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Broadband Characterization of Plastic and High Intensity Therapeutic Ultrasound Phantoms using Time Delay Spectrometry—with Validation using Kramers-Kronig Relations

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Abstract

We extended Time Delay Spectrometry (TDS) for broadband characterization of plastics (low-density polyethylene, LDPE) and tissue-mimicking material (TMM). Our results suggest that TDS and the conventional broadband pulse method give comparable measurements for frequency-dependent attenuation coefficient and phase velocity near the center frequency, where signal-to-noise ratio is high. However, TDS measurements show enhanced bandwidth for attenuation coefficient of 30–40% (LDPE) and 89–100% (TMM) and for phase velocity of 43% (LDPE) and 36% (TMM) for a single transmitter / receiver pair. In addition, TDS provides measurements of dispersion that are consistent with predictions based on the Kramers-Kronig relations to within 5 m/s over the band from 2 – 12 MHz in low-density polyethylene (LDPE) and to within 1 m/s in TMM over the band from 0.5 – 29 MHz.

Keywords

High intensity focused ultrasound; tissue-mimicking materials; metrology; Kramers-Kronig relations

I. INTRODUCTION

Broadband measurement of attenuation and phase velocity is important in the characterization of tissues and materials. Time Delay Spectrometry (TDS) (Heyser, 1967) can be used to measure both the magnitude and phase of the frequency response of a system or sample and has been previously validated for hydrophone calibration (Wear *et al.*, 2011). TDS has two main advantages over conventional pulser receiver methods. First, TDS utilizes a swept frequency source rather than a single broadband pulse, resulting in broader bandwidth. Second, TDS uses a tracking filter to block undesired multipath signals such as reflections from walls of a water tank. The first advantage (broader bandwidth) may also be achieved using compensated frequency-modulated excitation (Costa-Felix and Machado, 2015). TDS bandwidth may be enhanced using pre-emphasis (Gammell *et al.*, 2010).

One timely application for TDS is characterization of tissue-mimicking materials (TMMs), which are used in phantoms designed for high intensity therapeutic ultrasound (HITU). A

well-characterized TMM is useful for determining acoustic output and temperature rise from HITU devices and also for validating computer simulation models (Maruvada *et al.*, 2015). A TMM developed in our laboratory has been characterized at frequencies up to 8 MHz (King *et al.*, 2011). Much of the early acoustic characterization of tissues and TMMs was done at frequencies up to 10 MHz (Duck, 1990; ICRU, 1998). Higher frequency characterization of TMMs for HITU is desirable since HITU devices produce higher order harmonics that contribute to both acoustic and thermal effects (Canney *et al.*, 2008; Sonesson, 2009; Kreider *et al.*, 2013).

Another important application is high-frequency ultrasound (frequencies greater than or equal to 20 MHz), which is becoming increasingly available for pre-clinical and clinical imaging (Foster *et al.* 2000; Kenwright *et al.* 2014; Rajagopal, S. *et al.*, 2014). High frequency applications have motivated broadband characterization of TMMs up to 60 MHz (Monteil *et al.*, 2017).

In this work, we compare two implementations of TDS and a conventional pulser receiver (PR) method to further the acoustic characterization of low density polyethylene (LDPE) as well as our HITU TMM. Since the acoustic properties of these two materials are quite different (see next section), they test the measurement methodology over a wide range of acoustic parameter values. Attenuation coefficient and dispersion (frequency dependence of phase velocity) are theoretically linked through the Kramers Kronig relations (O'Donnell *et al.*, 1981). The mathematical form for dispersion of a material with attenuation coefficient proportional to frequency to the n^{th} power is known (Waters *et al.*, 2005). Therefore, we compare experimental measurements of dispersion to predictions of dispersion based on measurements of attenuation coefficient and Kramers-Kronig relations. Finally, we compare TDS measurements with PR measurements to assess potential increase in bandwidth.

