs[3]). In both cases, the sediment must be enclosed inside a jacket to maintain integrity inside the pulse tube. The jacket can be made from a range of materials, such as plastic tubes with sealing endcaps that can slide up and down inside the jacket to accommodate the strain resulting from applied external and internal pore fluid pressures. For geological materials, it is important to control both confining and pore fluid pressures to replicate the *in situ* effective pressure. This requires a small diameter (mm-scale), flexible, stainless steel, pore fluid pipe attached to the jacketed sample that passes through the top end cap for pressure control separate from the confining water pressure in the pulse tube (that is controlled using a separate pressure pump system). Ideally, flexible rubber sleeves allow the best effective pressure control, although they tend to give larger attenuation calibration corrections than more rigid plastic jackets. McCann et al.[2] showed that the effect of sample jackets on the acoustic measurements can be calibrated out with acceptable errors.

For sea ice samples, unjacketed, synthetic samples were prepared by replicating natural ice formation processes as far as possible. This was achieved using a steel tube inside a freezer at -24 °C in which water was circulated from below while exposed to freezing air temperatures from above. See Figure 4. The circulation water was kept at a slightly higher temperature than the freezing point to prevent clogging of the flow pipes. The circulation fluid pipes were also insulated to prevent them from freezing. The setup was left in this condition to allow ice formation, taking almost one month to form one sample. Once the ice had formed, we removed the steel tube from the freezer, and then removed the insulation slowly to ensure no sudden temperature change occurred, which could have fractured the sample (thermal shock). We kept the steel tube at room temperature for 2 hours so the outer edges of the ice sample could melt just enough to facilitate removal from the steel tube. The ice sample was allowed slowly to come out of the steel tube on its own to minimise any mechanical damage to the ice. The ice sample was then kept in the freezer until it was time for the acoustic measurements. Both ends of the sample were made flat at right angles to the side walls before acoustic measurements in the pulse tube using a saw and warm plate (at 30 °C).