II. MATERIALS AND METHODS

A. LDPE and an FDA-developed HITU tissue-mimicking material

The first material used in this work was an LDPE plate (thickness = 6.1 mm). Measurements of attenuation coefficient for LDPE have been reported to be 150 Np/m (13 dB/cm) at 5 MHz (Zellouf *et al.*, 1996, and 21 dB/cm at 3 MHz (He, 2000). Measurements of phase velocity for LDPE have been reported to be 2340 m/s at 5 MHz (Zellouf *et al.*, 1996) and 2050 m/s at 5 MHz (He, 2000). Attenuation coefficient for polyethylene (density unspecified) has been reported to be 3 Np/cm (26 dB/cm) at 5 MHz (O'Donnell *et al.*, 1981). Acoustic properties of LDPE probably depend somewhat on the fabrication process, which may explain differences in reported values. In the present study, the same LDPE plate was used for all measurements to eliminate this potential source of variability. Plate thickness was measured using digital caliper. The uncertainty in thickness measurement was estimated to be 0.1 mm.

The second material used in this work was a TMM based on a formulation developed in our lab for use in HITU system characterization (King *et al.*, 2011). The TMM is a high-temperature hydrogel matrix (gellan gum) combined with different sizes of aluminum oxide particles and chemicals to control physical properties. The ultrasonic properties (attenuation

coefficient, speed of sound, acoustical impedance, and the thermal conductivity and diffusivity) were characterized as functions of temperature from 20 to 70°C. The backscatter coefficient and nonlinearity parameter B/A were measured at room temperature. The attenuation coefficient is approximately 0.5 dB/cmMHz, which is similar to many mammalian soft tissues at 37°C. Most of the other relevant physical parameters are also close to the reported values, although backscatter signals are low compared with typical human soft tissues. This TMM is appropriate for developing standardized dosimetry techniques, validating numerical models, and determining the safety and efficacy of HIFU devices.

B. Methods to measure attenuation and phase velocity

1. Time delay spectrometry (TDS)—Figure 1 depicts TDS operation. TDS was originally developed for use in the audio frequency range (Heyser, 1967). TDS utilizes a source transducer driven with a signal whose frequency is swept linearly in time. When TDS is used with an ultrasound transmitter and an ultrasound receiver in “pitch/catch” mode, the received frequency differs from the transmitted frequency by the “TDS offset frequency,” $f = S\tau$, where S is the TDS source sweep rate (e.g., in MHz/sec) and τ is the propagation delay between the transmitter and the receiver. The receiver circuitry incorporates a “tracking filter” that tracks the transmitted frequency with an appropriate preset time delay. The tracking filter blocks stray signals that do not have the desired path length and time delay (such as reflections off of the walls of a water tank). The width of the tracking filter’s time acceptance window, $t = BW/S$, where BW is the resolution bandwidth setting of the tracking filter. Because the receiver uses such a narrow band filter, considerable improvement in signal-to-noise ratio (SNR) is realized compared to pulsed techniques.

2. Conventional TDS (CTDS)—Figure 2 shows a block diagram of the CTDS system. The CTDS system is a custom-built, double conversion, heterodyne system described in detail previously (Harris *et al.*, 2004a; Harris *et al.*, 2004b). Briefly, a Hewlett Packard (now Agilent Technologies) 3325A Synthesizer/Function Generator was used to generate a swept-frequency source. This unit was modified to bring out an internally generated tracking signal, which is 30 MHz higher than the regular output. The output of the function generator was fed into the transmitting transducer. The output of the receiving transducer was mixed with the tracking signal of the function generator. The output of the mixer (essentially a multiplier) contained components at frequencies corresponding to the sum and the difference of the tracking signal and the receiving transducer output signal. The difference frequency was 30 MHz plus or minus the TDS offset frequency mentioned above, $f = S\tau$. The sum frequency was eliminated by a bandpass filter (30 MHz center frequency, 0.4 MHz bandwidth). The resulting signal, which was the first intermediate frequency (IF), was 30 MHz $- f$ for an up-sweep or 30 MHz $+ f$ for a down sweep. This signal was then amplified. The amplified signal was then mixed with a cw signal from the offset oscillator (a second function generator) to select the desired time delay that was accepted by the second IF at 250 kHz. To achieve this, the offset oscillator was set to a frequency equal to the difference of the IF frequencies: 29.750 MHz $\pm f$, the sign depending on whether an up or down sweep was used. The resulting difference frequency (250 kHz) was then selected by a Tektronix 7L5 spectrum analyzer plug-in, which was both the second intermediate frequency