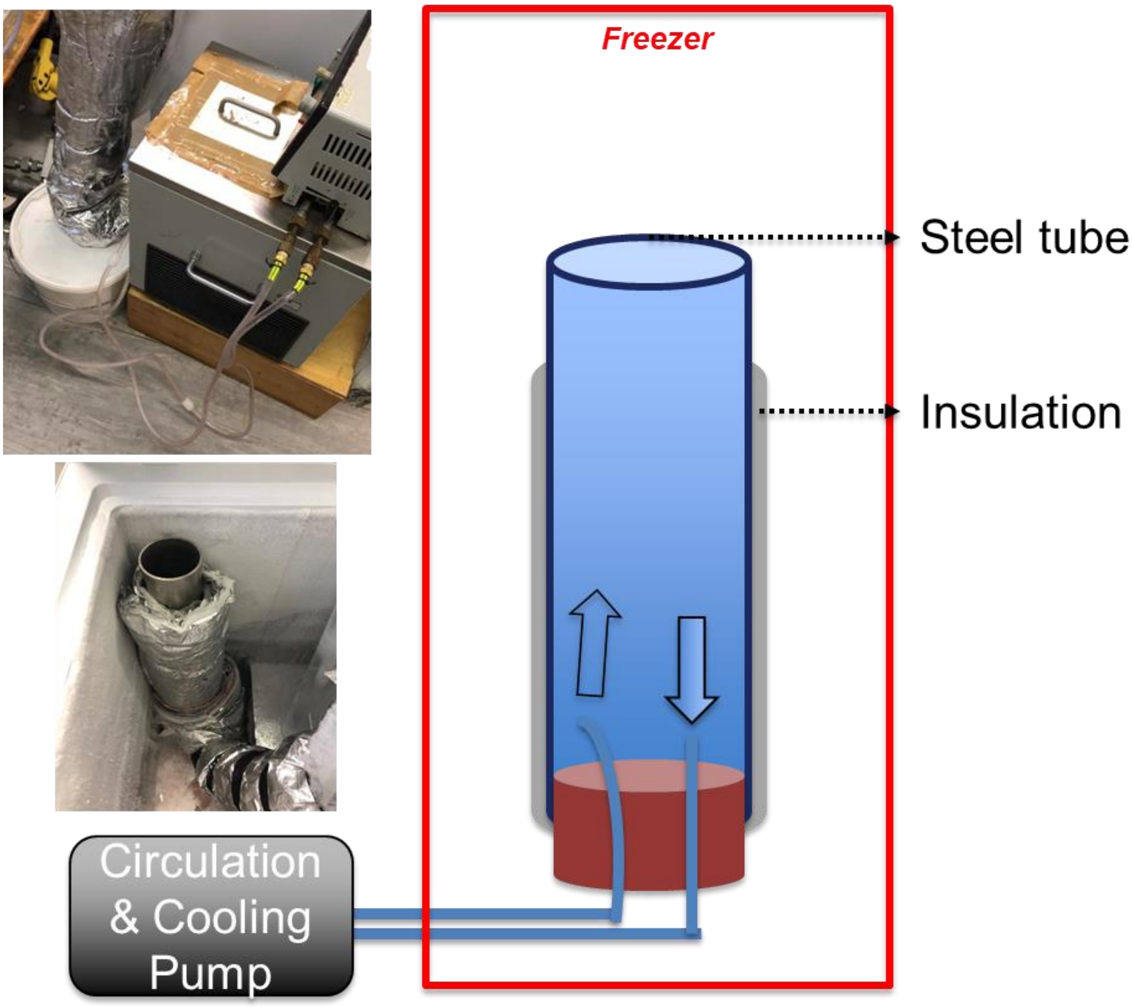

Figure 4. Method for creating synthetic sea ice samples with a steel tube inside a freezer using recirculation of water from below and freezing from above. The steel tube's internal diameter is 69 mm.

The method described above allows for changes in circulation water speed and temperature control. In principle, different volumes of fluid inclusions can be achieved by controlling the circulation speed, freezer and circulating fluid temperatures. We did several tests to find the optimum conditions for forming solid ice. When the circulation speed is too high, we found that the water does not freeze even after two months. When the circulation speed is too low, water freezes with more trapped air. The ability to control the amount of trapped air is useful for sea ice studies, as the amount of trapped air controls elastic wave and mechanical properties of interest to various applications. Examples of various pulse tube samples are given in Figure 5.

a)
b)
c)