amplifier and logarithmic detector. The 7L5 was set for a fixed frequency of 250 kHz. Its bandwidth setting determined the width of the window of time delays that were accepted. The log-magnitude signal generated by the TDS system was averaged ($n=64$) by the digitizing oscilloscope (DSA602A, Tektronix, Beaverton, OR).

Attenuation coefficients were measured using a substitution technique (Gammell *et al.*, 2007). This system was not configured for measurement of phase velocity.

3. Digital TDS (DTDS)—Figure 3 shows a block diagram of the DTDS system. The DTDS system has been described in detail previously (Wear *et al.*, 2014; Wear *et al.*, 2015). Briefly, a Tektronix (Beaverton, OR) AFG 3102 function generator was used to generate a swept frequency source. As with the CTDS system, the output of the function generator was fed into the transmitting transducer. The output of the receiver was amplified using an Olympus (Waltham, MA) 5676 40 dB amplifier and mixed (ZAD-3, Mini-Circuits, Brooklyn, NY) with the output of the function generator. The output of the mixer contained components at frequencies corresponding to the sum and the difference of the function generator and receiver output signals. The signal oscillating at the difference frequency, $f = f_r - f_t$, (also called the “dechirped signal”) was recovered by applying a programmable bandpass filter (model 3384, Krohn-Hite, Brocton, MA), centered at the TDS offset frequency. Signals were averaged ($n=64$) and digitized at 2.5 GHz (11 bits) with a Tektronix DPO 3054 digitizing oscilloscope. Data analysis was performed with MATLAB (Natick, MA). Table I shows TDS parameters for the DTDS system configured with three source transducer / receiving transducer pairs.

Attenuation coefficient and phase velocity were measured using a substitution method adapted from a previously-reported method to measure magnitude and phase of hydrophone sensitivity (Wear *et al.*, 2011). However, instead of comparing two measurements through water acquired using two different receivers (*e.g.*, hydrophones), two measurements were compared using the same source / receiver combination with and without the sample (LDPE or TMM) in the water path.

The substitution experiment measures total signal loss, which includes transmission losses at boundaries and attenuation within the sample. The pressure transmission coefficient of a plane wave due to passage through a planar interface is $T_{1,2} = 2 / (1 + r_1/r_2)$ for a medium propagating from medium 1 into medium 2 with characteristic acoustic impedances $r_1 = \rho_1 c_1$, ρ_i = density of medium i and c_i = phase velocity of medium i (Kinsler *et al.*, 1982). Although this formula is derived for a fluid-fluid interface, it is valid at normal incidence for a large class of solids provided the appropriate value for phase velocity is used (Kinsler *et al.*, 1982). Pressure transmission coefficients were computed based on measurements of density and phase velocity. Through-transmission measurements on LDPE were compensated by the pressure transmission coefficient for the water / LDPE interface on the front side and again for the LDPE / water interface on the back side. Since the LDPE plate was many wavelengths thick and had relatively high attenuation, potential interference effects that can happen due to reverberations within thin layers were assumed to be negligible. The transmission loss correction was not applied to TMM, but the validity of this approach was checked by evaluating pressure transmission coefficients for water / TMM and

TMM / water interfaces. The density of the LDPE plate was measured (mass divided by volume, dimensions measured using digital calipers) to be $\rho_{LDPE} = 0.92 \text{ g/cm}^3$. The density of TMM was $\rho_{TMM} = 1.03 \text{ g/cm}^3$ (King *et al.*, 2011). The density of fresh water was taken to be $\rho_{water} = 0.998 \text{ g/cm}^3$ (Kinsler *et al.*, 1982).