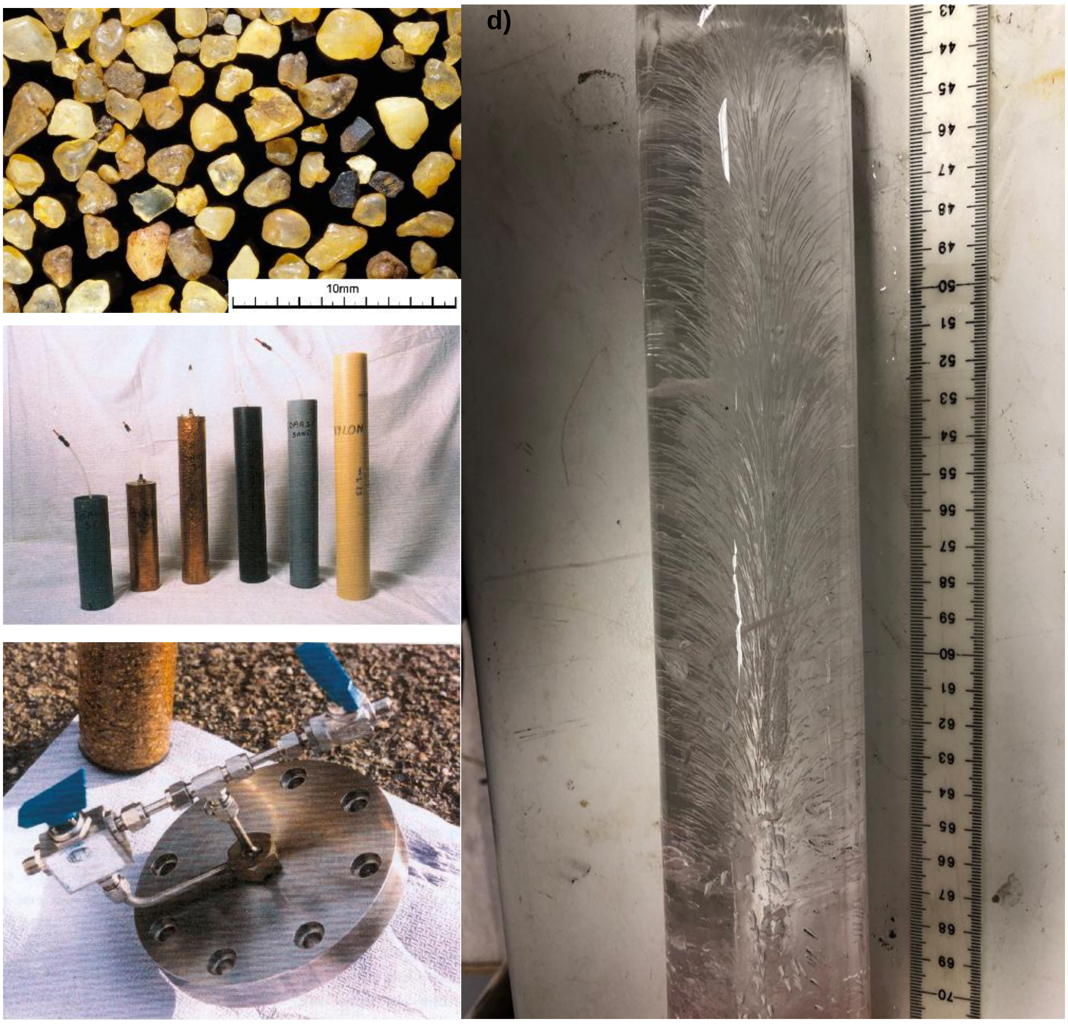

Figure 5. Examples of: a) sand sediment, b) various jacketed sediment samples, c) top cap with pore fluid control port (from McCann et al.[2]), d) synthetic sea ice sample with trapped air with cm scale.

2.3 Laboratory resonant column

We use a geotechnical resonant column to obtain complementary shear wave velocity and attenuation measurements on sub-samples from the pulse tube samples. The Gas Hydrate Resonant Column (GHRC) was originally developed for measuring the seismic properties of hydrate-bearing sediments for marine geophysical studies[5]. However, it also lends itself to ice sample measurements because of its rigidity and cold temperature control ability compared to standard geotechnical resonant column apparatus on which its design is based. It enables accurate measurements of P- and S-wave velocity and attenuation of cylindrical samples 7 cm in diameter, 14 cm long under elevated pressure (up to 20 MPa) and temperatures between -18 °C to 22 °C. It measures the forced vibration natural resonance frequency of samples that generally falls below 500 Hz and depends on the resonant mode and sample elastic properties; the free vibration resonance amplitude decay curve is also measured. From these measurements and sample density, the velocity and attenuation of different vibration modes (torsional, extensional, longitudinal flexure) and their associated elastic moduli (shear modulus, compressional modulus, Young's modulus, Poisson's ratio) can be derived. The resonant column gives S-wave velocity and attenuation accuracies of ± 1% and ± 20%.

Of particular interest are the S-wave velocity and derived dynamic shear wave modulus, needed for inferring material strength properties. Recent theoretical leaky Lamb wave studies[6] indicate that S-wave velocity could be estimated from under ice sonar measurements using acoustic reflection modelling techniques. Knowledge of typical S-wave velocities of sea ice would help interpretation of leaky Lamb waves and other acoustic reflection techniques for deriving sea-ice thickness from upwards-looking sonars.

3 EXAMPLE RESULTS

3.1 Synthetic sea ice

Example pulse tube (4 - 10 kHz) spectra are given in Figure 6, and a comparison of pulse tube and resonant column results for 4 synthetic ice samples are given in Table 1.

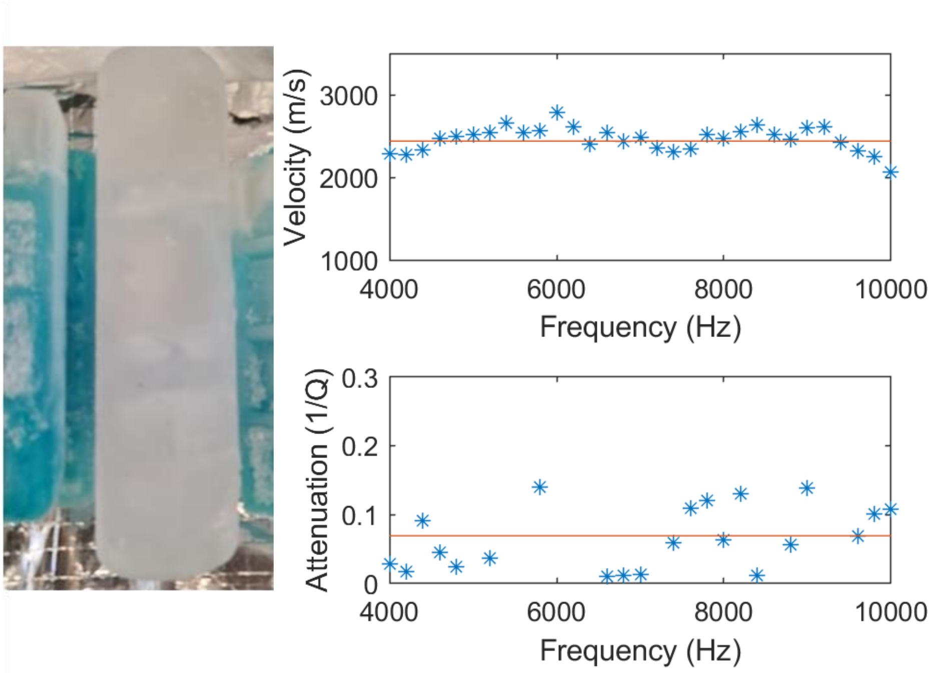

Figure 6. Example acoustic pulse tube velocity and attenuation (Q^{-1}) spectra (4 – 10 kHz) for a synthetic ice core (Sample No. 17, diameter 6.8 cm, shown left) with sub-mm diameter trapped air bubbles. The blue asterisks are measurements, and the red lines are bandwidth average values.

Table 1. Comparison of seismic resonant column and acoustic pulse tube results for synthetic ice samples with trapped air (content by volume assumed equivalent to porosity).

Measured parameter	Resonant column (~ 300 Hz)		Acoustic pulse tube (4 – 10 kHz) [Stoneley waves]	
	Sample 14	Sample 13	Sample 16	Sample 17
Density	905 kg.m^{-3}	886 kg.m^{-3}	900 kg.m^{-3}	851.8 kg.m^{-3}
Porosity	1.45%	4.7%	1.5%	7.1%
P-wave velocity, V_p	3400 m/s	3100 m/s	3272 m/s [3090 ± 273 m/s]	2550 m/s [2465 ± 146 m/s]

Shear wave velocity, V_s	1250 m/s	1150 - 1050 m/s	-	-
Q_p^{-1}	0.070 - 0.098	0.055 - 0.065	[0.06 ± 0.04] 0.061	[0.03 ± 0.07] 0.031
Q_s^{-1}	0.13 - 0.25	0.23 - 0.31	-	-

3.2 Partially water saturated sand

Example acoustic pulse tube spectra (1 – 20 kHz) for a partially water saturated sand pack are given in Figure 7.

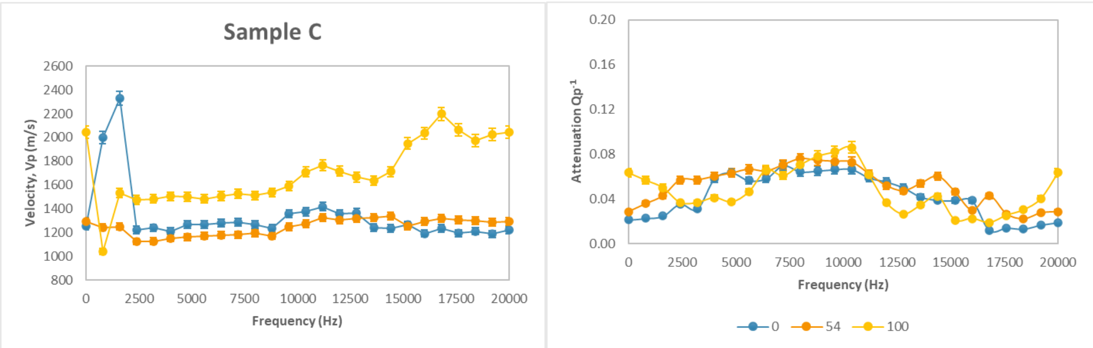

Figure 7. Acoustic pulse tube frequency spectra for a) velocity and b) attenuation (Q^{-1}) on a quartz sand pack at three different water/air saturations (legend values are for water saturation = 0%, 54%, 100%). Effective pressure is 10 MPa, temperature is 4 °C. After Sutiyoso et al.[4].

4 CONCLUSIONS

Novel acoustic pulse tube measurements supported by resonant column shear wave measurements provide well-constrained datasets suitable for modelling using effective medium theory such as Biot-related models. Well constrained models are needed for quantifying *in situ* greenhouse gases in polar sea ice and seafloor sediments using remote acoustic methods.

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