Attenuation coefficients were fit (minimum least square difference) to a power law of frequency, $\alpha(\omega) = \alpha_0 \omega^y$ where $\omega = 2\pi f$, f is frequency, and α_0 and y were fitting parameters. Dispersion was predicted using Kramers-Kronig theory (Waters *et al.*, 2005),

$$\frac{1}{c(\omega)} - \frac{1}{c(\omega_0)} = \alpha_0 \tan\left(\frac{\pi y}{2}\right) (\omega^y - 1 - \omega_0^y - 1)$$

where $c(\omega)$ is the frequency-dependent phase velocity, and ω_0 is a reference frequency. The parameters α_0 and y are material-dependent parameters with $0 < y < 2$ and $y > 1$. The reference frequency ω_0 was chosen to be within the frequency band of analysis. The theoretical phase velocity at the reference frequency $c(\omega_0)$ was set equal to the mean experimental measurement of phase velocity at the reference frequency. Therefore, the Kramers-Kronig analysis investigated only the *frequency dependence* of the phase velocity (*i.e.*, dispersion) but not the *absolute level* of phase velocity.

4. Pulser-Receiver (PR) method—A broadband pulse technique (Madsen *et al.*, 1999) was used to compare with the two TDS techniques. A Panametrics 5900 pulser receiver was used in through-transmission mode to send a broadband pulse to the source transducer. Receiver signals were obtained with and without a sample (LDPE or TMM) in the water path. Substitution methods were used to measure attenuation coefficient (Kuc and Schwartz, 1979) and phase velocity (Wear, 2010). Transmit and receive gain settings on the pulser receiver were optimized by setting to the maximum values that did not result in saturation of the received signal. Signals were averaged ($n=64$) and digitized at 2.5 GHz (11 bits) with a Tektronix DPO 3054 digitizing oscilloscope. and processed offline with MATLAB.

5. Function Fits for Attenuation Coefficient—Measured attenuation coefficients were least-squares fit to two functional forms. The first functional form was $\alpha(\omega) = \alpha_0 \omega^y$ to enable prediction of dispersion based on Kramers-Kronig theory using the equation above (Waters *et al.*, 2005). The second functional form was $\alpha(\omega) = a_1 + a_2 \omega^n$ as addition of the constant term has been reported to result in more accurate fits in some cases.

C. Experimental setup

The same experimental setup inside the water tank was used for CTDS, DTDS, and PR methods. In order to span a wide range of frequencies for application of Kramers-Kronig analysis, three sets of through-transmission measurements were performed with 3 transmitter / receiver pairs. Table I shows transducer and TDS parameters. For the low-frequency measurements, the source was a custom wideband biconcave transducer with usable band from 100 kHz to 2 MHz (Harris and Gammell, 2004) and the receiver was a custom-built membrane hydrophone with a 1 mm sensitive element (Wear *et al.*, 2014). For the intermediate-frequency measurements, the source was a 10 MHz center frequency, 12.7

mm diameter planar transducer (Panametrics, Waltham, MA) and the receiver was a 10 MHz center frequency, 12.7 mm diameter planar transducer (Valpey-Fisher, Hopkinton, MA). For the high-frequency measurements, both source and receiver were Olympus (Waltham, MA) 25 MHz center frequency, 6.25 mm diameter, 50 mm focal-length transducers. TDS sweep rate (S) and filter bandwidth (BW) were chosen to make frequency resolution and time resolution constant for the three sets of experiments. Water temperature for all experiments was measured using a digital thermometer and was used to estimate the temperature-dependent reference sound speed as reported previously (Wear, 2000).

Potential sources of systematic uncertainty for this experimental setup include 1) refraction error if interfaces were not perfectly perpendicular to the propagating ultrasound beam, 2) diffraction error due to the wavelength in the sample being different from the wavelength in water for the substitution experiments, and 3) phase cancellation at the receiver. However, these factors would be expected to have the same effect for CTDs, DTDS, and PR measurements and therefore should have had little effect on the comparison of the three methods.

The objective of the first set of experiments was to compare the effective bandwidths of the CTDs, DTDS, and PR methods. For these experiments, a set of triplicate measurements (CTDS, DTDS, PR) were performed using the intermediate frequency setup (10 MHz source and 10 MHz receiver, see Table I). These consisted of 1) 7 triplicate measurements on a LDPE plate (thickness = 6.1 mm) on four different days, with the LDPE plate repositioned between measurements, and 2) 6 triplicate measurements made on TMM samples (thickness = 20.0 mm), on three different days, with TMM sample repositioned between measurements. The TMM measurements involved three different batches of TMM, so the true values for attenuation coefficient and phase velocity of TMM were approximately the same for all three measurements but not exactly equal.

The objective of the second set of experiments was to synthesize a broad bandwidth for testing the Kramers-Kronig prediction for dispersion in TMM. For these experiments, CTDs and DTDS measurements were performed on TMM samples for low, intermediate, and high frequency experimental configurations (see Table I). For the low frequency measurements, 3 measurements were performed on a sample with thickness of 39.0 mm and 3 measurements were performed on a sample with thickness of 38.0 mm. For the intermediate frequency measurements, 6 measurements were performed on a sample with thickness of 39.0 mm. For the high frequency measurements, 3 measurements were performed on a sample with thickness of 17.8 mm and 3 measurements were performed on a sample with thickness of 8.0 mm. Thinner samples were required at higher frequencies because the TMM attenuation coefficient is a monotonically increasing function of frequency. TMM samples were always repositioned between measurements.

III. RESULTS AND DISCUSSION

Figure 4 shows measurements of attenuation coefficient versus frequency for the LDPE plate (thickness = 6.1 cm) for the intermediate frequency setup (10 MHz source and 10 MHz receiver, see Table I). Since attenuation coefficient is known to monotonically increase with

frequency, declines in measurements above 15 MHz are due to exceeding the valid measurement frequency band. All three methods show similar results between 2 and 12 MHz. The CTDS method shows plausible measurements between 1 and 15 MHz, corresponding to a 40% improvement in bandwidth. The DTDS method shows plausible measurements between 1 and 14 MHz, corresponding to a 30% improvement in bandwidth. The reduced standard deviations for CTDS and DTDS outside the range from 2 to 12 MHz are likely due to the swept-frequency source extending useful measurements to frequencies outside the PR usable bandwidth. The attenuation coefficient value at 5 MHz, approximately 22 dB/cm, is roughly consistent with values reported by others (see Section II.A), considering disparity among different formulations. The two-parameter power law fit for attenuation coefficient was $\alpha(f) = 3.12 f^{1.20}$ dB/cmMHz^{1.20} over the range from 4 to 14 MHz and was used for computing the Kramer-Kronig prediction for dispersion shown in Figure 5. The three-parameter power law fit for attenuation coefficient yielded a constant term of 0.0000 and was therefore essentially identical to the two-parameter power law fit. The root-mean-square difference (RMSD) between the DTDS measurements and the power law fit was 0.26 dB/cm over the range from 4 to 14 MHz.

Figure 5 shows measurements of phase velocity vs. frequency for the LDPE plate for the intermediate frequency setup (see Table I). The dotted lines show predicted dispersion based on the measured attenuation coefficient power law and the Kramers-Kronig relations. Both methods show similar results between 4 and 11 MHz. However, the DTDS method shows frequency-dependent phase velocity consistent with Kramers-Kronig relations from 2 to 12 MHz, corresponding to a 43% improvement in bandwidth. The speed of sound value at 5 MHz, approximately 2130 m/s, is roughly consistent with values reported by others (see Section II.A), considering disparity among different formulations. The reference frequency ω_0 (where the theoretical phase velocity was set equal to the experimental phase velocity) was 9 MHz. From values of $c_{LDPE} = 2150$ m/s, $c_{water} = 1480$ m/s, $\rho_{LDPE} = 0.92$ g/cm³, and $\rho_{water} = 0.998$ g/cm³ (Kinsler *et al.*, 1982), pressure transmission coefficients may be computed as $T_{water,LDPE} = 1.14$ and $T_{LDPE,water} = 0.86$. Their combined effect on the pressure wave passing through the LDPE plate was the product $T_{water,LDPE} T_{LDPE,water} = 0.98$. This correction factor was used in processing the attenuation coefficient data in Figure 4. The RMSD between the DTDS measurements and predictions based on Kramers-Kronig relations was 9 m/s over the range from 2 to 12 MHz.

Figure 6 shows measurements of attenuation coefficient versus frequency for TMM (thickness = 20 cm) for the intermediate frequency setup (see Table I). All three methods show similar results between 2 and 11 MHz. The CTDS method shows plausible measurements between 1 and 19 MHz, corresponding to a 100% improvement in bandwidth. The DTDS method shows plausible measurements between 1 and 18 MHz, corresponding to an 89% improvement in bandwidth. The two-parameter power law fit for attenuation coefficient was $\alpha(f) = 0.27 f^{1.31}$ dB/cmMHz^{1.31} over the range from 2 to 18 MHz and was used for computing the Kramer-Kronig prediction for dispersion shown in Figure 7. The three-parameter power law fit for attenuation coefficient was 0.24 dB/cm + $0.21 f^{1.38}$ dB/cmMHz^{1.38}. The RMSD between the DTDS measurements and the power law fit was 0.10 dB/cm over the range from 2 to 18 MHz.

Figure 7 shows measurements of phase velocity vs. frequency for TMM (thickness = 20 cm) for the intermediate frequency setup (see Table I). Both methods show similar results between 5 and 16 MHz. However, the DTDS method shows frequency-dependent phase velocity consistent with Kramers-Kronig relations from 2 to 17 MHz, corresponding to a 36% improvement in bandwidth. The reference frequency ω_0 (where the theoretical phase velocity was set equal to the experimental phase velocity) was 10 MHz. From values of $c_{\text{TMM}} = 1495$ m/s, $c_{\text{water}} = 1480$ m/s, $\rho_{\text{TMM}} = 1.03$ g/cm³, and $\rho_{\text{water}} = 0.998$ g/cm³ (Kinsler *et al.*, 1982), pressure transmission coefficients may be computed as $T_{\text{water,TMM}} = 1.02$ and $T_{\text{LDPE,TMM}} = 0.98$. Their combined effect on the pressure wave passing through the LDPE plate was the product $T_{\text{water,LDPE}} T_{\text{LDPE,water}} = 0.9996$. This correction factor was not applied to attenuation coefficient data as it was expected to be small relative to experimental error. The RMSD between the DTDS measurements and predictions based on Kramers-Kronig relations was 1.7 m/s over the range from 2 to 18 MHz.

Figure 8 shows composite DTDS attenuation data for TMM acquired using all three transmitter / receiver transducer pairs (see Table I). Useful attenuation data was acquired from 0.5 to 29 MHz. The power law fit for attenuation was $\alpha(f) = 0.25 f^{1.35}$ dB/cmMHz^{1.35} over the range from 0.5 to 29 MHz and was used for computing the Kramer-Kronig prediction for dispersion shown in Figure 9. The RMSD between the DTDS measurements and the power law fit was 0.55 dB/cm over the range from 0.5 to 29 MHz.

Figure 9 shows composite DTDS phase velocity data for TMM acquired using all three transmitter / receiver transducer pairs (see Table I). The data agree well with dispersion predicted using the Kramers-Kronig relations and the measured attenuation power law parameters. The reference frequency ω_0 (where the theoretical phase velocity was set equal to the experimental phase velocity) was 15 MHz. Note that the data in Figures 7/8 and 9/10 were generated from different batches of TMM. Attenuation and phase velocity vary somewhat from batch to batch. The data in Figure 7 were acquired using three different batches of TMM, which led to bigger error bars. Figure 9 was based on a single batch. The RMSD between the DTDS measurements and predictions based on Kramers-Kronig relations was 0.4 m/s over the range from 0.5 to 29 MHz.

IV. CONCLUSION

The TDS phase velocity and attenuation are compared to values obtained using a conventional PR through-transmission method. While attenuation and phase velocity of LDPE and a TMM used for HITU show excellent agreement between the two methods of acquisition (TDS and PR) to within 1%, the TDS measurements provide superior bandwidth over the PR measurements due to better SNR. TDS provides measurements of frequency-dependent phase velocity that are consistent with predictions based on the Kramers-Kronig relations and measurements of attenuation coefficient to within 5 m/s over the band from 2 – 12 MHz in low-density polyethylene (LDPE) and to within 1 m/s in TMM over the band from 0.5 – 29 MHz. Therefore, TDS is a powerful tool for characterizing a wide range of materials, including tissue-mimicking materials used for medical device testing.

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Figure 1.
(color online) Depiction of TDS operation.

Figure 2.
Block diagram of conventional TDS (CTDS) system.

Figure 3.
Block diagram of digital TDS (DTDS) system.

Figure 4. (color online) Attenuation coefficient for LDPE measured using CTDS, DTDS, and PR methods. Error bars denote standard deviations. Means and standard deviations were computed from 7 broadband through-transmission measurements.

Figure 5.

(color online) Phase velocity for LDPE measured using CTDS, DTDS, and PR methods. Error bars denote standard deviations. Means and standard deviations were computed from 7 broadband through-transmission measurements.

Figure 6. (color online) Attenuation coefficient for TMM measured using CTDS, DTDS, and PR methods. Error bars denote standard deviations. Means and standard deviations were computed from 6 broadband through-transmission measurements.

Figure 7.
(color online) Phase velocity for TMM measured using CTDS, DTDS, and PR methods. Error bars denote standard deviations. Means and standard deviations were computed from 6 broadband through-transmission measurements.

Figure 8.

(color online) Attenuation coefficient for TMM measured using DTDS. Error bars denote standard deviations. A power law fit is also shown. Means and standard deviations were computed from 12 through-transmission measurements (3 low frequency, 6 intermediate frequency, and 3 high-frequency—see Table I for definitions of low, intermediate and high frequencies).

Figure 9.

(color online) Phase velocity for TMM measured using DTDS. Error bars denote standard deviations. The Kramers-Kronig relation prediction of dispersion is also shown. Means and standard deviations were computed from 12 through-transmission measurements (3 low frequency, 6 intermediate frequency, and 3 high-frequency—see Table I for definitions of low, intermediate and high frequencies).

Table I.

Transducer and TDS parameters for three sets of experiments for low, intermediate, and high frequency ranges.

	Frequency Range:	Low	Intermediate	High
Source Transducer	Center frequency (MHz)	1	10	25
	Diameter (mm)	40	12.7	6.25
	Focal Length (mm)	200	∞	25
Receiving Transducer	Center frequency (MHz)	(hydrophone)	10	25
	Diameter (mm)	1	12.7	6.25
	Focal Length (mm)	∞	∞	25
	Source / Receiver Separation z (cm)	15	30	10
TDS Parameters	Delay Time $t_D = z/c$ (μ s)	101	203	68
	Maximum Sweep Frequency (MHz)	20	20	40
	Sweep Time (s)	0.2	0.334	0.267
	Sweep Rate S (MHz/s)	100	60	150
	TDS Offset Frequency $f = S t_D$ (kHz)	10.1	12.1	10.1
	Filter bandwidth (BW) (kHz)	0.67	0.4	1
	Frequency Resolution S / BW (MHz)	0.15	0.15	0.15
	Time resolution $t = BW / S$ (μ s)	6.7	6.7	6.7